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# Sports Medicine and Physical Fitness

Edited by
Ewan Thomas, Ivan Chulvi-Medrano and Elvira Padua

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# Sports Medicine and Physical Fitness

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Editors

**Ewan Thomas**
**Ivan Chulvi-Medrano**
**Elvira Padua**

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*Editors*
Ewan Thomas
Department of Psychology, Educational Science and Human Movement
University of Palermo
Palermo
Italy

Ivan Chulvi-Medrano
Department of Physical and Sports Education. Faculty of Physical Activity and Sport Sciences.
University of Valencia
Valencia
Spain

Elvira Padua
Department of Human Sciences and Promotion of the Quality of Life
San Raffaele University of Rome
Roma
Italy

*Editorial Office*
MDPI
St. Alban-Anlage 66
4052 Basel, Switzerland

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# About the Editors

**Ewan Thomas**

Ewan Thomas is an Associate Professor of research methodology applied to biomedical context and human movement at the University of Palermo, his research interests are exercise prescription for special populations, stretching and balance evaluation. He is also a certified Osteopath.

**Ivan Chulvi-Medrano**

Ivan Chulvi Medrano is a Professor at the University of Valencia, his main research interests are pediatric resistance training, clinical exercise and blood flow restrictions exercises. He is also a certified Strength and Conditioning Specialist and an NSCA associate.

**Elvira Padua**

Elvira Padua is an Associate Professor at the San Raffaele University of Rome. Her research interests are training theory in childhood, adolescence and elderly, injury prevention, and physical activity adapted to main metabolic disorders.

# Preface to "Sports Medicine and Physical Fitness"

Sports Medicine and Physical Fitness has been a successful Special Issue, which addressed novel topics in any subject related to sports medicine, physical fitness, and human movement. The article collection was able to positively evaluate three systematic reviews, nineteen originals articles, and one brief report. These encompassed a broad range of topics ranging from accident kinematics, soccer monitoring, children's physical evaluation, adapted physical activity, physical evaluation for people with intellectual disabilities, performance analysis in rowers, ultramarathon racers, karateka's, rugby players, volleyball and basketball players, and cross-fit athletes, and also aspects related to biomechanics, fatigue and injury prevention in racing motorcycle riders, gymnasts and cyclists.

These scientific contributions within the field of Sports Medicine and Physical Fitness broaden the understanding of specific aspects of each analyzed discipline.

It has been a pleasure for the Editorial Team to have served the International Journal Of Environmental Research and Public Health.

**Ewan Thomas, Ivan Chulvi-Medrano, Elvira Padua**
*Editors*

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*Article*

# Full-Face Mask Use during SCUBA Diving Counters Related Oxidative Stress and Endothelial Dysfunction

**Morgan Levenez [1], Kate Lambrechts [1], Simona Mrakic-Sposta [2], Alessandra Vezzoli [2], Peter Germonpré [1,3,4], Hadrien Pique [1], Fabio Virgili [5,*], Gerardo Bosco [6], Pierre Lafère [1,4] and Costantino Balestra [1,4,7,*]**

1 Environmental, Occupational, Aging (Integrative) Physiology Laboratory, Haute Ecole Bruxelles-Brabant (HE2B), 1180 Brussels, Belgium; mlevenez@he2b.be (M.L.); klambrechts@he2b.be (K.L.); pgermonpre@gmail.com (P.G.); phadrien98@gmail.com (H.P.); plafere@he2b.be (P.L.)
2 Institute of Clinical Physiology, National Research Council (IFC-CNR), Piazza dell'Ospedale Maggiore, 20162 Milano, Italy; simona.mrakicsposta@cnr.it (S.M.-S.); alessandra.vezzoli@cnr.it (A.V.)
3 Hyperbaric Centre, Queen Astrid Military Hospital, 1120 Brussels, Belgium
4 DAN Europe Research Division, Contrada Padune, 64026 Roseto, Italy
5 Council for Agricultural Research and Economics—Food and Nutrition Research Centre (CREA-AN), Via Ardeatina 548, 00187 Rome, Italy
6 Environmental Physiology & Medicine Laboratory, Department of Biomedical Sciences, University of Padova, 35122 Padova, Italy; gerardo.bosco@unipd.it
7 Physical Activity Teaching Unit, Motor Sciences Department, Université Libre de Bruxelles (ULB), 1050 Brussels, Belgium
* Correspondence: fabio.virgili@crea.gov.it (F.V.); costantinobalestra@gmail.com (C.B.)

**Abstract:** Impaired flow mediated dilation (FMD), an index of vascular stress, is known after SCUBA diving. This is related to a dysfunction of nitric oxide (NO) availability and a disturbance of the redox status, possibly induced by hyperoxic/hyperbaric gas breathing. SCUBA diving is usually performed with a mask only covering "half face" (HF) and therefore forcing oral breathing. Nasal NO production is involved in vascular homeostasis and, as consequence, can significantly reduce NO possibly promoting vascular dysfunction. More recently, the utilization of "full-face" (FF) mask, allowing nasal breathing, became more frequent, but no reports are available describing their effects on vascular functions in comparison with HF masks. In this study we assessed and compared the effects of a standard shallow dive (20 min at 10 m) wearing either FF or a HF mask on different markers of vascular function (FMD), oxidative stress (ROS, 8-iso-PGF2$\alpha$) and NO availability and metabolism ($NO_2$, NOx and 3-NT and iNOS expression). Data from a dive breathing a hypoxic (16% $O_2$ at depth) gas mixture with HF mask are shown allowing hyperoxic/hypoxic exposure. Our data suggest that nasal breathing might significantly reduce the occurrence of vascular dysfunction possibly due to better maintenance of NO production and bioavailability, resulting in a better ability to counter reactive oxygen and nitrogen species. Besides the obvious outcomes in terms of SCUBA diving safety, our data permit a better understanding of the effects of oxygen concentrations, either in normal conditions or as a strategy to induce selected responses in health and disease.

**Keywords:** hypoxia; hyperoxia; hyperbaric breathing; nitric oxide; vascular reactions; breathing; extreme environments

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## 1. Introduction

Recreational SCUBA (self-contained underwater breathing apparatus) diving is considered a safe leisure activity. However, it is known to induce (generally mild) adaptive responses potentially interfering with different physiological pathways, some of them being possibly harmful. When SCUBA divers stay at depth, they are exposed to inert gas supersaturation that may be translated into vascular gas emboli (VGE) during and following ascent while decompressing [1]. Although decompression-induced bubble formation is a pivotal event in decompression sickness (DCS), the exact pathophysiological mechanisms linking VGE to DCS are still unclear; however, both are linked and evidently related to ambient pressure drop.

Changes in flow mediated dilation (FMD), a sensitive marker of a physiological response of the vascular system, has been repeatedly reported to occur after diving, suggesting vascular dysfunction of large conductance arteries [2–4]. This dysfunction, which is usually recovered to normality a few hours after surfacing, is however to be considered an index of vascular stress. More recently, diving has been reported to induce a response extended to the microvascular endothelium [2] and to the macro and microvascular smooth muscle [2,5]. The predive administration of bioactive molecules belonging to a very large family known as polyphenols and frequently reported as having a putative "antioxidant capacity" have been reported to partially prevent postdive alterations of FMD [6–8], suggesting the implication of an oxidative stress in this response. Indeed, impaired FMD [4,9] and increased oxidative stress [7,10] were also reported postdive even in the absence of VGE, suggesting that the organism casts out a physiological response to high oxygen, which does not necessarily result in a clinically relevant dysfunction. It seems also plausible that other factors contribute to postdive alteration of vascular function [11]. For instance, it has been shown that circulating bubbles can lead to vascular dysfunction [12] either by a direct "mechanical" contact between circulating bubbles and endothelial cells [13,14] or by an uncontrolled activation of the coagulation cascade [15–17], or by a combination of these two mechanisms. Activation of haemostatic pathways contributes to the postdive increase of circulating microparticles, which in turn leads to leukocytes activation [18,19] and their adhesion to the endothelium [20].

For several years, preconditioning strategies to reduce this "decompression stress" have been considered and investigated [21]. Nutritional strategies with polyphenols-rich food supplementation (dark chocolate and red orange complex or vitamin C, to name a few) have been shown to reduce vascular dysfunction [8,22]. Physical interventions (predive vibration, oxygen breathing, exercise, sauna) appear capable in limiting the generation of VGE after a dive through the reduction of pre-existing gas micronuclei [21]. Two decades ago, specific attention and focus was given to nasal breathing and vascular dysfunction. In fact, nitric oxide production by the nasal fossae and sinuses mucosae is an important variable involved in vascular homeostasis and, as a consequence, oral breathing can significantly reduce circulating nitric oxide (NO), possibly promoting vascular dysfunction [23]. Some specific abnormalities can interfere with normal NO production by the nasal mucosae and a lead to discomfort or even some surgical interventions; none of our subjects declared such abnormalities [24,25] during the eligibility discussion.

In this study we aimed to investigate the role of nasal breathing on vascular function occurring after diving, starting from the observation that all previously available studies in diving have been conducted using oral breathing, with conventional "half-face" masks, and none utilizing nasal breathing by means of the so-called "full-face" masks. To limit confounding factors, we specifically planned an experimental design based on a known "bubble free" dive profile.

## 2. Materials and Methods

### 2.1. Experimental Protocol

After written informed consent, 16 (6 females and 10 males) (Figure 1) healthy nonsmoking divers (minimum certification "Autonomous Divers" according to European norm EN 14153-2 or ISO 24801-2 with at least 50 logged dives) volunteered for this study. None of them had a history of previous cardiac abnormalities or were under any cardio- or vaso-active medication. They were selected from a large population of divers in order to have a homogenous sample: aged 44.7 ± 12.4 years old (mean ± SD); height 173 ± 6.6 cm; weight 75.2 ± 13.7 kg.

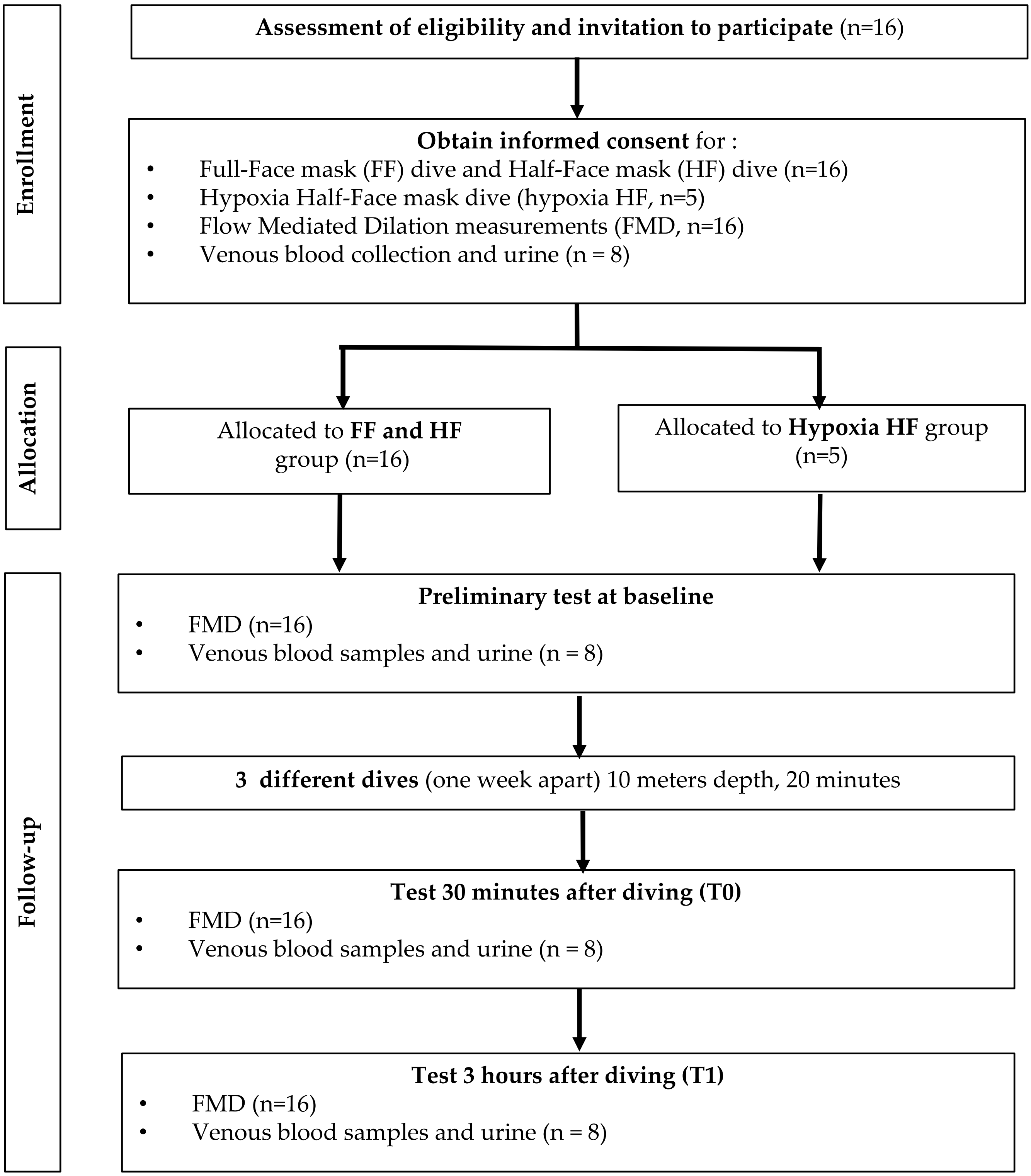


**Figure 1.** Flowchart of the experimental protocol.

All experimental procedures were conducted in accordance with the Declaration of Helsinki [26] and approved by the Ethics Committee approval from the Bio-Ethical Committee for Research and Higher Education, Brussels (N° B200-2020-088).

Participants were prospectively randomized into two groups of 8 persons each. They were assigned to either "full-face mask" (Ocean Reef, Neptune Space G-Divers IDM mask, see Figure 2) or "half-face" (usual diving mask, see Figure 2) mask group for the first dive, and vice versa for the second one, making each diver his own control. Another specific experiment was also performed ($n$ = 5) using a usual diving mask but breathing a gas mixture corresponding to 16% of oxygen at depth, to reduce oxygen reactive species inhalation. This mixture was a hypoxic trimix composed of 8% oxygen mixed with helium and nitrogen (Trimix); this mixture, being hypoxic at surface, can only be breathed at depth, the divers were using air during their descent and their ascent, these two portions of the dive took around one minute each, the slightly hypoxic breathing took 20 min.

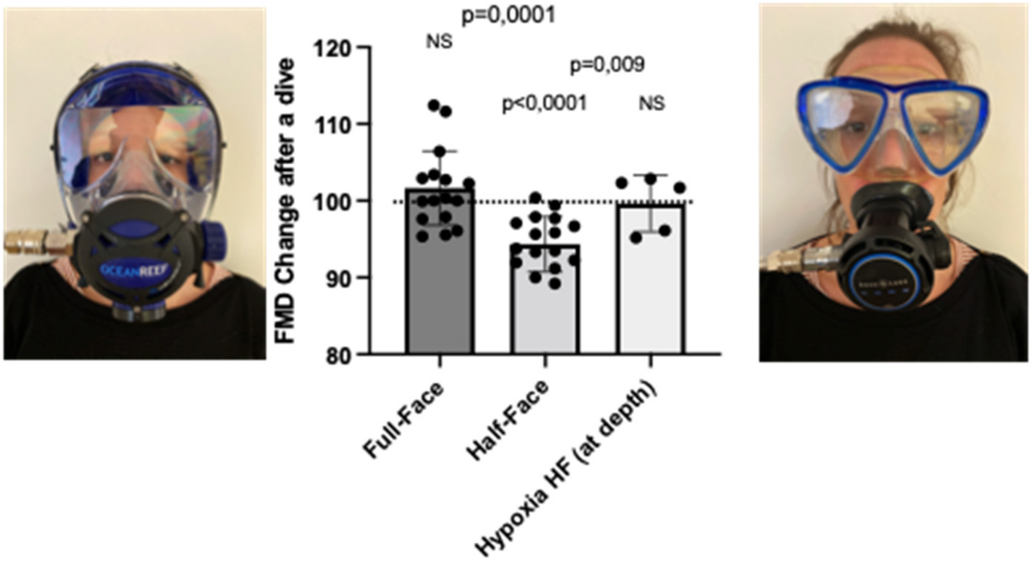


**Figure 2.** Flow mediated dilation (FMD) changes after a dive (10 m for 20 min) either wearing a full-face mask or a classical "half-face" diving mask ($n$ = 16). In hypoxic dives ($n$ = 5), subjects were breathing a gas mixture providing 0.16 ATA of $PO_2$ at depth. FMD changes are expressed as % of predive values, every diver acting as his own control. Results are expressed as percentage (mean ± SD); NS = nonsignificant.

All dives were performed in a pool environment dedicated to SCUBA diving (NEMO 33, Brussels, Belgium). The dive profile was specifically chosen to avoid any bubble formation (10 m depth, 20 min). Indeed, this dive does not require any decompression procedure as for every decompression table actually accepted the no-decompression time for a depth of 10 m is far over 200 min. To be sure, we chose 10 times less. Additionally, the postdive bubble measurements as previously reported were "no-bubble" using the same bubble measurements protocol performed by our group, see Balestra et al. 2016 [27].

However, divers were submitted to a significant oxidative stress in order to interfere with the endothelial function since at that depth, oxygen inspired fraction is close to 40% (0.4 $PO_2$ ± 300 mmHg).

### 2.2. Flow Mediated Dilation (FMD)

FMD, an established measure of the endothelium-dependent vasodilation mediated by nitric oxide (NO) [28], was used to assess the effect of diving on main conduit arteries. Subjects were at rest for 15 min in a supine position before the measurements were taken; they were asked not to drink caffeinated beverages for 6 h preceding measurements. Subjects were instructed not to perform strenuous physical exercise 24 h before or stay in altitude up to 2 weeks before and during the entire study protocol. Brachial artery diameter was measured by means of a 5.0–10.0 MHz linear transducer using a Mindray DP-30 digital diagnostic ultrasound system immediately before and 1 min after a 5 min ischemia induced by inflating a cuff placed on the forearm to 180 mmHg, as described previously [29].

All ultrasound assessments were performed by an experienced operator with more than 100 scans/year, which is recommended to maintain competency with the FMD method [30].

When the images were chosen for analysis, the boundaries for diameter measurement were identified manually with an electronic caliper (provided by the ultrasonography software) in a threefold repetition pattern to calculate the mean value. In our laboratory, the mean intra observer variability for FMD measurement for the operator (KL) recorded the same day, on the same site and on the same subject, was 1.2 ± 0.2%.

Post-dive values were obtained 20–30 min after surfacing. FMD was calculated as the percent increase in arterial diameter from the resting state to maximal dilation.

### *2.3. Venous Blood Samples and Urine*

Among the 16 participants, 8 accepted venous blood collection. Venous blood samples were collected at baseline (before diving), 30 min (T0) and 3 h (T1) after diving. Fifteen milliliters of blood were collected in EDTA and heparinized vacutainer tubes for separation of plasma. Urine was collected by voluntary voiding in a sterile container and stored in multiple aliquots at −20 °C. All samples were stored in multiple aliquots at −80 °C until assayed and performed within one month from the collection.

### *2.4. Blood Sample Analysis*

#### 2.4.1. ROS Production

EPR, X-band instrument (E-Scan—Bruker BioSpin, GmbH, Ettlingen, Germany) was adopted. ROS production rate was determined by means of a well-consolidated method in blood [31–34]. Spin probe, CMH (1-hydroxy-3-methox-ycarbonyl-2,2,5,5-tetramethylpyrrolidine) was used for determination, and stable radical CP· (3-Carboxy2,2,5,5-tetramethyl-1-pyrrolidinyloxy) was used as external reference to convert ROS determinations in absolute quantitative values ($\mu mol \cdot min^{-1}$). Samples were stabilized at 37 °C by "Bio III" controller unit, interfaced to the spectrometer.

#### 2.4.2. 8-Isoprostane

Lipid peroxidation was assessed in urine by competitive immunoassay (Cayman Chemical, Ann Arbor, MI, USA) measuring 8-isoprostane (8-iso-PGF2α) concentration following the manufacturer's recommendations. The 8-iso-PGF2α concentrations were determined using a standard curve. Samples and standards were spectrophotometrically read at a wavelength of 412 nm.

#### 2.4.3. Nitric Oxide Metabolites (NOx)

NOx concentrations were determined for urine via a colorimetric method based on the Griess reaction, using a commercial kit (Cayman Chemical, Ann Arbor, MI, USA) as previously described [35,36]. Samples were spectrophotometrically read at 545 nm.

#### 2.4.4. Inducible Nitric Oxide Synthase (iNOS)

To assess inducible nitric oxide synthase (iNOS) expression in plasma, a human NO2/iNOS ELISA kit (catalog number EH0556; FineTest, Wuhan, China) was used. This assay was based on sandwich enzyme-linked immune-sorbent assay technology. NOS2/iNOS protein synthesis was determined using a standard curve.

#### 2.4.5. Nitrotyrosine (3-NT)

The concentration of 3-NT on plasma was measured by competitive-ELISA method, using an assay kit (catalog number EU2560; FineTest, Wuhan, China). The analysis was carried out in accordance with the manufacturer's instructions, and the 3-NT concentration was measured spectrophotometrically at a wavelength of 450 nm by comparing the sample OD (optical density) to a standard curve.

All the samples and standards were read by a microplate reader spectrophotometer (Infinite M200, Tecan Group Ltd., Maännedorf, Switzerland). The determinations were assessed in duplicate, and the interassay coefficient of variation was in the range indicated by the manufacturer.

### *2.5. Statistical Analysis*

Normality of data was performed by means of Shapiro–Wilk or D'Agostino–Pearson tests. When a Gaussian distribution was assumed, data were analyzed with a one-way ANOVA for repeated measures with Dunnett's post hoc test; when comparisons were limited to two samples, a paired or nonpaired *t*-test was applied. If the Gaussian distribution was not assumed, the analysis was performed by means of a nonparametric multiple comparisons Dunn's test. Taking the baseline measures as 100% (percentage or fold change), changes were calculated for each diving protocol, allowing an appreciation of the magnitude of change rather than the absolute values. All statistical tests were performed using a standard computer statistical package, GraphPad Prism version 5.00 for Windows (GraphPad Software, San Diego, CA, USA). A threshold of $p < 0.05$ was considered statistically significant. All data are presented as mean ± standard deviation (SD). Sample size was calculated by setting the power of the study at 95% and assuming that variables associated with diving would have been affected on a similar extent than that observed in our previous studies [10].

## **3. Results**

### *3.1. Nasal–Oral Breathing by Wearing a Full-Face Mask and Breathing a Hypoxic Air Mixture Prevents FMD Reduction after a Shallow Dive, in Comparison to a Half-Face Mask*

We previously demonstrated that diving is associated with a significant reduction of NO-related endothelial function of large arteries, and that predive administration of polyphenol-rich food items (chocolate) or plant extract from red orange significantly counters this response [8,22]. The utilization of full-face masks during SCUBA diving allows breathing through the nose, which is a confirmed physiological strategy to increase circulating NO [8], therefore potentially modulating the effects of diving on FMD. Accordingly, FMD variation values were 102 ± 6.7% ($p = 0.168$, NS = nonsignificant) and 94.3 ± 3.6% ($p < 0.0001$) when utilizing a full-face mask and a half-face mask (regular mask), the difference between both conditions being highly significant ($p = 0.001$) (Figure 2). FMD returned to normal values 3 h after half mask exposure and remained stable after full-face exposure; these values were, respectively, 100.6 ± 2.5% and 100.2 ± 2.8%.

The hypoxic dive experiment was performed on 5 subjects (4 male and 1 female) out of the divers that already performed the set of dives described above, using a regular (half-face) mask (and therefore breathing only orally). This experiment would let the diver breath at depth a hypoxic mixture ($FiO_2$ of 8% corresponding to a $PO_2$ of 0.16 ATA) corresponding to 16% of oxygen at surface, thus reducing the absolute inspired pressure of oxygen, significantly reducing, in theory, the oxidative stress associated with high oxygen.

In this case, we observed no difference in postdive FMD variations in subjects with a half-face mask (breathing hypoxic mixture at depth) directly postdive 99.6 ± 3.6 %, after 30 min (98.8 ± 0.7% relative to predive values), neither after 3 h (99.6 ± 0.6%). Comparing this with the significant difference observed in the same subjects when in hyperoxic conditions (half-face mask, breathing air at depth, 0.42 atmospheres inspired oxygen pressure) (94.3 ± 3.6%), it can be concluded that breathing a hypoxic air mixture does not induce a significant decrease of FMD potentially associated with vascular dysfunction, even in oral breathing conditions (Figure 2).

### *3.2. ROS Production and Lipid Peroxidation*

In association to a shallow dive, independent of the mask worn and the air mixture, ROS production, assessed by means of the EPR detection of the Spin probe CMH, was significantly increased on return to the surface (T0). ROS production increased from 0.16 ± 0.01

to 0.19 ± 0.01 μmol·min$^{-1}$ and from 0.16 ± 0.01 to 0.20 ± 0.01 μmol·min$^{-1}$ when wearing a full-face mask and a half-face device, respectively. Breathing a hypoxic mixture utilizing a half mask, ROS production increased from 0.16 ± 0.01 to 0.21 ± 0.01 μmol·min$^{-1}$ (Figure 3A). In all cases, a trend to a recovery to the predive value was observed at T1 corresponding to 3 h from surface, without reaching a significant level within the short window of experimental time.

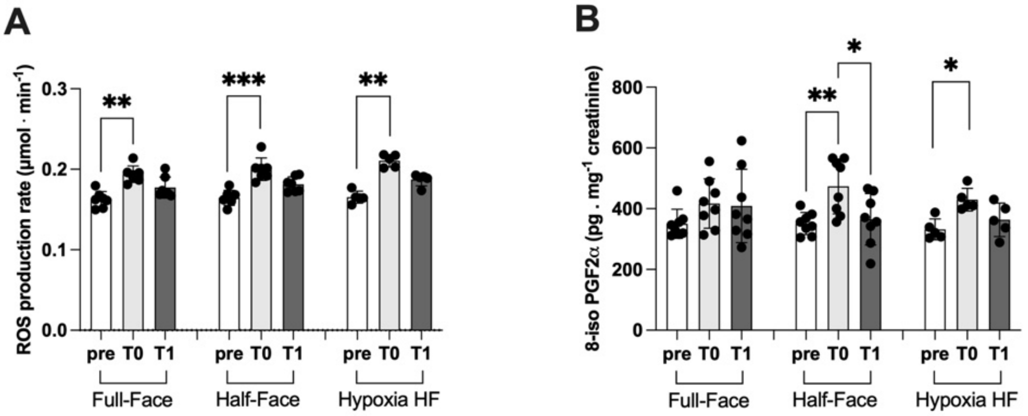


**Figure 3.** Panels show the histogram plot (mean ± SD) of (**A**) ROS production (EPR), and (**B**) 8-iso PGF2-α concentration (ELISA). * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$ significant difference.

Similarly (Figure 3B), the concentration of 8-iso PGF2-α, a marker of lipid peroxidation, was significantly increased after the dive session wearing a half-face mask. When breathing atmospheric air, values increased from 351.10 ± 36.35 to 473.40 ± 90.06 pg·mg$^{-1}$ creatinine, returning to 364.90 ± 84.50 pg·mg$^{-1}$ creatinine within the experimental window of time. A significant increase (331.90 ± 34.16 vs. 430.0 ± 37.35 pg·mg$^{-1}$ creatinine) associated with a shallow dive was also observed when subjects were submitted to hypoxia while wearing a HF device. Additionally, in this case we observed a trend toward recovery after 3 h from surfacing (363.50 ± 54.80 pg·mg$^{-1}$ creatinine), which was not significant within the observation window of time. On the other hand, no significant changes were observed when wearing a full-face mask.

### 3.3. Nitric Oxide Synthase and Nitric Oxide Metabolites

As mentioned in the introduction, oral breathing can significantly reduce circulating nitric oxide (NO), possibly promoting in turn the basis for an endothelial dysfunction [8]. Considering the observed decrease of nitrotyrosine levels when wearing either the full-face or the half-face mask (Figure 4C), we sought to assess the presence of a parallel modulation of nitric oxide metabolites and of nitric oxide synthase activity.

We observed a significant modulation of both nitric oxide metabolites (NOx) and, more specifically $NO_2$ levels, only in subjects wearing the half-face mask but not the full-face mask. Similarly, a shallow dive performed while breathing a hypoxic mixture was not associated with significant changes in NOx and $NO_2$ levels. The time after surface was not associated with significant changes of both NOx and $NO_2$, within the temporal window of time considered (Figure 4A,B).

Plasma levels of nitrotyrosine, a product of tyrosine nitration mediated by reactive nitrogen species such as peroxynitrites and nitrogen dioxide and therefore identified as a marker of cell damage and inflammation, significantly decreased at the end of a shallow dive both when wearing a full-face and a half-face mask. At 3 h from surface there was still no full recovery to baseline values except during hypoxic breathing, when no significant changes were observed (Figure 4C).

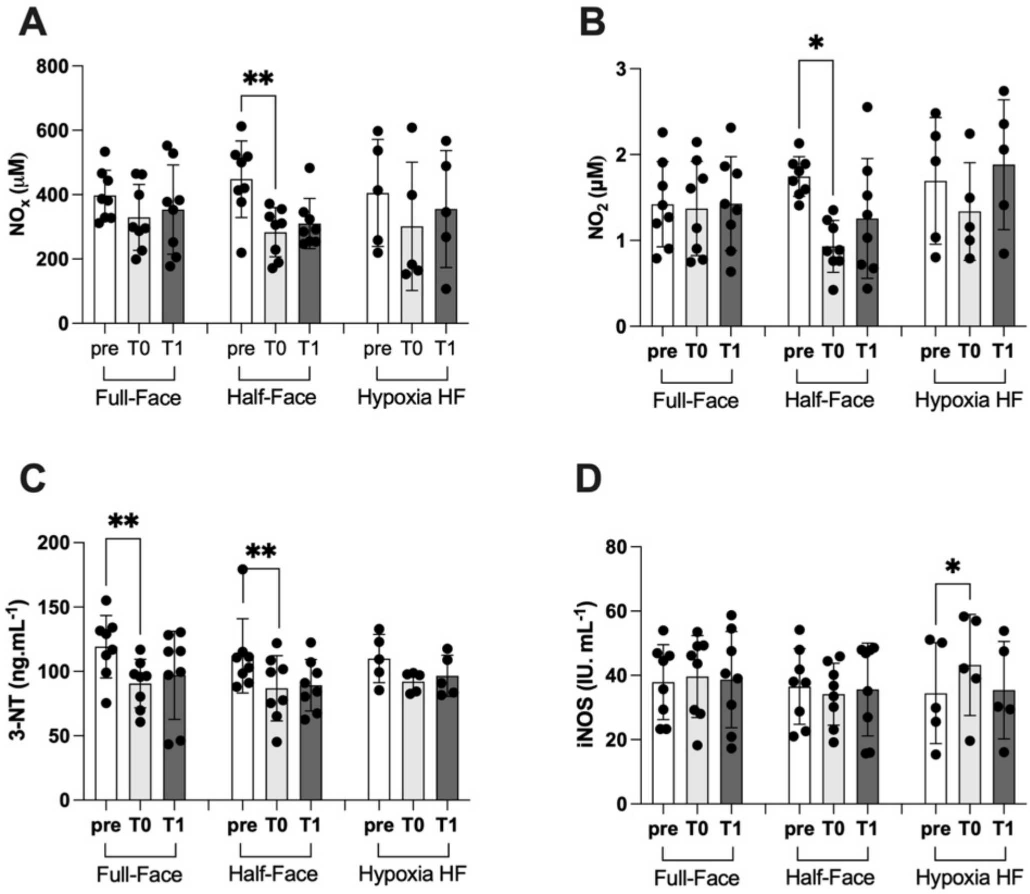


**Figure 4.** Panels show the histogram plot (mean ± SD) of (**A**) NO metabolites (NOx) (ELISA), (**B**) nitrite ($NO_2$) (ELISA), (**C**) nitrotyrosine (3-NT) (ELISA) and (**D**) inducible nitric oxide synthase (iNOS) (ELISA). * $p < 0.05$, ** $p < 0.01$ significant difference.

Interestingly, we observed no significant variations in the activity of iNOS, the inducible form of nitric oxide synthase, in association with a shallow dive performed by utilizing both the half- and the full-face mask. On the other hand, and somehow surprisingly, we observed a significant increase of iNOS activity at the surface, which is not attributable to a positive transcriptional regulation, being the diving time too short to justify a de novo synthesis. In all cases, no significant variations of iNOS activity were observed at 3 h from surfacing (Figure 4D).

## 4. Discussion

As a preliminary tenet to the discussion of our results, it is important to remark that we do not attribute a necessary negative value to alteration specific biochemical/physiological parameters, characterized by the involvement of a huge number of variables and homeostatic switches. These should be, at least initially, considered and interpreted as “response” and not as “biomarkers for an occurring damage”.

This is the case of the transient significant decrease of FMD observed after a SCUBA dive and, in particular, when performed while wearing a mask that allows breathing only through the mouth. Therefore, rather, we have utilized this parameter as a sensitive indication for a different physiological response to high oxygen breathing performed according to two different experimental modalities.

Sex differences in endothelial functions, and therefore on FMD response, have been reported and considered a confounding variable that amplify the within-group variability [37]. However, the number of subjects enrolled in the study was based on the variability observed in previous studies from our laboratory and others. We assumed a similar effect on

FMD response after diving (roughly 5–7%), which is indeed comparable with a commonly accepted span observed in a specific sex group.

Newly published data indicate that FMD variations can be related to circulating microparticles [35], which were not considered in the study reported herein. FMD after hypoxic breathing showed a trend to increase, therefore suggesting that the influence of hypoxia-triggered microparticle formation is limited in our setting and, possibly, a greater influence of inspired NO.

Our results on FMD variation after a dive that was not prone to produce bubbles are comparable to previously published data from our group and others, although bubbles have been occasionally observed within different experimental settings [2,5,37]. Interestingly, previous studies have also demonstrated the occurrence of endothelial dysfunction after breath-hold diving [9,36,38]. This effect was prevented by nutritional supplementation of molecules putatively having either an antioxidant activity or affecting endogenous machinery involved in redox regulation [9,10,38]. These observations suggest that the effects of diving on FMD are possibly due to a decrease of NO generation or bioavailability [38,39]. It is plausible that an exceeding generation of reactive species could interact with NO, subtracting it to the vascular function and increasing the condition of oxidative stress induced by the increased partial pressure of oxygen at depth. This situation is present in SCUBA divers and breath-hold divers, but slightly different mechanisms are involved. Noteworthy, several studies have already addressed the effect of restricting breathing by mouth on respiratory and cardiovascular parameters, NO production and metabolism at surface, not associated with underwater diving or, generally, to either hyperoxia or hyperbaric oxygen exposure, suggesting that nasal breathing plays an important role in vascular performances [40,41].

After a shallow dive, we observed a significant increase of ROS generation in all conditions tested, eventually returning at baseline levels at 3 h from reaching the surface (T1). An increase of ROS generation is less expected after hypoxia, however; this observation is in agreement with several previous studies indicating that low oxygen concentration induces dysregulation of cellular oxygen metabolism and increased generation of ROS and 8-iso PGF2-$\alpha$ [42,43] in nonadapted subjects. However, these acute variations of oxidative status seem not to remain for long and return back to baseline within three hours (T1), after all exposures of diving-associated hyperoxia.

In agreement with the hypothesis described above, both hyperoxic and hypoxic exposure have been reported to induce an increase of oxidative stress [42]. ROS production significantly increased in all experimental conditions. The lesser increase observed in dives with a full-face mask (+15%) with respect to the half-face mask (+25%) and hypoxia wearing a half-face mask (+31%). This observation supports the hypothesis that nasal breathing, inducing NO production, could counteract ROS oxidative stress (Figure 3). Accordingly, we observed a significant increase of the marker of lipid peroxidation 8-iso PGF2-$\alpha$ when diving was performed using the classical half-face mask, both breathing hyperoxic or hypoxic mixture at depth but not when wearing a full-face device.

It has been previously reported [44], that high levels of oxygen breathing acutely alter NOS-dependent NO generation in healthy subjects. In our study, we observed a significant reduction in plasmatic levels of NO metabolites (NOx and $NO_2$, respectively, in Figure 4A,B), which are widely accepted as markers of systemic NO generation. This reduction was evident and more pronounced in subjects wearing the half mask than in those utilizing the full-face device (−37 vs. −17% respectively). This difference confirms that nasal breathing hinders, at least in part, the impairment of NO availability, possibly due to the interaction with ROS, thus preventing endothelial dysfunction as measured by FMD [38].

A dive session performed at 10 m and lasting 20 min was not associated with any significant variation of iNOS activity when the subjects were wearing either a full-face mask or a half-face mask. Conversely, when the dive was conducted in slightly hypoxic conditions (16% oxygen at depth), wearing a classical half-face mask, we observed an increase of iNOS expression and activity, suggesting hypoxia and not hyperbaria is the factor inducing the upregulation of iNOS expression. This result is in agreement with previous studies showing that oxygen deprivation results in a significant increased expression of iNOS due to the activation of the nuclear transcription factor kappa B (NF-κB) [45,46]. Two points remain open to further investigation: first is in the extreme rapidity of iNOS induction in our experimental condition [47]. The second is that the increase of iNOS after hypoxia is not accompanied by an increase of NO metabolites. We hypothesized that the hyperoxic breathing during diving associated with an increase of ROS generation might have led to a decrease of NO availability and therefore to a decrease of circulating NOx [48].

It is well known that NO production at vascular level relies on two different mechanisms: an inducible synthase (iNOS) expressed upon the activation of a specific set of redox sensitive transcription factors, NF-κB possibly being the most important, and a constitutive one, the endothelial form eNOS, mainly regulated by Ca availability. We previously reported that variations of the composition and pressure of air breath are associated with a specific pattern of activation of oxygen-sensing transcription factors, including NF-κB, NRF2 and HIF [49]. In the present study, targeting the effect of nasal breathing on NO production as related to oxidative stress due to increased oxygen partial pressure, we focused our attention on the inducible form, but we also did not exclude that eNOS activity could be affected by a temporary alteration of intracellular Ca availability from the endoplasmic reticulum [50]. iNOS expression after a dive performed while breathing a hypoxic air mixture and wearing a mask that only allows mouth breathing can be due to the activation of NF-κB transcription factor, as confirmed by several publications [51]. Conversely, in the presence of basic hyperoxia, a more complex response, including a Ca release from endoplasmic reticulum, is likely to occur [52].

Accordingly, we observed a decrease of 3-NT in hyperoxia, irrespective if breathing through a half-face or a full-face mask, but not in hypoxia. Peroxidative nitration by nitrite and $H_2O_2$ forms 3-NT [53,54], which, in turn, needs superoxide ion to be produced. Lower 3-NT levels can be directly associated with the decreased nitrite level observed while wearing half-face mask and possibly lower ROS levels observed while wearing a full-face mask.

An increase of 3-NT levels is usually interpreted as an index of redox imbalance. In fact, 3-NT is a product of tyrosine nitration mediated by reactive nitrogen species. In our experimental conditions, we observed a decrease of NO metabolites (Figure 4A,B) in divers breathing from mouth only and no significant variations when using a full-face mask or in hypoxic conditions. Therefore, we can speculate that nitrotyrosine, which is formed in the presence of peroxynitrite, mainly generated following the reaction between NO and superoxide, are reduced accordingly. The increase of ROS generation assessed by means of EPR technology does not allow discrimination between different reactive oxygen species. As also mentioned above, we hypothesize that the predominant species are superoxide in hyperoxia and hydroxyl radical during hypoxia, due to metabolic production [54].

In our experimental setting, we acknowledge a ROS increase regardless of oxygen exposure. Nevertheless, we can hypothesize that the amount of ROS produced during the hypoxic period would mainly originate from metabolism, since exogenous oxygen is reduced. In this perspective, we can assume that a relatively higher superoxide ion generation occurs during hyperoxia and more hydroxyl radicals during hypoxia, due to metabolic production [54]. This will result in an increase of 3-NT during hyperoxic periods but not during hypoxia (Figure 4C). Moreover, 8-iso PGF2-α is increased during hypoxia and during hyperoxic oral breathing (HF-mask) marking increased lipid peroxidation, which depends more on the availability of hydroxyl radicals. During HF hyperoxic breathing, the increased isoprostane can be due to the higher generation of ROS concomitantly demonstrated by the increased lipid peroxidation associated with NOx and $NO_2$ reduction.

As mentioned, hyperoxic breathing is likely to be associated with an increase in ROS and, therefore, the reduction in NO bioavailability is probably due to the formation of superoxide, which reacts with NO to form peroxynitrite, which in turn, nitrates proteins to form 3-NT. However, our previous studies indicate that peroxynitrite reaction associated with diving does not always follow the expected pattern [9,22]. Accordingly, other researchers found a similar pattern of NOx levels in blood samples obtained both underwater and after diving [55]. These observations highlight the evidence that other "actors" and mechanisms are involved in NO metabolism under modified oxygen concentration and under an altered respiratory pattern.

It should also be noted that any organism's response to a stimulus (in this case diving and forced oral breathing) is not likely to be placed "exactly" at surfacing. Rather, a progressive adaption to a contingent environment occurs, involving a systemic response. Time points adopted in our study plan must be considered indicative "reference points". It is therefore possible to hypothesize that there is no perfect synchronicity between ROS and NO generation: while the former is a "continuous", starting from the exposure to high oxygen (independently of nasal or oral breathing), iNOS activation requires the transfer of signals through an oxygen sensor to sensitive transcription factor (NF-κB) and, lastly, protein synthesis. Finally, it should also be considered that other possible pathways allowing NO elimination exist besides the formation of peroxynitrate, which are impossible to be tested in an in vivo clinical study, possibly leading to a blunted and unexpectedly unchanged 3-NT production in the presence of hyperoxia [56].

## 5. Conclusions

Our study indicates that evident endothelial reactions occur while diving and that endothelial function can be "protected" using a full-face mask that allows nasal breathing. Moreover, a reduction of oxygen partial pressure attained by breathing a hypoxic (16% $O_2$ at depth) countered FMD decrease even when only oral breathing was allowed. It is therefore very likely that oxidative stress is one, if not the unique, determinant of endothelial NO production (or more available) by nasal breathing and it is directly responsible for maintaining the function, probably by ROS scavenging activity. This phenomenon has already been described to explain hyperoxic vasoconstriction [57,58]. In fact, the vasodilatory effect of superoxide dismutase in hyperoxia was not seen in animals given prior doses of the NO synthase inhibitor [58]. These results provide evidence that one mechanism for hyperoxic vasoconstriction in the brain consists of inactivation of NO by superoxide anions, decreasing its basal vasorelaxing action. The direct physiological response is clearly present, although the biochemical markers are less evidently triggered, and their response is still partially blunted.

To our knowledge, this is the first study describing these aspects of diving physiology and, therefore, more investigations are needed to better understand this apparent difference in the response time. However, besides the obvious outcomes in terms of SCUBA diving safety, our data permit a better understanding of the effects of oxygen concentrations, either in normal conditions or as a strategy to induce selected responses in health and disease.

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**Institutional Review Board Statement:** The study was conducted in accordance with the Declaration of Helsinki, and received ethical approval from the Bio-Ethical Committee for Research and Higher Education, Brussels (N° B 200-2020-088).

**Informed Consent Statement:** Informed consent was obtained from all subjects involved in the study.

**Data Availability Statement:** Data are available from the authors by request.

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**Conflicts of Interest:** The authors declare no conflict of interest.

## Abbreviations

| | |
|---|---|
| EPO | Erythropoietin |
| EPR | Electron paramagnetic resonance |
| FMD | Flow mediated dilation |
| GSH | Intracellular reduced glutathione |
| HPLC | High-performance liquid chromatography |
| iNOS | Inducible nitric oxide synthase |
| 8-iso PGF2-a | 8-Isoprostane |
| MPPs | Matrix metallopeptidases |
| NF-κB | Nuclear factor kappa-light-chain-enhancer of activated B cells |
| $NRF_2$ | Nuclear factor (erythroid-derived 2)-like 2 |
| NO | Nitric oxide |
| $NO_2$ | Nitrite |
| NOx | NO metabolites (NO2+NO3) |
| 3-NT | Nitrotyrosine |
| $PO_2$ | Oxygen partial pressure |
| ROS | Reactive oxygen species |

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# Effect of High-Intensity Interval Training on Quality of Life, Sleep Quality, Exercise Motivation and Enjoyment in Sedentary People with Type 1 Diabetes Mellitus

**Jesús Alarcón-Gómez [1], Iván Chulvi-Medrano [2], Fernando Martin-Rivera [3,*] and Joaquín Calatayud [4]**

[1] Department of Physical Education and Sports, University of Valencia, 46010 Valencia, Spain; jesusadol18@gmail.com
[2] UIRFIDE Sport Performance and Physical Fitness Research Group, University of Valencia, 46010 Valencia, Spain; ivan.chulvi@uv.es
[3] Research Group in Prevention and Health in Exercise and Sport, University of Valencia, 46010 Valencia, Spain
[4] Exercise Intervention for Health Research Group (EXINH-RG), Department of Physiotherapy, University of Valencia, 46010 Valencia, Spain; joaquin.calatayud@uv.es
* Correspondence: fernando-martin.rivera@uv.es or fernando.martin-rivera@uv.es

**Abstract:** (1) Background: Type 1 diabetes mellitus (T1DM) people's health-related quality of life (HRQoL) is affected by glycemic control. Regular exercise is strongly recommended to these patients due to its cardiovascular and metabolic benefits. However, a large percentage of patients with T1DM people present a sedentary behavior because of the fear of a post-exercise hypoglycemia event, lack of time, lack of motivation and the complicated management of exercise, glycemic and insulin dose interaction. High-intensity interval training (HIIT) is an efficient and safe methodology since it prevents hypoglycemia and does not require much time, which are the main barriers for this population to doing exercise and increasing physical conditioning. (2) Methods: Nineteen sedentary adults (37 ± 6.5 years) with T1DM, were randomly assigned to 6 weeks of either HIIT (12-16-20 × 30-s intervals interspersed with 1-min rest periods) performed thrice weekly, or to the control group, which did not train. HRQoL, sleep quality, exercise motivation and enjoyment were measured as psychological variables. (4) Results: HRQoL improved in physical and social domains, PF (1.9%); PR (80.3%); GH (16.6); SF (34.1%). Sleep quality improved in the HIIT group by 21.4%. Enjoyment improved by 7% and intrinsic motivation was increased by 13%. (5) Conclusions: We suggest that the 6-week HIIT program used in the present study is safe, since no severe hypoglycemia were reported, and an effective strategy in improving HRQoL, sleep quality, exercise motivation and enjoyment which are important psychological well-being factors in T1DM people.

**Keywords:** diabetes type 1; HIIT; sleep quality; exercise motivation; quality of life

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## 1. Introduction

Type 1 diabetes mellitus (T1DM) is a chronic metabolic disorder characterized by the insufficient production of endogenous insulin due to pancreatic beta cells autoimmune destruction which is associated with multiple clinical manifestations [1]. Reports from the International Diabetes Federation and the World Health Organization suggest that 25–45 million adults (>20 years old) suffer from T1DM worldwide [2]. Furthermore, it is estimated that the number of people with T1DM will increase by 25% by 2030 [2,3].

T1DM generates several negative consequences affecting health-related quality of life (HRQoL) [4]. For instance, frequent self-monitoring of blood glucose, worry about hypoglycemia and lifestyle changes management derived from the disease increase stress situations, depression, anxiety and fear [5,6]. In addition, sleep quality (a determinant factor in glycemic control and physical and mental well-being) is decreased among T1DM patients, with shorter sleep duration and more episodes of apnea than healthy people [7].

Treatment of T1DM requires a rigorous balance among diet, physical activity and exogenous insulin administration to maintain blood glucose in normal ranges [8]. From all these factors, exercise is commonly known as an essential tool to improve HRQoL among those with T1DM [9]. However, exercise has shown some negative effects on sleep quality in this population due to the increase of exercise-induced nocturnal hypoglycemia [6]. T1DM people are mostly sedentary due to, mainly, the following reasons: (a) fear of hypoglycemia, (b) lack of time and (c) lack of motivation [10–12]. Given this background, new exercise methods eliciting enjoyment and motivation are needed to increase adherence, and consequently, improve HRQoL of T1DM people, helping to avoid sleep disturbances. Thus, the aforementioned barriers that T1DM people face might be overcome with high-intensity interval training (HIIT). This training method involves repeated brief bouts of high intensity (>85% $VO_2$max) intermitted with passive or active recovery periods, requiring lower exercise duration than moderate-intensity continuous training (MICT) [13,14]. In addition, HIIT also prevents hypoglycemic events, typical of MICT, due to its anaerobic predominance, avoiding nocturnal hypoglycemia as well [12]. There is also evidence to suggest that HIIT elicits at least the same psychological effects, including enjoyment, as MICT among healthy and pathologic populations such as obesity, Type 2 diabetes and cardiovascular disease [15–18]. However, there are no studies investigating its possible application to improve psychological well-being and exercise adherence in T1DM people. The safety and time efficiency of HIIT make this exercise method an interesting alternative for this population. So far, HIIT was only applied in T1DM people to analyze the long-term effects in aerobic capacity and glycemic control [19–21]. Therefore, the aim of this study was to analyze the effect of HIIT on variables that influence psychological well-being in T1DM individuals, previously inactive.

## 2. Materials and Methods

### *2.1. Participants and Research Design*

Nineteen sedentary adults clinically diagnosed as T1DM (10 males and 9 females) from the Valencian Diabetes Association (VDA) and social media announcement were selected to be part of the sample (Table 1). The following inclusion criteria were set: (1) aged 18–45 years, (2) duration of T1DM > 4 years, (3) HbA1C < 10% (4) no structured exercise training programs in the previous 6 months, (5) no known comorbidities related or not to diabetes. Smoking regularly, taking any medication that affects heart rate, suffering overweight or obesity and having planned major surgery were adopted as exclusion criteria (Figure 1). The institutional gym was the lab where all the activities were conducted. Participants were informed of the purposes and risks involved in the study before giving their informed written consent to participate. Furthermore, they completed two questionnaires before the beginning of the measurement protocols: the PAR-Q to assess participants' level of risk to safely participate and the IPAQ (short version), to ensure the previous sedentary behavior of the subjects. All the procedures were developed in accordance with the principles of the Declaration of Helsinki and were approved by the local Institutional Review Board (H1421157445503).

**Table 1.** Participants.

| | HIIT ($n$ = 11) | | Control ($n$ = 8) | |
|---|---|---|---|---|
| | **Pre** | **Post** | **Pre** | **Post** |
| Age (years) | 38 ± 5.5 | - | 35 ± 8.2 | - |
| Sex (male/female) | 6 m/5 f | - | 4 m/4 f | - |
| Duration of T1DM (years) | 20.58 ± 8.4 | - | 21.16 ± 6.5 | - |
| BMI (kg/m$^2$) | 25.1 ± 0.4 | 24.9 ± 0.6 | 25.2 ± 0.8 | 25.3 ± 0.6 |
| HbA1 (mmol/mol) | 58.1 ± 15.3 | 54.9 ± 11.6 | 59.1 ± 10.1 | 59.3 ± 9.5 |
| $VO_2$max. (mL/min/kg) | 37.1 ± 4.1 | 40.4 ± 3.8 | 37.0 ± 5.5 | 37.2 ± 5.1 |

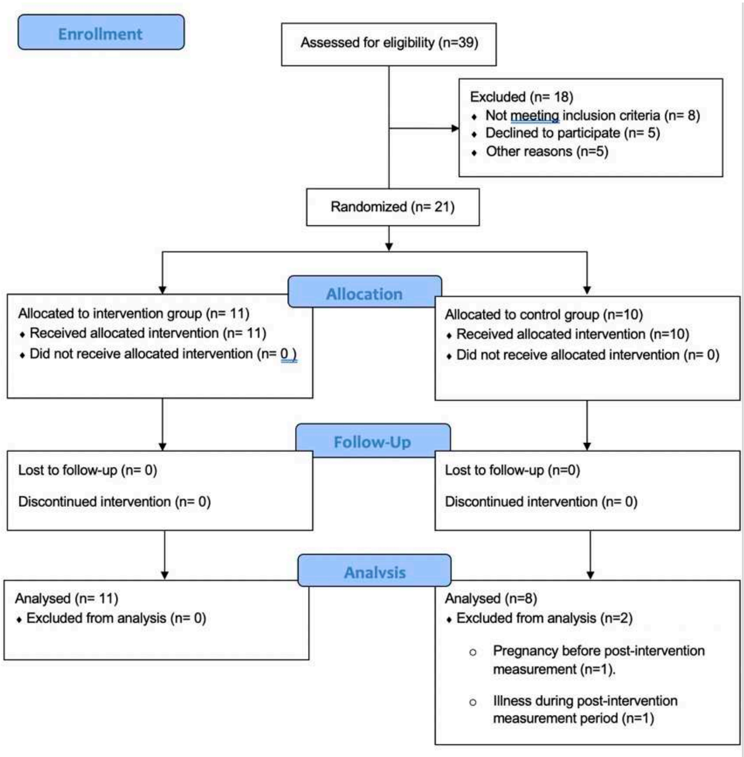


**Figure 1.** Shows the recruitment process.

This is a randomized controlled trial with parallel design in which the eligible subjects were randomly allocated by the researchers (www.randomizer.org, accessed on 2 January 2019) to the experimental or to the control group, and classified by gender to ensure a balanced number of men and women in each group. They all were asked to maintain their habitual diet and not to exercise outside of the study.

### *2.2. Measures*

All tests were completed online before starting the experimental period and after the last training session with a previous period of instruction to the participants to ensure the total comprehension of the questionnaires which were used. Nonetheless, patients were instructed to ask any doubt that might arise to the investigators while the questionnaires were being completed. All the procedures were exactly conducted in the same way both times.

#### 2.2.1. Health-Related Quality of Life

Health-related quality of life (HRQoL) was self-reported by completing the short form 36 health survey (SF-36) [22]. This questionnaire is a valid and reliable generic instrument to assess HRQoL and its components [23,24]. This questionnaire contains 36 questions including an eight-domain profile of functional health and well-being scores (physical functioning, role limitation due to physical problems, bodily pain, general health, vitality, social functioning, role limitation due to emotional problems and mental health). For each parameter, scores are coded, summed and transformed to a scale from 0 (the worst possible condition) to 100 (the best possible condition) [25,26].

#### 2.2.2. Sleep Quality

Sleep quality was evaluated by the Pittsburgh Sleep Quality Index (PSQI), a clinical sleep-behavior questionnaire that has been validated for use in patients with different chronic diseases and the general population [27,28]. The PSQI is an instrument that aims to measure subjective sleep quality and related disorders and involves seven domains:

(i) subjective sleep quality (very good to very bad), (ii) sleep latency ($\leq$15 min to >60 min), (iii) sleep duration ($\geq$7 h to <5 h), (iv) sleep efficiency ($\geq$85% to <65% h sleep/h in bed), (v) sleep disturbances (not during the past month to $\geq$3 times per week), (vi) use of sleeping medications (none to $\geq$3 times a week), and (vii) daytime dysfunction (not a problem to a very big problem), divided into 10 questions, of which questions 1–4 are open and 5–10 are semi-open [29]. The PSQI scoring scale ranges from 0 to 21. Each domain has a set weight between zero and three and the global score is given by the sum of the scores in the seven domains [30]. A PSQI global score higher than 5 indicates poor sleep quality [31].

#### 2.2.3. Exercise Motivation

The behavioral regulation in the exercise questionnaire (BREQ-2) was used to measure participants' underlying motivational regulation relating to HIIT participation [32]. It is comprised of five subscales: (1) intrinsic (e.g., "I exercise because it's fun"); (2) identified (e.g., "I value the benefits of exercise"); (3) introjected (e.g., "I feel guilty when I don't exercise"); (4) external (e.g., "I exercise because other people say I should"); and (5) amotivation (e.g., "I don't see why I should have to exercise") [32–34]. A 5-point Likert scale ranging from; 1 = "not true for me" to 5 = "very true for me" is used to rate each of its 19 items with the generation of each subscale score based on mean score across subscale items [35].

#### 2.2.4. Exercise Enjoyment

To assess HIIT enjoyment, participants were asked to complete the 16-item Physical Activity Enjoyment Scale (PACES) [36]. This instrument consists of questions relating to enjoyment of exercise with the instruction "When I am active ... ". This 16-item survey is scored on a 5-point bipolar scale from 1 (totally disagree) to 5 (totally agree). Example items include "I enjoy it/I hate it", "I find it energizing/I find it tiring", "It gives me a strong sense of accomplishment/It does not give me any sense of accomplishment at all" [37]. The score was obtained with the sum of the positive elements and the restoration of the negative elements with higher scores indicating higher levels of enjoyment [36].

### *2.3. Exercise Interventions*

Initially, an incremental test on a cycle ergometer was performed by all the participants (Excite Unity 3.0, Technogym S.p.A, Cesena, Italia) to determine peak power output (PPO) and peak oxygen consumption ($VO_2$peak) using a gas collection system (PNOE, Athens, Greece) that was calibrated in each test by means of ambient air [38]. Capillary blood glucose concentrations were checked before the commencement of the incremental test by their own blood glucose monitoring devices. They were told to arrive at the lab with a glycemic level >100 mg/dL and less than 300 mg/dL in absence of ketones. If the glycemic level was optimum, the participant began the test normally. If not, the intake of 15–30 g of fast-acting carbohydrates (CHO) we had available was compulsory when glycemia was <100 mg/dL and a small corrective insulin dose was used if hyperglycemia appeared without ketones. In the presence of ketones, the exercise was canceled. Exercise was not allowed to start until blood glucose was correct. In the same way, it was recommended that patients not exercise at the peak of insulin action [39].

Firstly, a warm-up of 5 min at 40 Watts (W) was performed. After that, the workload was increased by 20 W every minute until volitional exhaustion. Participants were verbally encouraged to give their maximum effort during the test. The test ends with a cool down of 5 min at 40 W. Monitoring of heart rate was carried out by a Polar H10 (Polar Electro, Kempele, Finland). $VO_2$peak was taken as the highest mean achieved within the last 15 s prior to exhaustion. Peak power output was registered to individualize the workloads in the HIIT protocol.

The hour of the day that each subject completed the test was recorded, as well as the menstrual phase of each female participant with the aim of repeating the same conditions in the second measurement to prevent their interference on the outcomes.

The training period was initiated the week after the pre-experimental measurements. Participants of the experimental group trained thrice weekly for 6 weeks under researcher supervision on a cycle ergometer (Excite Unity 3.0, Technogym S.p.A, Cesena, Italy). Heart rate while exercising was monitored with a Polar H10 (Polar Electro, Kempele, Finland) that was preconfigured with their heart rate zones. The HIIT protocol performed was a type 1:2, which means that the high-intensity intervals lasted exactly half the time that the rest intervals did. The saddle height was always adjusted to the height of the subject's iliac crest. The training session began with a 5-min warm-up at 50 W. Then, they performed 30-s sets of high-intensity cycling at a workload selected to elicit 85% of their individual PPO interspersed with 1 min of active recovery at 40% PPO (Figure 2). The number of high-intensity intervals increased from twelve reps in weeks 1 and 2, to sixteen reps in weeks 3 and 4, to twenty reps in weeks 5 and 6. Training ends with a 5-min cool down performed at 50 W. After the session, participants were told to check their glycemia level frequently (every 1–2 h) and notify the investigators if a glycemia drop below 70 mg/dL occurred during the 24 h following the exercise even though felt well.

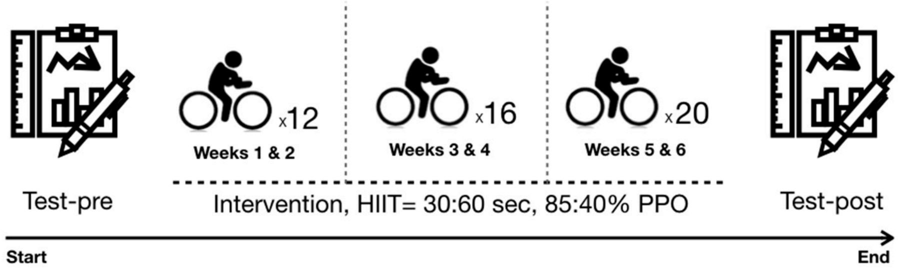


**Figure 2.** Represents the study timeline.

All sessions were supervised by the investigators and participants were asked not to fast before the training and not to exercise within 30 min of a meal, aiming to perform the HIIT under real-world conditions. For that reason, no adjustments were made in insulin dose. Glucose levels were checked at least before and immediately after each exercise session, it was re-checked when glucose was not in the safe range (100–250 mg/dL). Fast-acting carbohydrates (15–30 g) were ingested when glycemia fell to ≤100 mg/dL. Hyperglycemia (250–300 mg/dL) was not set as a reason for postponing exercise if the patient felt well and ketones were negative [19,21]. Subjects assigned to the control group were instructed to maintain their current lifestyle and dietary intakes during the study period.

### *2.4. Statistical Analysis*

All variables were expressed as a mean and standard deviation and were analyzed using a statistical package (SPSS Inc., Chicago, IL, USA). Normality assumption by Shapiro-Wilks was checked for each variable. A mixed factorial ANOVA (2 × 2) was performed to assess the influence of "condition" (i.e., control group vs. experimental group) and "time moment" variable (i.e., pre-intervention, post-intervention). In the event that the Sphericity assumption was not met, freedom degrees were corrected using Greenhouse–Geisser estimation. Post-hoc analysis was corrected using Bonferroni adjustment. The Wilcoxon and Mann–Whitney U tests were used for the variables that did not meet the normality (quality of life and exercise motivation). Cohen's D was used to assess the magnitude of mean differences between control vs. experimental conditions.

## **3. Results**

### *3.1. Health-Related Quality of Life*

The Mann–Whitney U and Wilcoxon tests showed significant differences between pre–post measurements of the following variables in the experimental group: Physical functioning, Physical role limitations, Pain, General health, Energy/Fatigue, Social functioning. In the control group, there were no differences between pre–post measurements. See Table 2.

**Table 2.** Health-related quality of life.

| | HIIT ($n$ = 11) | | Control ($n$ = 8) | | |
|---|---|---|---|---|---|
| | **Pre** | **Post** | **Pre** | **Post** | **ES** |
| Physical functioning (PF) | 96.3 ± 3.2 | 98.1 ± 2.5 * | 98.7 ± 2.3 | 99.3 ± 1.7 | 0.24 |
| Physical role limitations (PR) | 34.0 ± 12.6 | 61.3 ± 17.2 * | 37.5 ± 13.3 | 31.2 ± 11.5 [2] | 0.66 |
| Pain | 44.5 ± 11.2 | 61.8 ± 7.5 * | 37.5 ± 11.6 | 45.0 ± 14.1 [2] | 1.53 |
| General health (GH) | 49.5 ± 6.1 | 57.7 ± 5.1 * | 51.25 ± 5.2 | 55.6 ± 6.2 | 0.81 |
| Energy/fatigue (E) | 23.1 ± 4.0 | 28.1 ± 4.6 * | 23.7 ± 3.5 | 22.5 ± 4.6 [2] | 0.24 |
| Social functioning (SF) | 53.4 ± 5.8 | 71.6 ± 5.8 * | 54.6 ± 9.3 | 60.9 ± 4.4 [2] | 0.87 |
| Emotional role limitations (ER) | 84.8 ± 17.4 | 96.9 ± 10.0 | 83.3 ± 17.8 | 87.5 ± 17.2 | 0.19 |
| Emotional well-being (EWB) | 57.8 ± 6.0 | 60.7 ± 3.5 | 58.0 ± 3.7 | 59.0 ± 2.8 | 0.24 |

Data are presented by mean ± standard deviation, * Significant difference between pre–post, [2] Significant difference between groups in that measurement point (pre or post), ES: effect size (Cohen's d), $p < 0.05$.

### 3.2. Sleep Quality

ANOVA revealed significant statistical differences for the main effect of "pre–post" ($F_{(1,17)} = 28.03$; $p < 0.001$), pair comparations showed significant differences between pre–post measurements in the experimental group. In the control group, there were no differences between pre–post measurements. See Table 3.

**Table 3.** Sleep quality.

| | HIIT ($n$ = 11) | | Control ($n$ = 8) | | |
|---|---|---|---|---|---|
| | **Pre** | **Post** | **Pre** | **Post** | **ES** |
| Sleep Quality | 6.1 ± 0.5 | 4.3 ± 0.5 * | 5.5 ± 0.9 | 5.1 ± 0.6 [2] | 0.54 |

Data are presented by mean ± standard deviation, * Significant difference between pre–post, [2] Significant difference between groups in that measurement point (pre or post), ES: effect size (Cohen's d), $p < 0.05$.

### 3.3. Exercise Motivation

The Mann–Whitney U and Wilcoxon tests showed significant differences between pre–post measurements of the following variables in the experimental group: Intrinsic, identified, Introjected, External, Amotivation. In the control group, there were no differences between pre–post measurements. See Table 4.

**Table 4.** Exercise motivation.

| | HIIT ($n$ = 11) | | Control ($n$ = 8) | | |
|---|---|---|---|---|---|
| | **Pre** | **Post** | **Pre** | **Post** | **ES** |
| Intrinsic | 16.2 ± 1.2 | 18.3 ± 0.5 * | 16.7 ± 1.5 | 17.6 ± 0.9 [2] | 0.96 |
| Identified | 15.9 ± 1.2 | 17.2 ± 0.9 * | 16.3 ± 0.7 | 16.6 ± 0.5 [2] | 0.82 |
| Introjected | 8.1 ± 0.8 | 8.0 ± 0.8 | 7.6 ± 0.7 | 7.7 ± 0.7 | 0.39 |
| External | 10.1 ± 1.3 | 6.6 ± 0.9 * | 10.1 ± 1.3 | 9.7 ± 1.4 [2] | 2.63 |
| Amotivation | 8.8 ± 0.7 | 4.7 ± 0.9 * | 8.7 ± 0.4 | 8.2 ± 0.8 [2] | 4.1 |

Data are presented by mean ± standard deviation, * Significant difference between pre–post, [2] Significant difference between groups in that measurement point (pre or post), ES: effect size (Cohen's d), $p < 0.05$.

### 3.4. Exercise Enjoyment

ANOVA revealed significant statistical differences for the main effect of "pre–post" ($F_{(1,17)} = 21.92$; $p < 0.001$), pair comparations showed significant differences between pre–post measurements in the experimental group. In the control group, there were no differences between pre–post measurements. See Table 5.

**Table 5.** Exercise enjoyment.

| | HIIT ($n$ = 11) | | Control ($n$ = 8) | | |
|---|---|---|---|---|---|
| | **Pre** | **Post** | **Pre** | **Post** | **ES** |
| Enjoyment | 72.5 ± 3.5 | 75.5 ± 3.4 * | 72.2 ± 3.0 | 72.7 ± 2.5 [2] | 0.94 |

Data are presented by mean ± standard deviation, * Significant difference between pre–post, [2] Significant difference between groups in that measurement point (pre or post), ES: effect size (Cohen's d), $p < 0.05$.

### 3.5. Adverse Events

There were three mild hypoglycemia cases (67.9 ± 2.6 mg/dL) of 198 total trainings (1.5%), occurring immediately after exercise which only required a few minutes of rest and carbohydrate ingestion to be solved. No adverse cardiac events, respiratory events or musculoskeletal injuries were reported in the experimental period. There were no episodes of hyperglycemia, nocturnal hypoglycemia or episodes of diabetic ketoacidosis.

## 4. Discussion

The main result of the study shows that a 6-week HIIT is sufficient to improve well-being and exercise adherence in the previously inactive T1DM population, since HRQoL, SQ, enjoyment and exercise motivation obtained better results in the experimental group. Moreover, the study showed that this training method is safe for this population since no insulin or carbohydrate intake adjustments were made. Moreover, only 3 of 198 total trainings, which means less than 1.5%, resulted in hypoglycemia, and they were mild cases (69.7 ± 2.6 mg/dL). No severe hyperglycemias were reported. These data suggest that HIIT prevents hypoglycemia as well as previous studies reported [12,21].

Our findings show that the HIIT group experimented gave significant HRQoL improvements in the physical and social domains, with better results than the control group at PR, BP, VT and SF domains. Previous studies among T1DM people—albeit mainly focused on children, adolescents and young adults—mostly reported better HRQoL when physical exercise is part of their lifestyle or after a training period [40,41], although it can also be perceived as a stressor and have no positive effects on this outcome [42]. Previous reviews which analyzed the effect of HIIT on HRQoL among heart failure patients—one of the most recurrent T1DM complications [43]—found that all dimensions improved after a period of HIIT. There was high heterogeneity in HIIT protocols, but it is worth mentioning that investigations that reported mental improvements in HRQoL used protocols of at least 10 weeks of duration [44,45]. In the present study, a 6-week HIIT was conducted, and thus, the lower exercise volume in our study could explain the absence of improvement in the mental components of HRQoL. Nevertheless, our results are in line with those obtained by Stavrinou and colleagues [46], who showed improvements in the physical components of the SF-36 but not in the mental dimension after a similar HIIT protocol conducted during 8 weeks among inactive healthy people.

To the best of our knowledge, there is only one previous publication that analyses HRQoL in T1DM after a HIIT protocol [47]. However, the aforementioned study used obese or overweight participants and the training consisted of 4 bouts of 4 min at 85–95% $HR_{peak}$ interspersed with 3-min recovery intervals at 50–70% $HR_{peak}$ for 12 weeks. The results from this study suggest no changes in HRQoL in the studied population, in contrast with our results. However, the previously mentioned study used a different questionnaire (Diabetes Quality of Life questionnaire), which might explain the different results. We used the SF-36 because analyzes domains of physical functionality and psychological well-being, while the Diabetes Quality of Life questionnaire predicts care behaviors and satisfaction with diabetes control [48] which is less specific/related to physical exercise domains.

Relevantly, we found that the HIIT group had a greater PSQI global score than the control group, with a 21.3% increase, which means moving from previous "poor sleep quality" to "good sleep quality" [49].

To date, the previous literature has focused on the effect of exercise on nocturnal hypoglycemia due to its relevance on sleep quality in T1DM, not directly measuring sleep quality measurement. Given that aerobic exercise has been shown to increase the likelihood of nocturnal hypoglycemia in T1DM people [50], recent studies have shown HIIT as an interesting training strategy to prevent nocturnal hypoglycemia, especially, if performed early in the morning [12,50]. This could explain the sleep quality improvement shown in our investigation of the HIIT group, insomuch as no severe hypoglycemia were reported, including nocturnal periods. Sleep disorders have a negative influence on mental and physical health and decrease the quality of life in T1DM. HIIT could be postulated as an interesting strategy to improve sleep quality, in part due to the reduction of post-exercise and nocturnal hypoglycemia preventing night-time awakenings and consequently, positively affect HRQoL in this population.

In reference to exercise type HIIT enjoyment, our results showed a greater improvement (4.1%) in the HIIT group. This result is in line with previous studies which reported that HIIT enhances exercise enjoyment in both inactive but healthy and people with pathologies such as obesity or Crohn's disease, using in most of them the PACES test to determine exercise enjoyment [17,51,52].

Lack of motivation is presented as one of the most important barriers of T1DM people to exercising [53]. We found that the used HIIT protocol increased self-determined domains of autonomous motivational regulation: intrinsic (11.5%) and identified (7.6%) dimensions. Conversely, external motivation (34.7%) and demotivation (46.6%) components provided lower scores ($p < 0.05$), which support the self-determined improvement. In agreement with these results, a previous study [54] found that autonomous regulation towards exercise was improved after only one HIIT session. Furthermore, a 10-month HIIT protocol including core and functional exercises performed by inactive obese women reported increased intrinsic regulation (33%) and identified regulation (88%) and decreased external regulation by 75%. These data are congruent with the obtained in the present study but with a higher effect, probably due to the greater duration of the intervention. Reasons that may explain that HIIT increases exercise motivation are related to different exercise effects and the special characteristics of HIIT.

The self-determination theory [55] considers three basic psychological needs (autonomy, competency and relatedness). Their satisfaction influences exercise motivation. In this way, this theory indicates that people show greater intrinsic regulation ("I do exercise because I enjoy it") if they perceived some decision capacity, efficacy in the task they are performing and good social relationship with people around them. Nevertheless, if the mentioned psychological needs are frustrated, probably the individual shows an external regulation ("I do exercise to get something, not because I like it") or demotivation [56]. We hypothesize that the protocol increased the most self-determined regulations and reduced the most external dimensions due to three main reasons: (i) Given that the protocol was a 1:2 HIIT, participants could complete the sessions effectively but with a high level of exigency, increasing their competency subjective perception; (ii) They were free to choose the hour of the training, listen to music or not and they had no strict instructions related to insulin or carbohydrate intake. Those factors could influence their autonomy perception; (iii) Participants were in touch between them, physically and through social media. They talked about the investigation and arranged meetings outside the lab. Those aspects could positively affect their social relationship [18,55]. Given that enjoyment and self-determined domains of motivation are highly correlated with adherence [17,57,58], it could be proposed that HIIT elicits exercise adherence and consequently, contribute physiological and psychological benefits to this population.

Since there are no previous studies with similar characteristics our results should be taken with caution. No medical specialists were included in the research group which would have contributed to a better quality in the metabolic adjustments. However, the medical services of the university were aware of the investigation development. Although the statistical power analysis performed with G*power 3.0 resulted in values higher than

0.80 for all variables and tests performed, the small sample size remains the main limitation. Furthermore, we did not use specific HRQoL questionnaires for T1DM or objective sleep quality measurements. However, the used questionnaires are valid and reliable, providing novel data in this population. The nutritional habits of the participants were not measured despite being asked to maintain them with no change. Future longer interventional studies which also compare additional interventions are needed to corroborate our results and add further insight into the effects of using HIIT among T1DM people.

## 5. Conclusions

In conclusion, a 6-week HIIT protocol 1:2 type, performing high-intensity intervals at 85% PPO and active rest intervals at 40% PPO in a cycle ergometer during three sessions per week, apart from being accessible and safe since participants were able to complete all the sessions with the intensity required without suffering any severe undesirable episode of hypoglycemia, was sufficient to improve HRQoL, sleep quality, exercise enjoyment and exercise motivation in previously inactive T1DM people.

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*Systematic Review*

# Resistance Training with Blood Flow Restriction Compared to Traditional Resistance Training on Strength and Muscle Mass in Non-Active Older Adults: A Systematic Review and Meta-Analysis

**Darío Rodrigo-Mallorca [1], Andrés Felipe Loaiza-Betancur [2], Pablo Monteagudo [1,3], Cristina Blasco-Lafarga [1,*] and Iván Chulvi-Medrano [1]**

[1] UIRFIDE (Sport Performance and Physical Fitness Research Group), Department of Physical and Sports Education, Faculty of Physical Activity and Sports Science, University of Valencia, 46010 Valencia, Spain; dariorodrigom@gmail.com (D.R.-M.); pmonteag@uji.es (P.M.); ivan.chulvi@uv.es (I.C.-M.)
[2] Department of Physical Education and Sports, Institute of Physical Education, University of Antioquia, Medellín 050010, Colombia; andres.loaiza@udea.edu.co
[3] Department of Education and Specific Didactics, Jaume I University, 12071 Castellon, Spain
* Correspondence: m.cristina.blasco@uv.es

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**Abstract:** Low-intensity training with blood flow restriction (LI-BFR) has been suggested as an alternative to high-intensity resistance training for the improvement of strength and muscle mass, becoming advisable for individuals who cannot assume such a load. The systematic review aimed to determine the effectiveness of the LI-BFR compared to dynamic high-intensity resistance training on strength and muscle mass in non-active older adults. A systematic review was conducted according to the Cochrane Handbook and reportedly followed the PRISMA statement. MEDLINE, EMBASE, Web of Science Core Collection, and Scopus databases were searched between September and October 2020. Two reviewers independently selected the studies, extracted data, assessed the risk of bias and the quality of evidence using the GRADE approach. Twelve studies were included in the qualitative synthesis. Meta-analysis pointed out significant differences in maximal voluntary contraction (MVC): SMD 0.61, 95% CI [0.10, 1.11], $p = 0.02$, $I^2$ 71% $p < 0.0001$; but not in the repetition maximum (RM): SMD 0.07, 95% CI [−0.25, 0.40], $p = 0.66$, $I^2$ 0% $p < 0.53$; neither in the muscle mass: SMD 0.62, 95% CI [−0.09, 1.34], $p = 0.09$, $I^2$ 59% $p = 0.05$. Despite important limitations such as scarce literature regarding LI-BFR in older adults, the small sample size in most studies, the still differences in methodology and poor quality in many of them, this systematic review and meta-analysis revealed a positive benefit in non-active older adults. LI- BFR may induce increased muscular strength and muscle mass, at least at a similar extent to that in the traditional high-intensity resistance training.

**Keywords:** hypertrophy; katsu; low-intensity training; occlusive exercise; sarcopenia

## 1. Introduction

The number of people over 60 years of age is increasing rapidly worldwide due to the increase in life expectancy and the decrease in the fertility rate. According to World Health Organization (WHO) data [1], the world population in this group of age is expected to reach 2 billion by 2050, reflecting an increase of 900 million from the 1.1 billion dated in 2015, up to the 22% of the total population compared to the current 12%. Maintenance of quality of life and prevention from disability (i.e., larger health span more than just life span), is of outermost importance and a current public health challenge [2].

In this scenery, physical activity (PA) has widely been confirmed to counteract the deterioration associated with aging and the sedentary behaviors intrinsic to these last stages of life [3,4]. PA reduces the risk of mortality and chronic pathologies [5,6]. It also helps to prevent dynapenia (decreased muscle strength) and sarcopenia (loss of strength, a decline in muscle mass, and final severe functional capacity impairment in the older adults, in this order) [7]. More specifically, physical exercise, especially strength training [8], emerges as a non-pharmacological tool in the management of this impairment of muscle function and structure which frequently leads older adults to the frailty syndrome [9]. Sarcopenia is indeed an emergency and expensive comprehensive health issue related to many other non-communicable diseases, such as larger number of falls and fractures [5,10,11], osteoporosis [12], diabetes [13], overall disability [12], but also cognitive impairment [14], reduced daily living autonomy, frequent hospitalization, and, finally, larger comorbidity and risk of death (See Cruz-Jentoft et al. [15], for Sarcopenia: revised European consensus on definition and diagnosis).

Resistance training is widely accepted as the most common strategy in this non-pharmacological approach to sarcopenia treatment [8]. Notwithstanding, in the last decade, research has revealed alternative training proposals to traditional high-intensity strength training (>70% RM), such as training with blood flow restriction (BFR), which consists of applying partial peripheral vascular occlusion during low-load strength training (20%–30% of 1RM), causing a local hypoxia effect in the muscle. Recent systematic reviews have analyzed responses on athletic population profiles [16,17] and active adults across the age spectrum (20–80 years) [18–20] indicating that BFR is a similarly effective intervention to high-intensity training in stimulating strength and muscle mass gains. Despite increasing research, the literature on BFR in older adults remains sparse on these issues and the subject's functional status and moderating variables (pressure, cuff size, application volume), making further research necessary to strengthen the evidence on the efficacy of BFR in older adults.

Therefore, the present systematic review and meta-analysis aimed to determine the effectiveness of the low-intensity resistance training with blood flow restriction compared to dynamic high-intensity resistance training on strength and muscle mass in non-active older adults.

## 2. Materials and Methods

### *2.1. Protocol and Registration*

This systematic review was conducted according to the Cochrane Handbook [21] and reported following the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) declaration [22]. It was registered in the International Prospective Register of Systematic Reviews (PROSPERO registration number: CRD42020214901).

### *2.2. Information Sources and Search*

We conducted a systematic search according to Chapter 4 of the Cochrane Handbook [21]. MEDLINE, Web of Science Core Collection, Scopus, and EMBASE databases were searched between September and October 2020. The search strategy applied was the following: old OR eld OR sarcopenic OR frail AND blood flow restriction OR occlusive training OR vascular occlusion OR kaatsu OR ischemic training.

### *2.3. Eligibility Criteria and Study Selection*

Selection criteria were built based on the participants, intervention, comparators, outcomes, study design (PICOs) approach acronym [21] as follows.

Participants: Participants over 65 years, physically inactive, and characterized as healthy by the authors, defined as not achieving 150 min of moderate-to-vigorous-intensity physical activity per week or 75 min of vigorous-intensity physical activity per week or an equivalent combination of moderate and vigorous-intensity activity [23,24].

Intervention: Low-intensity blood flow restriction training (LI-BFR), based on the restriction of afferent and efferent blood flow during the performance of a low-intensity dynamic resistance exercise (20–50% of 1RM), causing a local hypoxia effect on the muscle using a pneumatic pressure cuff placed in the proximal region of the limb [25].

Comparators: Resistance training (RT) interventions were considered as any form of physical activity that is designed to improve muscular fitness by exercising a muscle or a muscle group against external resistance, performed systematically in terms of frequency, intensity, and duration, and is designed to maintain or enhance health-related outcomes. Resistance can come from fixed or free weights, elastic bands, body weight (against gravity), and water resistance. It may also involve static or isometric strength (holding a position or weight without moving against it). Often presented as a percentage of the participant's one-repetition maximum (1-RM), the maximum weight they can lift/move if they only must do it once [26].

Outcomes: Muscular strength (Kg and Nm) and muscle mass ($cm^2$).

Study design: Randomized controlled trial (RCT) where the intervention was RT with a follow-up period of at least 4 weeks. RCT is understood as a study in which many similar people are randomly assigned to 2 (or more) groups to test a specific drug, treatment, or other intervention. One group (the experimental group) has the intervention being tested, the other (the comparison or control group) has an alternative intervention, a sham dummy intervention (placebo), or no intervention at all. The groups are followed up to see how effective the experimental intervention was. Outcomes are measured at specific times and any difference in response between the groups is assessed statistically. This method is also used to reduce bias.

Eligibility criteria were applied independently by two blinded authors and disagreements were solved through consensus and active participation of a third author, likewise, the same authors inspected the reference lists from key journals and systematic reviews with a similar PICO to identified all promising or potential studies.

### *2.4. Data Collection Process*

Two authors independently performed data extraction. Relevant data were extracted to a computer-based spreadsheet. The reviewers extracted the following information: authors' information, publication year, functional status, BRFT characteristics (cuff size and pressure) resistance training protocols (frequency, intensity, length, duration, and volume), and effect estimates (mean, standard deviation, standard error) (Table 1).

**Table 1.** Characteristics of included studies.

| Study | N | Age (yrs) | Functional Status | % 1RM | Cuff (cm) | Pressure (mmHg) | Frequency (d/wk) | Duration (wk) | Protocol (st × rp) | Measurements |
|---|---|---|---|---|---|---|---|---|---|---|
| Cook et al., 2017 [27] | 36 | 69–82 | Non active and risk of functional limitation | RT: 70%<br>LI-BFR: 30% (LE and LC) and 50% (LP) | 6 | 184 ± 25 | 2 | 12 | RT: 3 × 10<br>LI-BFR: 3 × 10 | CSA-MRI; MVC |
| Cook et al., 2019 [28] | 21 | 67–85 | Non active and risk of functional limitation | RT: 70%<br>LI-BFR: 30% (LE and LC) and 50% (LP) | 6 | 184 ± 25 | 2 | 12 | RT: 3 × 10<br>LI-BFR: 3 × 10 | CSA-MRI; MVC; 10RM Test |
| Letieri et al., 2018 [29] | 56 | 68.8 ± 5.09 | Non active | RT: 80%<br>BFR: 30% | Not stated | BFRH: 185 ± 5<br>BFRL: 105 ± 6 | 3 | 16 | RT: 3 × 6–8<br>LI- BFR: 1 × 30 + 3 × 15 | MVC |
| Letieri et al., 2019 [30] | 23 | 69.4 ± 5.73 | Non active | RT: 80%<br>BFR: 30% | 13 | 80% | 3 | 16 | RT: 3 × 6–8<br>LI-BFR: 1 × 30 + 3 × 16 | AMM; MVC |
| Libardi et al., 2015 [31] | 25 | 64.7 ± 4.1 | Non active | RT: 80%<br>BFR: 20% | 18 | 50% | 3 | 12 | RT: 4 × 10<br>LI-BFR: 1 × 30 + 3 × 15 | CSA-MRI; RM Test |
| Silva et al., 2015 [32] | 15 | 61.8 ± 6.01 | Non active | RT: 80%<br>BFR: 30% | 18 | 80% | 2 | 12 | RT: 4 × Fail<br>LI-BFR: 4 × Fail | RM Test |
| Thiebaud et al., 2013 [33] | 14 | 60.5 ± 3.5 | Non active | RT: 80%<br>BFR: 30% | 18 | 80-120 | 3 | 8 | RT: 3 × 10<br>LI-BFR: 1 × 30 + 2 × 15 | CSA-MRI; RM Test |
| Vechin et al., 2015 [34] | 23 | 59–71 | Non active | RT: 80%<br>BFR: 30% | 18 | 50% | 2 | 12 | RT: 4 × 10<br>LI-BFR: 1 × 30 + 3 × 15 | CSA-MRI; RM Test |
| Yasuda et al., 2014 (a) [35] | 17 | 61–85 | Non active | Not stated | 3 | 196 ± 18 | 2 | 12 | RT: 4 × 10<br>LI-BFR: 1 × 30 + 3 × 16 | CSA-MRI; MVC |
| Yasuda et al., 2014 (b) [36] | 16 | 61–78 | Non active | Not stated | Not stated | 120–270 | 2 | 12 | RT: 4 × 10<br>LI-BFR: 1 × 30 + 3 × 17 | CSA-MRI; 10RM Test |
| Yasuda et al., 2015 [37] | 14 | 61–85 | Non active | Not stated | Not stated | 202 ± 8 | 2 | 12 | RT: 4 × 10<br>LI-BFR: 1 × 30 + 3 × 18 | CSA-MRI; MVC |
| Yasuda et al., 2016 [38] | 30 | 61–86 | Non active | Not stated | 5 | 160–200 | 2 | 12 | RT: 3 × 12<br>LI-BFR: 1 × 30 + 3 × 15 | CSA-MRI; MVC |

Abbreviations: yrs, years; RT, resistance training exercise group; LI-BFR, low-intensity blood flow restriction exercise group; d, days; wk, week; st, sets; RP, repetitions; LC, leg curl; LE, leg extension; LP, leg press; CSA, cross-sectional area; MRI, magnetic resonance imaging; MVC, maximal voluntary contraction.

### 2.5. Risk of Bias of Individual Studies

Two authors independently assessed the risk of bias. In the case of disagreement, the subject was discussed with another author. The risk of bias was assessed using the Cochrane risk-of-bias tool for randomized controlled trials (RoB 2.0) [39], which evaluates the risk of bias in five domains: the randomization process, deviations from intended interventions, missing outcome data, measurement of the outcome, and selection of the reported result. A study is considered to be at a "low risk of bias" if all five domains have been judged to be at low risk of bias. A study is considered to have "some concerns" if it has been judged to raise some concerns in at least one domain. A study is considered to be at a "high risk of bias" overall if it is judged to be at a high risk of bias in at least one domain. The tool was applied to each outcome of interest.

### 2.6. Summary Measures

For continuous outcomes, the group size, the mean values, and the standard deviations (SDs) were recorded for each group compared in the included studies. Pooled effects were calculated using an inverse of variance model, and the data were pooled to generate a standardized mean difference (SMDs) with a corresponding 95% confidence interval (CIs). Most studies for each outcome reported data in the same units, so it was possible to pool all studies regardless of whether they reported changes in-between data at baseline and final data. Significance was set at $p < 0.05$. A random-effects model was used. We used Cohen's guidelines (no effect <0.2, small effect = 0.2 to 0.49, moderate effect = 0.5 to 0.79, large effect $\geq$ 0.80) [40] to report the magnitude of the effect and help with the interpretation of SMDs. All analyses were performed by a single reviewer using Review Manager (RevMan Version 5.4.1 The Cochrane Collaboration, 2020) and checked against the extracted data by the other author.

### 2.7. Additional Analysis

Subject to data availability, the subgroup analysis were performed considering the medium used to evaluate muscle strength and muscle mass on a specific muscle group or the evaluated kinetic chain.

### 2.8. Certainty of the Evidence: GRADE Approach

The reviewers decided *a posteriori* to evaluate the certainty of the evidence using the grading of recommendations, assessment, development, and evaluation (GRADE) approach to making the systematic review more usable for clinicians, trainers, decision-makers, and developers of clinical practice guidelines. We followed the GRADE approach to assess the certainty (or quality) of evidence in three major outcomes. The GRADE approach considers the risk of bias and the body of evidence to rate the certainty of the evidence into one of four levels:

High certainty: We are very confident that the true effect lies close to that of the estimate of the effect.

Moderate certainty: We are moderately confident in the effect estimate—the true effect is likely to be close to the estimate of the effect, but there is a possibility that it is substantially different.

Low certainty: Our confidence in the effect estimate is limited—the true effect may be substantially different from the estimate of the effect.

Very low certainty: We have very little confidence in the effect estimate—the true effect is likely to be substantially different from the estimate of effect.

## 3. Results

### *3.1. Literature Search and Article Selection*

Initial database searches yielded a total of 1659 articles. After performing screening by title and abstract, and then removing duplicates, a total of 326 research papers were discarded, thus obtaining a total of 48 RCTs for full-text review. Subsequently, 36 RCTs were excluded for not assessing muscle mass and strength; apply BFR in aerobic exercise; results recorded on graphs only; apply BFR in pathological older adults. In total 12 studies were included in the Systematic Review [27–38] (Figure 1).

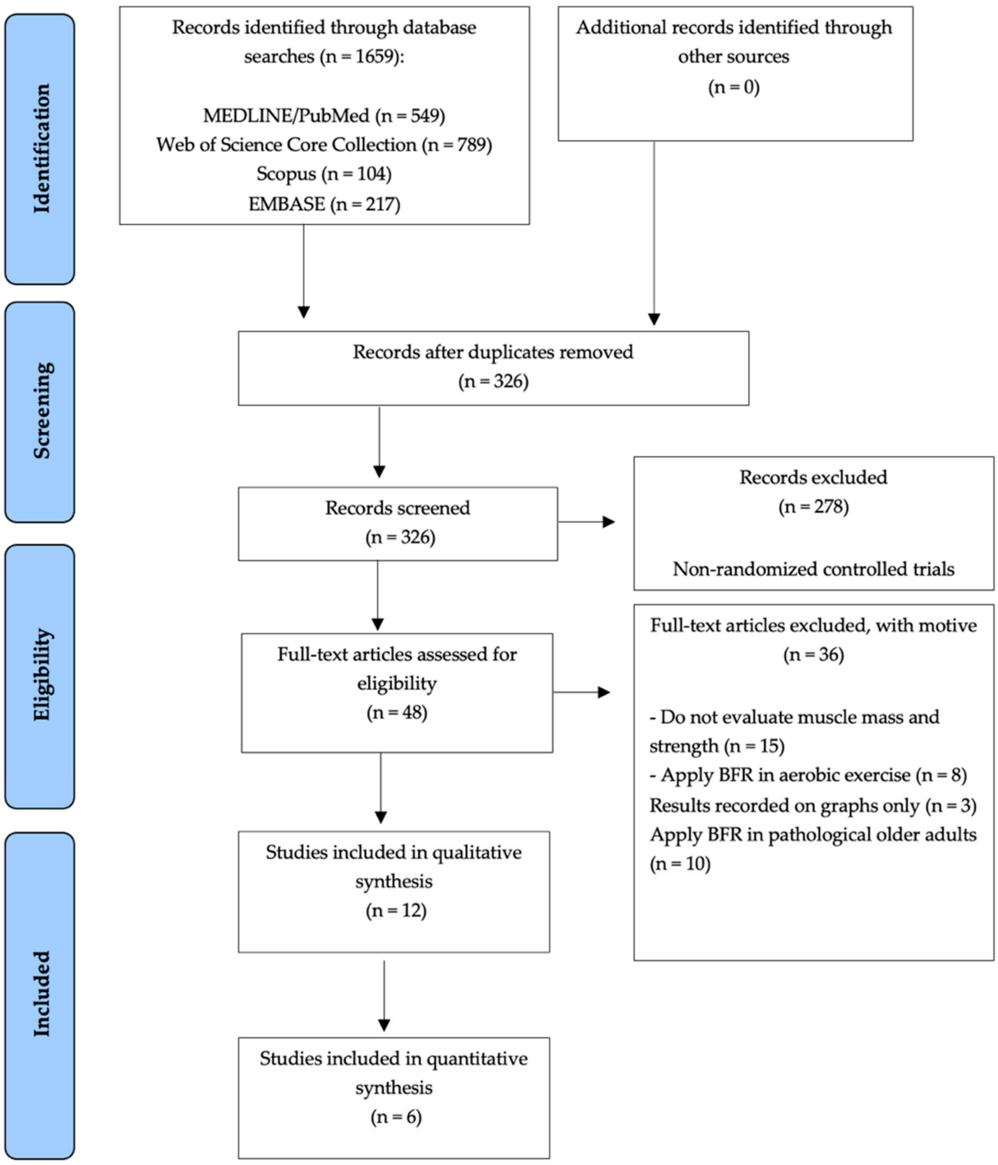


**Figure 1.** Preferred reporting items for systematic reviews and meta-analyses (PRISMA) flow-chart of the study selection.

### *3.2. Risk of Bias Individual Studies*

The twelve studies present some methodological problems.

#### 3.2.1. Muscular Strength Outcome (RM Test)

Four (57%) studies were judged of low risk of bias in at least one domain. One of them (14%) related to the random sequence generation and deviations from intended interventions [32]; three (43%) related to the missing data outcome [28,32,36]; and the remaining one (14%) for the measurement of the outcome domain [28]. For further information on the risk of bias, see Figure 2.

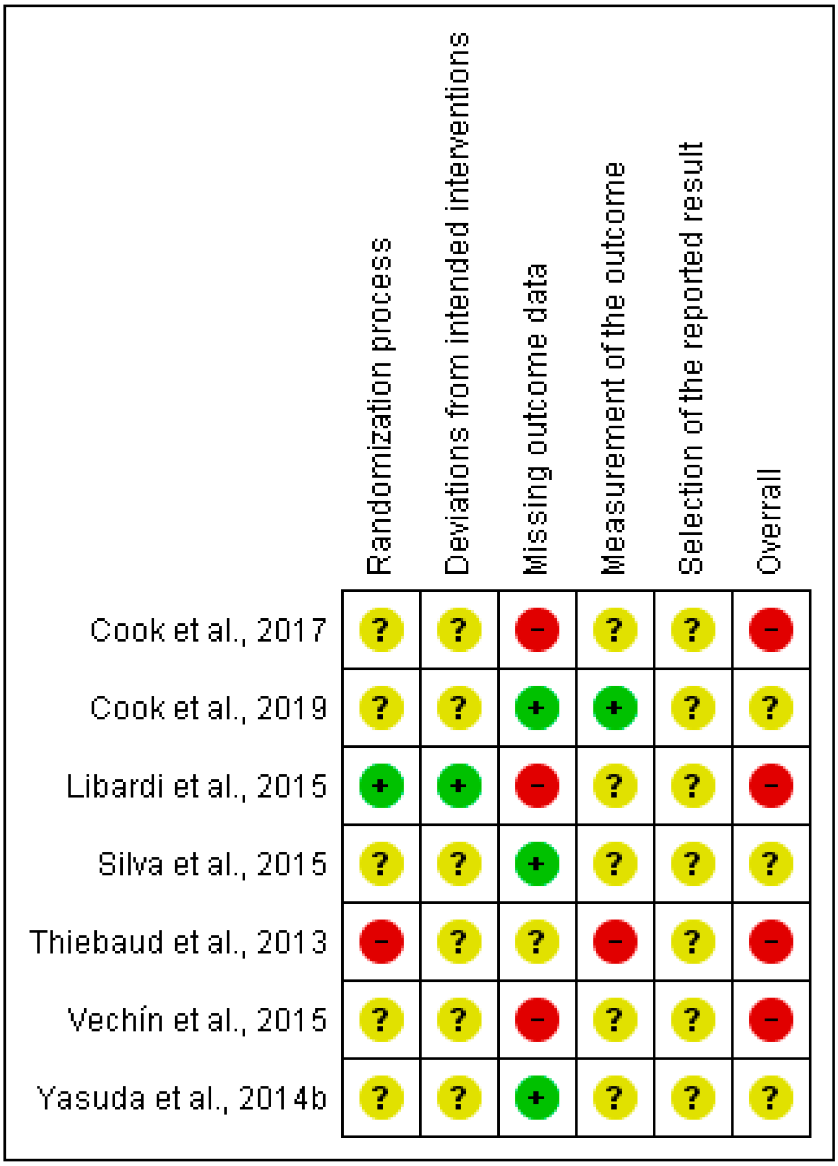


**Figure 2.** Risk of bias summary: review authors' judgments about each risk of bias item for muscular strength outcome.

#### 3.2.2. Muscular Strength Outcome (MVC Test)

Four (57%) studies were judged of low risk of bias in at least one domain. Two of them (29%) were judged at low risk of bias in all domains [30,31]; four (57%) related to the missing data outcome [28–30,37], and the remaining three (43%) for the measurement of the outcome domain [28–30]. For further information on the risk of bias, see Figure 3.

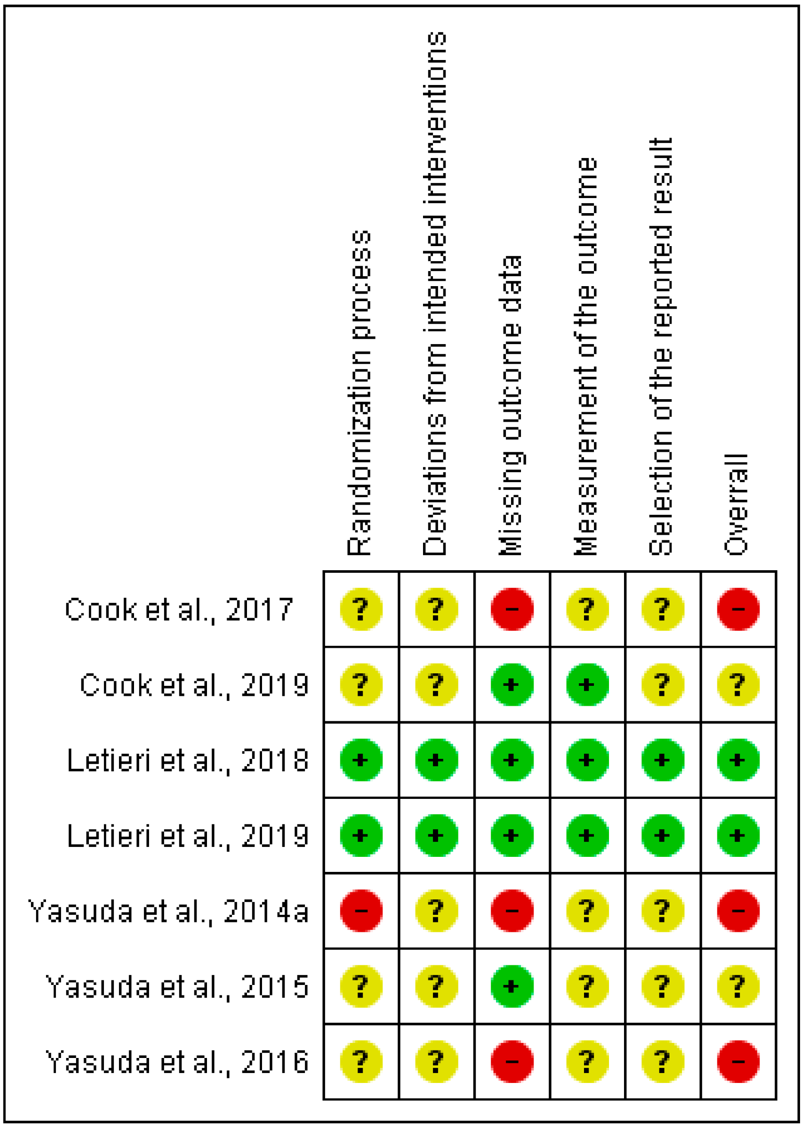


**Figure 3.** Risk of bias summary: review authors' judgments about each risk of bias item for muscular strength outcome.

3.2.3. Muscle Mass Outcome (cm$^2$)

Four (44%) studies were judged of low risk of bias in at least one domain. One of them (11%) related to the random sequence generation and deviations from intended interventions [31]; three (33%) related to the missing data outcome [29,36,37]; and the remaining one (11%) for the measurement of the outcome domain [28]. For further information on the risk of bias, see Figure 4.

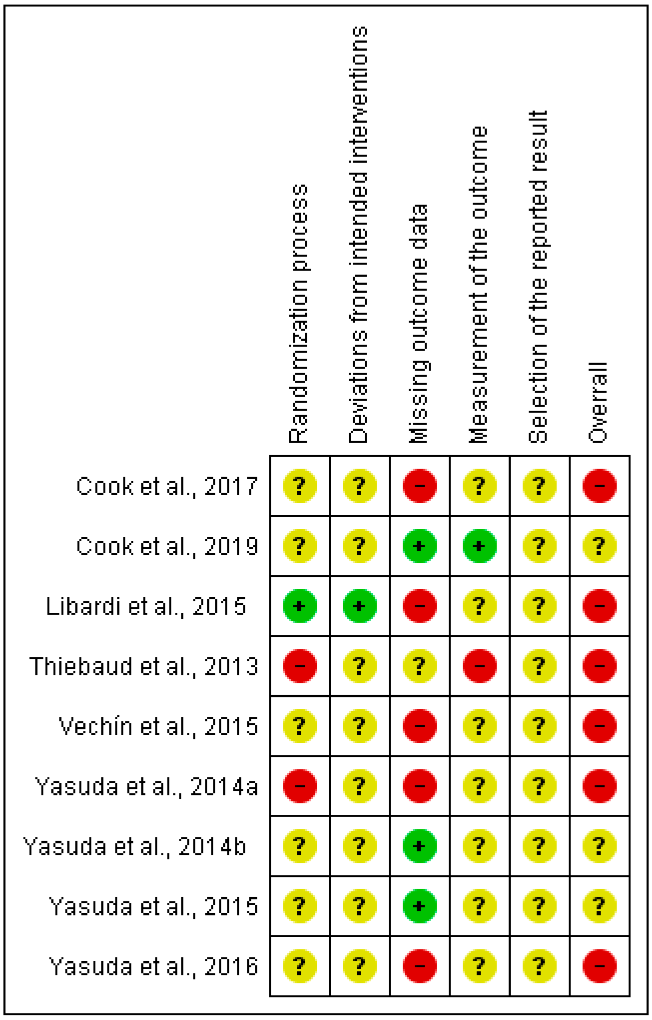


**Figure 4.** Risk of bias summary: review authors' judgments about each risk of bias item for muscle mass outcome.

### 3.3. Main Findings

#### 3.3.1. Narrative Synthesis

Twelve studies investigated the effect of the LI-BFR on strength and muscle mass compared to RT [27–38]. All studies that measured strength gains by direct RM test (kg) indicated significant improvements in weight lifted ($p < 0.05$) [28,31–34,36]. However, in the case of the studies that measured strength employing the MVC (Nm) [27–30,35,37,39], the evidence is a bit more uncertain, as two of the seven studies that performed this test did not find significant improvements in strength ($p > 0.05$) [27,35]. Table 2 describes the articles not included in the meta-analysis.

**Table 2.** Data from studies not included in the meta-analysis.

| Study ID | Population | Intervention | Comparison | Outcome | | |
|---|---|---|---|---|---|---|
| | | | | **LI-BFR (Mean/PI ± SD)** | **RT (Mean/PI ± SD)** | **CON (Mean/PI ± SD)** |
| Cook et al. (2017)<br>-<br>United States | 36 elderly males and females non-active and risk of functional limitation with ages between 69 and 82 years | LI-BFR<br>(n = 12) | RT and stretching (CON):<br>RT (n = 12)<br>CON (n = 12) | LE (RM-kg): 9.1, 95% CI [5, 13.2] $p < 0.01$<br>LC (RM-kg): 5.4, 95% CI [0.5, 10.2] $p < 0.01$<br>LP (RM-kg): 18.7, 95% CI [9.0, 28.4] $p < 0.01$<br>MVC (Nm): 11.2, 95% CI [-2.7, 25] $p = 0.14$<br>CSA (cm$^2$): 3.23, 95% CI [1.29, 5.16] $p < 0.01$ | LE (RM-kg): 21.2, 95% CI [13, 29.5] $p < 0.01$<br>LC (RM-kg): 8.2, 95% CI [5.4, 11.1] $p < 0.01$<br>LP (RM-kg): 31.7, 95% CI [13.6, 50] $p < 0.01$<br>MVC (Nm): 19.3, 95% CI [8.3, 30.3] $p = 0.14$<br>CSA (cm$^2$): 2.86, 95% CI [1.87, 3.86] $p < 0.01$ | LE (RM-kg): 0.6, 95% CI [−4.2, 5.3] $p < 0.01$<br>LC (RM-kg): 0.4, 95% CI [−1, 1.8] $p < 0.01$<br>LP (RM-kg): −0.2, 95% CI [−10.4, 10.1] $p < 0.01$<br>MVC (Nm): 3.5, 95% CI [−7.3, 14.3] $p = 0.14$<br>CSA (cm$^2$): 0.07, 95% CI [−0.67, 0.82] $p < 0.01$ |
| Letieri et al. (2019)<br>-<br>Brazil | 56 elderly females non-active with ages between 63 and 74 years | LI-BFR<br>(n = 11) | RT (n = 12) | HG (kg): 23.02 ± 3.2, $p = 0.432$ | HG (kg): 23.04 ± 5.97, $p = 0.432$ | No control group |
| Libardi et al. (2015)<br>-<br>Brazil | 25 elderly males and females non-active with ages between 60 and 69 years | LI-BFR<br>(n = 10) | RT and other unspecified (CON):<br>RT (n = 8)<br>CON (n = 7) | Percent increase (PI)<br>Strength (RM-kg): 35.4%, $p = 0.001$<br>CSA (cm$^2$): 7.6%, $p < 0.0001$ | Percent increase (PI)<br>Strength (RM-kg): 38.1%, $p < 0.001$<br>CSA (cm$^2$): 7.3%, $p < 0.0001$ | Percent increase (PI)<br>Strength (RM-kg): −4.3%, $p > 0.05$<br>CSA (cm$^2$): −2.2%, $p > 0.05$ |
| Yasuda et al. (2014) (a)<br>-<br>Japan | 17 elderly males and females non-active with ages between 61 and 85 years | LI-BFR<br>(n = 9) | RT (n = 8) | Percent increase (PI)<br>EF (MVC-Nm): 7.8%, $p = 0.0082$<br>EE (MVC-Nm): 16.1%, $p = 0.0131$<br>EF (CSA-cm$^2$): 17.6%, $p < 0.0001$<br>EE (CSA-cm$^2$): 17.4%, $p = 0.0131$ | Percent increase (PI)<br>EF (MVC-Nm): No changes<br>EE (MVC-Nm): No changes<br>EF (CSA-cm$^2$): No changes<br>EE (CSA-cm$^2$): No changes | No control group |
| Yasuda et al. (2014) (b)<br>-<br>Japan | 16 elderly males and females non- active with ages between 61 and 78 years | LI-BFR<br>(n = 8) | RT (n = 8) | LE (RM-kg): 66 ± 27, $p < 0.01$<br>LP (RM-kg): 191 ± 60, $p < 0.01$<br>QD (CSA-cm$^2$): 49.1 ± 9.6, $p < 0.01$<br>AD (CSA-cm$^2$): 24.2 ± 8.4, $p > 0.05$<br>HM (CSA-cm$^2$): 22.1 ± 4.8, $p > 0.05$<br>GM (CSA-cm$^2$): 40.8 ± 7, $p = 0.07$ | LE (RM-kg): 63 ± 24, $p > 0.05$<br>LP (RM-kg): 158 ± 44, $p > 0.05$<br>QD (CSA-cm$^2$): 44.7 ± 8.9, $p > 0.05$<br>AD (CSA-cm$^2$): 20.8 ± 3.6, $p > 0.05$<br>HM (CSA-cm$^2$): 20.8 ± 3.6, $p > 0.05$<br>GM (CSA-cm$^2$): 36.5 ± 7.7, $p > 0.05$ | No control group |
| Yasuda et al. (2016)<br>-<br>Japan | 30 elderly females non- active with ages between 61 and 86 years | LI-BFR<br>(n = 10) | RT and other unspecified (CON):<br>RT (n = 10)<br>CON (n = 10) | Percent increase (PI)<br>Strength (RM-kg): 16.4%, $p < 0.001$<br>Strength (MVC-Nm): 13.7%, $p = 0.028$<br>CSA (cm$^2$): 6.9%, $p < 0.001$ | Percent increase (PI)<br>Strength (RM-kg): 17.6%, $p < 0.001$<br>Strength (MVC-Nm): No changes, $p = 0.196$<br>CSA (cm$^2$): 1.5%, $p = 0.871$ | Percent increase (PI)<br>Strength (RM-kg): No changes $p = 0.912$<br>Strength (MVC-Nm): No changes, $p = 0.810$<br>CSA (cm$^2$): −2.2%, $p = 0.395$ |

Abbreviations: LI-BFR, Low-intensity blood flow restriction exercise group; RT, resistance training exercise group; CON, control group; LE, leg extension; LC, leg curl; LP, leg press; HG, handgrip; EF, elbow flexion; EE, elbow extension; QD, quadriceps; AD, adductors; HM, hamstrings; GM, gluteus maximus, CI, confidence interval; PI, percent increase; SD, standard deviation.

In the measurements concerning muscle mass of the included studies, those that measured changes in quadriceps thickness reported significant differences [27,28,31,33,34,36,38], however, for the lower limb, one study found no significant differences for adductors, hamstrings, and gluteus maximus [36]. In the case of upper extremities, one study reported significant differences in elbow flexor and extensor muscles [37].

#### 3.3.2. Quantitative Synthesis

The effects of BFR on muscular strength assessed in the RM-test, MVC-test, and muscle mass ($cm^2$) are shown in Figures 5–7, respectively.

##### LI-BFR vs. RT Alone on Muscular Strength via RM Test

As shown by Figure 5, when compared to resistance training alone, LI-BFR may have little to no effect in muscular strength measured by the RM test (SMD 0.07 (95% CI: −0.25 to 0.40) $p$ = 0.66; $I^2$ = 0%, $p$ = 0.53). However, this evidence is very uncertain. Likewise, this evidence is very uncertain when analyzing this comparison separately in leg press, knee extension, and knee flexion (ES 0.01, ES 0.08, and 0.12, respectively; see Table 3).

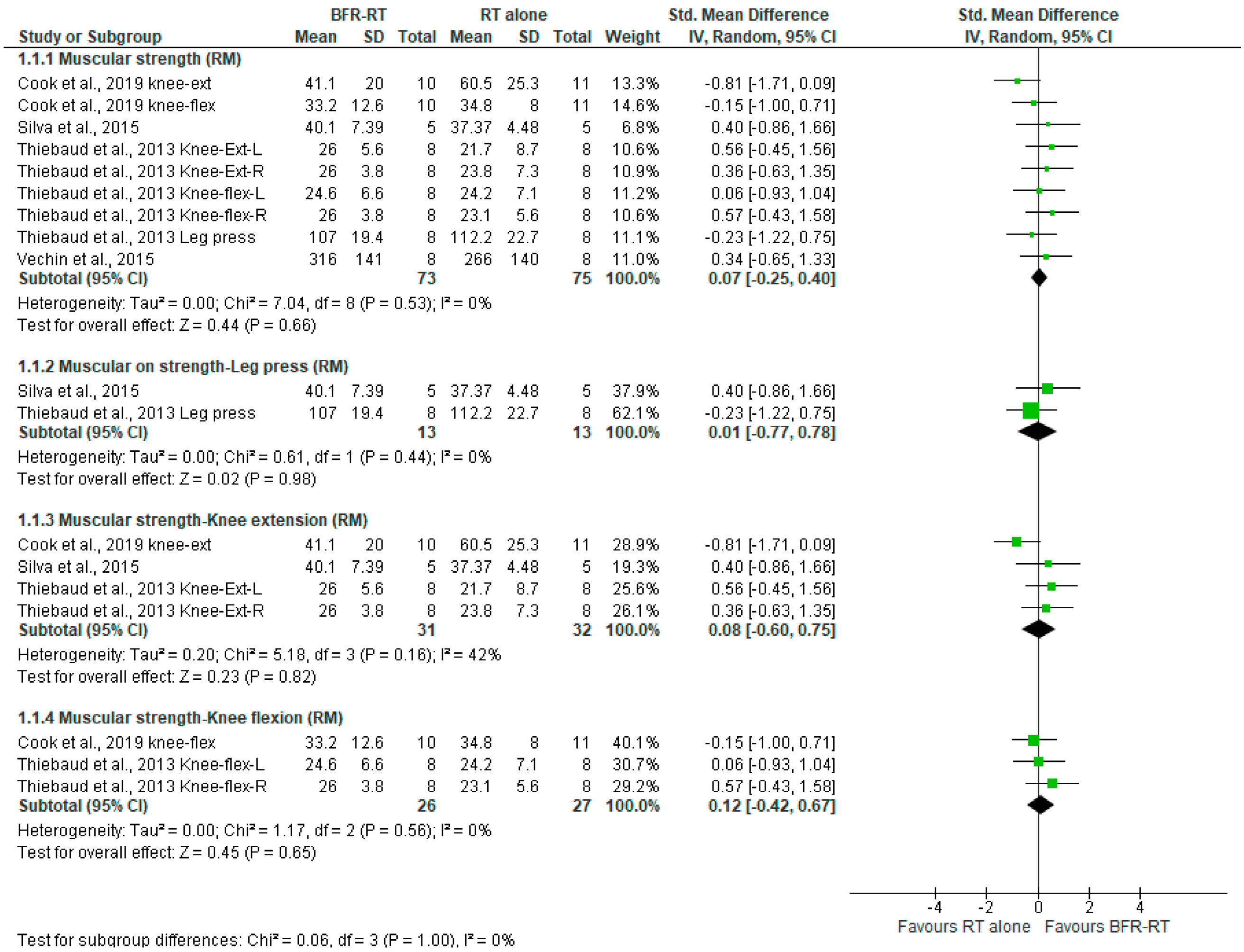


**Figure 5.** LI-BFR versus RT on muscular strength (RM test), standard means difference (SMD).

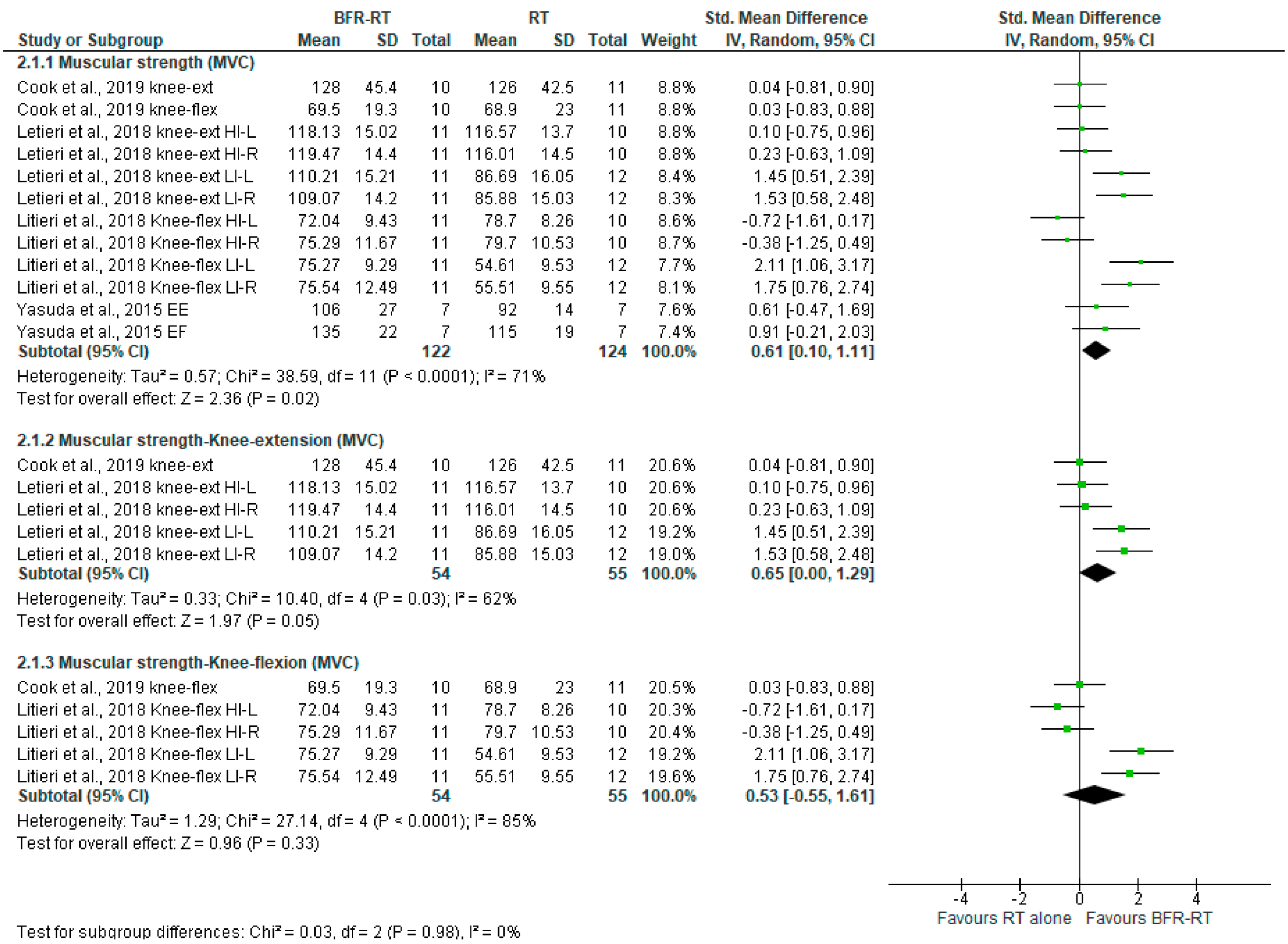


**Figure 6.** LI-BFR versus RT on muscular strength (MVC test), standard means difference (SMD).

LI-BFR vs. RT Alone on Muscular Strength via the MVC Testing

The LI-BFR effect on muscular strength measured using the MVC is larger than the one of RT alone (SMD 0.61, 95% CI [0.10 to 1.11], $p = 0.02$; $I^2 = 71\%$, $p < 0.0001$), but again, the evidence of this benefit is very uncertain.

Subgroup analysis by movement patterns reveals that this benefit is mainly due to the knee extension pattern, which is also significant ($p = 0.05$) and has a similar larger effect (SMD 0.65, 95% IC [0.00, 1.29]). Benefits in knee flexion are smaller and non-significant (SMD 0.53, 95% IC [−0.55, 1.61]; $p = 0.33$). Equally, there is also very uncertain evidence about this comparison on the MVC, both in the knee extension (ES 0.65), and in the knee flexion (ES 0.53). Table 4 shows this information.

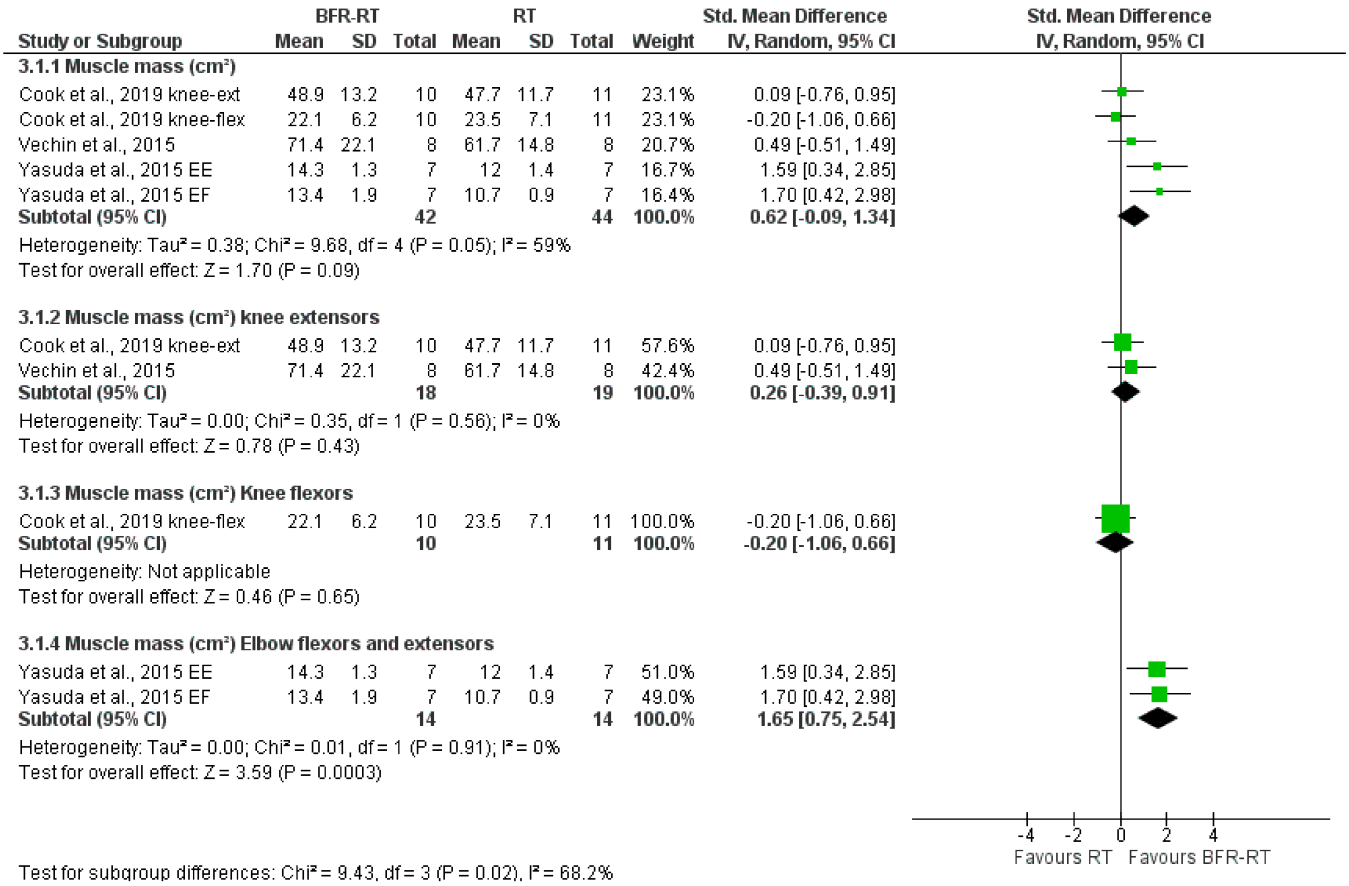


**Figure 7.** LI-BFR versus RT on muscle mass, standard means difference (SMD).

LI-BFR vs. RT Alone on Muscle Mass ($cm^2$)

Our data point out that LI-BFR trend to increase muscle mass over resistance training alone with a moderate effect size (SMD 0.62, 95% CI [−0.09 to 1.34], $p$ = 0.09; $I^2$ = 59%, $p$ = 0.05), but the evidence is very uncertain (Figure 7). Likewise, the evidence is very uncertain about the effect of low-load BFR-RT when compared with RT alone on muscle mass in knee extensors (ES 0.26) and knee flexors (ES −0.20), and elbow flexors and extensors (ES 1.65), see Table 5.

**Table 3.** Summary of findings for the comparison: LI-BFR versus RT alone on muscular strength (RM test).

**Resistance Training with Blood Blow Restriction Versus Resistance Training Alone**

**Population:** Non-Active older adults
**Intervention:** resistance training with blood flow restriction
**Comparison:** resistance training
**Setting:** laboratory

| Outcomes | Relative Effect (95% CI) | Anticipated Absolute Effect * (95% CI) | | N° of Participants (Studies) | Certainty of the Evidence (Grade) |
|---|---|---|---|---|---|
| | | Assumed Risk with Control | Assumed Risk with Intervention | | |
| **Muscular strength (RM Test)** Up to 12 weeks | SMD 0.07 * (−0.25 to 0.40) | 21.7 to 266 | Mean strength in intervention was 0.07 higher (0.25 lower to 0.40 higher) | 148 (4 RCTs) | ⊕○○○ VERY LOW [1,2] |
| **Muscular strength-Leg press (RM Test)** Up to 12 weeks | SMD 0.01 * (−0.77 to 0.78) | 37.37 to 112.2 | Mean strength in intervention was 0.01 higher (0.77 lower to 0.78 higher) | 26 (2 RCTs) | ⊕○○○ VERY LOW [1,2] |
| **Muscular strength-Knee extension (RM Test)** Up to 12 weeks | SMD 0.08 * (−0.60 to 0.75) | 21.7 to 60.5 | Mean strength in intervention was 0.08 higher (0.60 lower to 0.75 higher) | 63 (3 RCT) | ⊕○○○ VERY LOW [1,2] |
| **Muscular strength-Knee flexion (RM Test)** Up to 12 weeks | SMD 0.12 * (−0.42 to 0.67) | 23.1 to 34.8 | Mean strength in intervention was 0.12 higher (0.42 lower to 0.67 higher) | 53 (2 RCTs) | ⊕○○○ VERY LOW [2,3] |

The risk in the intervention group (and its 95% confidence interval) is based on the assumed risk in the comparison group and the relative effect of the intervention (and its 95% CI). CI: Confidence interval; RM: maximum repetitions; SMD: Standard mean difference. * Effects size: 0.2 represents a small effect, 0.5 a moderate effect, and 0.8 a large effect [29]. [1] Downgraded by two levels due to no randomization process, selection of the reported result, and measurement of the outcome. [2] Downgraded by two-level due to small sample size and wide confidence intervals (imprecision); [3] Downgraded by one level due to no randomization process, and selection of the reported result.

**Table 4.** Summary of findings for the comparison: LI-BFR versus RT alone on muscular strength (MVC test).

**Resistance Training with Blood Blow Restriction Versus Resistance Training**

**Population:** Non-active older adults
**Intervention:** resistance training with blood flow restriction
**Comparison:** resistance training
**Setting:** laboratory

| Outcomes | Relative Effect (95% CI) | Anticipated Absolute Effect * (95% CI) | | N° of Participants (Studies) | Certainty of the Evidence (Grade) |
|---|---|---|---|---|---|
| | | Assumed Risk with Control | Assumed Risk with Intervention | | |
| **Muscular strength (MVC test)** Up to 16 weeks | SMD 0.61 * (0.10 to 1.11) | 54.61 to 126 | Mean strength in intervention was 0.61 higher (0.10 lower to 1.11 higher) | 246 (3 RCTs) | ⊕○○○ VERY LOW [1,2] |
| **Muscular strength-Knee extension (MVC test)** Up to 16 weeks | SMD 0.65 * (0.00 to 1.29) | 85.88 to 126 | Mean strength in intervention was 0.65 higher (0.00 lower to 1.29 higher) | 109 (2 RCTs) | ⊕○○○ VERY LOW [1,2] |
| **Muscular strength-Knee flexion (MVC test)** Up to 16 weeks | SMD 0.53 * (−0.55 to 1.61) | 85.88 to 126 | Mean strength in intervention was 0.53 higher (0.55 lower to 1.61 higher) | 109 (2 RCTs) | ⊕○○○ VERY LOW [1,2] |

The risk in the intervention group (and its 95% confidence interval) is based on the assumed risk in the comparison group and the relative effect of the intervention (and its 95% CI). CI: Confidence interval; MVC: Maximum voluntary contraction; SMD: Standard mean difference. * Effects size: 0.2 represents a small effect, 0.5 a moderate effect, and 0.8 a large effect [29]. [1] Downgraded by one level due to inconsistency; [2] Downgraded by two-level due to small sample size and wide confidence intervals (imprecision).

**Table 5.** Summary of findings for the comparison: LI-BFR versus RT alone on muscle mass (cm$^2$).

**Resistance Training with Blood Blow Restriction Versus Resistance Training**

**Population:** Non-active older adults
**Intervention:** resistance training with blood flow restriction
**Comparison:** resistance training
**Setting:** laboratory

| Outcomes | Relative Effect (95% CI) | Anticipated Absolute Effect * (95% CI) | | N° of Participants (Studies) | Certainty of the Evidence (Grade) |
|---|---|---|---|---|---|
| | | Assumed Risk with Control | Assumed Risk with Intervention | | |
| **Muscle mass (cm$^2$)** Up to 12 weeks | SMD 0.62 * (−0.09 to 1.34) | 10.7 to 61.7 | Mean strength in intervention was 0.62 higher (0.09 lower to 1.34 higher) | 86 (3 RCTs) | ⊕○○○ VERY LOW [1,2,3] |
| **Muscle mass knee extensors (cm$^2$)** Up to 12 weeks | SMD 0.26 * (−0.39 to 0.91) | 47.7 to 61.7 | Mean strength in intervention was 0.26 higher (0.39 lower to 0.91 higher) | 37 (2 RCTs) | ⊕○○○ VERY LOW [1,3] |
| **Muscle mass knee flexors (cm$^2$)** Up to 12 weeks | SMD −0.20 * (−1.06 to 0.66) | 23.5 | Mean strength in intervention was −0.20 higher (−1.06 lower to 0.66 higher) | 21 (1 RCTs) | ⊕○○○ VERY LOW [1,3] |
| **Muscle mass elbow flexors and extensors (cm$^2$)** Up to 12 weeks | SMD 1.65 * (0.75 to 2.54) | 10.7 to 12 | Mean strength in intervention was 1.65 higher (0.75 lower to 2.54 higher) | 28 (1 RCTs) | ⊕○○○ VERY LOW [1,3] |

The risk in the intervention group (and its 95% confidence interval) is based on the assumed risk in the comparison group and the relative effect of the intervention (and its 95% CI). cm$^2$: Square centimeters; CI: Confidence interval; SMD: Standard mean difference. * Effects size: 0.2 represents a small effect, 0.5 a moderate effect, and 0.8 a large effect [29]. [1] Downgraded by one level due to no randomization process; [2] Downgraded by one level due to inconsistency; [3] Downgraded by one level due to small sample size and wide confidence intervals (imprecision).

## 4. Discussion

### *4.1. Summary of Main Results*

Our review aimed to determine the effectiveness of the low-intensity resistance training with blood flow restriction compared to dynamic high-intensity resistance training on strength and muscle mass in non-active older adults. We included 6 randomized controlled trials in the meta-analysis, revealing that low-intensity blood flow restriction led to larger significant improvements in muscular strength (MVC test) compared to traditional resistance training. This larger benefit was reduced to a trend when considering the effect on the muscle mass (cross-sectional area, in cm) and even disappeared when comparing differences in muscular strength improvements assessed utilizing the RM test. Particularly, all these outcomes shared a very low level of certainty due to poor quality study designs and disparities in the methodological approach.

Notably, subgroup analysis by movement patterns revealed that the above-mentioned benefit on muscular strength assessed utilizing the MVC was mainly due to the knee extension pattern.

### *4.2. Certain of Evidence*

The included studies evaluated different resistance training programs with or without BFR. The protocols in these studies differed in terms of the number of sets and repetitions, exercises, and muscle groups involved, as well as in the level of occlusion cuff pressure. Their positions regarding the characteristics of the participants, more specifically on the functional status, were neither entirely clear, as they previously justify the use of BFR in older adults with sarcopenia, yet no information on specific diagnostic tests for sarcopenia was found [15]. Moreover, the functional status of the subjects was determined as inactive (more than 6 months without physical activity), but older adults are a highly heterogeneous population [41], and their exercise-response is also heterogeneous [42], which needs further details. Therefore, the articles included in this review lack clear and unified criteria in the process of sample selection.

Very low-quality evidence formed all the comparisons in this systematic review. Our certainty in the evidence was downgraded due to limitations in the risk of bias assessment, including lack of both randomization process, measurement of the outcome, and selection of the reported result. The absence of blinding of both participants and investigators can lead to an overestimation of the effect estimate, although in exercise interventions it is not easy to blind participants. Of outermost importance, this blinding process is even more difficult in protocols with blood flow restriction, since if familiarization with the device and prior measurement of arterial occlusion pressure with Doppler ultrasound (which all the included studies affirm) have been properly conducted, it is easy to know whether the cuff is exerting pressure on the involved limb. Blinding the intensity is a challenge. Furthermore, most of the studies had low numbers of participants, wide confidence intervals, and high heterogeneity in the effects across them. Importantly, undertaking a sensitivity analysis to explore these limitations was not appropriate due to the low number of studies, which could bias any effect estimate.

### *4.3. Potential Biases in the Review Process*

The strength of this systematic review was the use of systematic methods to assess the certainty of the evidence. An important limitation in the review process has been, as mentioned above, the heterogeneity of the training and BFR protocols.

Regarding strength training protocols, the number of repetitions was very disparate among the included studies with a range between 6 and 30 repetitions, including one study on muscle failure [32]. This high heterogeneity makes a comparison between studies difficult because the influence of the exercise program on the BFR effect cannot be completely isolated.

Another example of the heterogeneity of the protocols is the occlusion pressure. The included studies used different pressure percentages within the range established by the current positionings [43], and the pressure was calculated in two different ways. Some studies used Doppler ultrasound to determine the maximum arterial occlusion pressure while others applied a pressure value 1.5 times the brachial systolic pressure. It also happens that some studies used variable occlusion protocols (no pressure exerted in the recovery periods between series) while the rest were based on a constant pressure during the entire intervention, making direct comparisons between the results of the studies difficult.

### 4.4. Agreements and Disagreements with Other Studies or Reviews

Our findings of low-quality evidence on the effects of BFR on strength and muscle mass align with those reported by two recent systematic reviews [20,44]. For instance, the increase in muscle strength was revealed with effect sizes ranging from 0.55 to 4.34 [44]. Aligned with it, Centner et al. [20] found a greater improvement in muscle strength with pooled effect sizes (ES) of 2.16 (95% CI 1.61 to 2.70). These authors also highlighted a very low level of evidence for the included studies due to the methodological diversity and the very small sample of participants. They included profiles of unhealthy subjects, and they also reported the variability of the profiles due to the high heterogeneity of the elderly. Similarly to us, these reviews revealed a favorable trend for LI-BFR in muscle mass gain, however, this effect did not reach statistical significance. Since the methodological diversity of the above-cited primary reviews [20,44] is similar to ours, we may conclude that the profile and heterogeneity of the physical condition of the participants, being in this systematic review and meta-analysis of older adults, may influence the results regarding LI-BFR resistance training. The agreement between their findings and ours could be also explained by several factors like the control of other important variables, such as the nutritional status [45].

### 4.5. Implications for Practice and Further Research

The findings of this systematic review highlight the need for more RCTs, but mostly with a more defined methodological approach in their interventions, since the disparity of the protocols is detrimental to the quality of the evidence, as determined by the grading of recommendations, assessment, development, and evaluation (GRADE). In addition, all the primary studies included, together with those found in other systematic reviews, analyze muscular strength gains through specific strength tests, but there is a lack of knowledge about the effect of LI-BFR on the functional status of the elderly. Of course, it has been previously proven that increasing strength and muscle mass benefits physical capacity in older adults [4,8], but future lines of research might include together strength testing some functional assessments, or even some specific motor tasks and challenges of daily living activities, to determine the impact of BFR on functional capacity and older individuals' autonomy.

## 5. Conclusions

The findings of this systematic review point out that strength training with blood flow restriction may induce increased muscular strength and muscle mass in non-active older adults, at least at a similar extent to that in the traditional high-intensity resistance training. However, caution should be when considering these findings, since the evidence is very uncertain about the effect of low-load BFR-RT when compared with RT alone on our outcomes. Further randomized controlled trials with a more defined and standardized methodological protocol are still required and more research is needed to reach a more certain conclusion.

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# The Anaerobic Power Assessment in CrossFit® Athletes: An Agreement Study

**Tomás Ponce-García [1,*], Javier Benítez-Porres [1], Jerónimo Carmelo García-Romero [1], Alejandro Castillo-Domínguez [2] and José Ramón Alvero-Cruz [1,*]**

[1] Department of Human Physiology, Histology, Pathological Anatomy and Sports Physical Education, University of Málaga, 29071 Málaga, Spain; benitez@uma.es (J.B.-P.); jeronimo@uma.es (J.C.G.-R.)
[2] Department of Nursing and Podiatry, University of Málaga, 29071 Málaga, Spain; alejandrocastillo@uma.es
* Correspondence: tomas_ponce@uma.es (T.P.-G.); alvero@uma.es (J.R.A.-C.)

**Abstract:** Anaerobic power and capacity are considered determinants of performance and are usually assessed in athletes as a part of their physical capacities' evaluation along the season. For that purpose, many field tests have been created. The main objective of this study was to analyze the agreement between four field tests and a laboratory test. Nineteen CrossFit® (CF) athletes were recruited for this study (28.63 ± 6.62 years) who had been practicing CF for at least one year. Tests performed were: (1) Anaerobic Squat Test at 60% of bodyweight (AST60); (2) Anaerobic Squat Test at 70% of bodyweight (AST70); (3) Repeated Jump Test (RJT); (4) Assault Bike Test (ABT); and (5) Wingate Anaerobic Test on a cycle ergometer (WG). All tests consisted of 30 s of max effort. The differences among methods were tested using a repeated-measures analysis of variance (ANOVA) and effect size. Agreement between methods was performed using Bland–Altman analysis. Analysis of agreement showed systematic bias in all field test PP values, which varied between −110.05 ($AST60_{PP}$—$WG_{PP}$) and 463.58 ($ABT_{PP}$—$WG_{PP}$), and a significant proportional error in $ABT_{PP}$ by rank correlation ($p < 0.001$). Repeated-measures ANOVA showed significant differences among PP values ($F(1.76,31.59) = 130.61$, $p =< 0.001$). In conclusion, since to our knowledge, this is the first study to analyze the agreement between various methods to estimate anaerobic power in CF athletes. Apart from ABT, all tests showed good agreement and can be used interchangeably in CF athletes. Our results suggest that AST and RJT are good alternatives for measuring the anaerobic power in CF athletes when access to a laboratory is not possible.

**Keywords:** anaerobic power; peak power; HIFT, high-intensity functional training; crossfit; athletes; field test

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## 1. Introduction

Anaerobic capacity has been defined as the total amount of ATP re-synthesized, by the whole body, during a maximal intensity and short duration effort by means of the anaerobic metabolic pathways [1]. The time interval to best measure the anaerobic capacity is 30 s [2] since up to 80% of the energy consumed in 30 s of maximal effort comes from anaerobic sources [3,4]. In addition, in a longer test, individuals tend not to apply the maximum intensity [5]. There are several laboratory tests to assess the anaerobic performance [6]. However, most are expensive and difficult to perform due to the specific equipment they require. For that reason, one of the most widely used laboratory tests to assess this ability is the Wingate test, which consists of pedaling with arms or legs at maximum effort for 30 s against a resistance determined by the participant's body weight. WG has shown to be a reliable test, having a test-retest correlation in many populations ranging from 0.89 to 0.98 [7]. Two main variables are determined from this test, peak power (PP) and mean power (XP). PP is also known as "anaerobic power" and is determined by the peak mechanical power recorded during the test, normally occurring in the first 5 to 10 s. In addition, XP is considered by many authors as the "anaerobic capacity" and represents the average mechanical power maintained during the 30 s, taken at 1, 3 or 5 s periods [7]. Some authors have shown PP and XP to be associate with performance in some team and individual sports, especially those performed at high intensity or a combination of low-moderate intensities with higher intensity peaks such as CF [8], surfing [9], alpine ski [10], soccer [11], track and field athletes [12] and many others.

In order to assess this ability out of the laboratory, numerous field tests, consisting of different exercises or tasks, have been created. Some of them based on different modalities of jumps [5,12–16]; running [14,17,18]; squat exercise [14,19,20]; and other exercises such as skipping [21]. All those tests have been studied in active individuals [17,18,21,22] as well as athletes of different sports such as soccer [14], volleyball [5,15], track and field [7,12,20,23], and cyclists [24,25]. They have shown to be valid tools to assess these parameters in athletes [5,12,18,19].

In the last decade, Functional Fitness Training has become one of the top fitness trends around the world [26,27]. One of these functional fitness programs, which has developed into a competitive sport, was branded as CrossFit®. CF is a multimodal high-intensity functional training program that combines weightlifting, gymnastics and athletics, among other movements in just one training or competition bout and develops all physical domains such as endurance, strength, stamina, etc. [28]. The multimodality characteristic of this sport, combined with the fact that the tests carried out in competition are not previously announced or standardized, means that CF athletes must be prepared for the unknown and therefore have an optimal development of all physical capacities such as maximum strength, stamina, power, speed, cardiorespiratory fitness, etc. [8,29–35]. Additionally, its intensity component indicates that CF competitors must exhibit a great deal of anaerobic performance to excel in this sport [29].

When a field test is developed to assess any ability of the athletes throughout the season, experts attempt to simulate the specific sporting gestures of the discipline for which it is created (running in soccer, for example). In the case of CF, as a multimodal sport made up of many elements of different kinds (squatting, jumping, running, lifting, etc.), it might seem challenging to succeed in choosing a specific exercise that encompasses all the skills and abilities necessary for this activity and evaluate any capacity accurately. Nevertheless, taking into account the specific characteristics of these athletes, it may be assumed that any field test might be a valid and interchangeable tool to assess any of the physical capacities. Hence, they might show a good performance in any test with jumping, running, cycling, squatting, etc.

In the current work, to assess the anaerobic performance by different exercises and determine their validity and level of agreement, four tests were chosen: a continuous jump test used in previous work by Dal Pupo et al. [5] (RJT), as well as three other tests that, to our knowledge, have not been used previously: two weighted deep squat tests (AST60 and AST70) at different percentages of the athlete's bodyweight (60% and 70%) and a test performed with a particular machine used in CF where upper and lower limbs are used simultaneously called Assault Bike® (ABT).

In CF athletes, some authors have evaluated the physiological determinants of performance in [8,30–35]. Most of them using laboratory tests to assess both the aerobic or anaerobic capacities and comparing the results with those obtained in standardized CF workouts. However, no study of agreement between field methods has been found. Therefore, the main purpose of this study is to analyze the agreement between four different modalities of field test measuring anaerobic performance (AST60, AST70, RJT and ABT) against the gold standard, Wingate test, in CF athletes.

## 2. Materials and Methods

### 2.1. Participants

Nineteen CF participants volunteered to participate in this study, approved by Málaga University Ethics Committee (CEUMA: 43-2018-H). They were experienced athletes who followed the same competitors' training program and had competed in some national or international competition. Data collection was carried out over four weeks off-season. Except for the rest periods established before each test, the athletes followed their regular training regimen throughout those weeks. They were asked to stop taking any supplementation or performance-enhancing products one week prior to data collection. The participants were recruited and tested in a local CF center. All participants provided written informed consent. As inclusion criteria, a minimum of one year of CF practice was established. Any participants with the presence or suspicion of any cardiac pathology, suffering or having suffered recently any musculoskeletal injury or any other condition that prevented exercising properly were excluded. Descriptive data are shown in Table 1.

**Table 1.** Descriptive data of the sample (*n* = 19).

| | **Mean** | **SD** |
|---|---|---|
| Age (years) | 28.63 | 6.62 |
| Height (cm) | 176.18 | 5.34 |
| Body Mass (kg) | 81.67 | 6.43 |
| Body Mass Index (kg/m$^2$) | 26.29 | 1.34 |
| Fat Mass (kg) | 24.71 | 6.35 |
| Fat Mass (%) | 20.10 | 5.18 |
| Muscle Mass (kg) | 35.03 | 3.74 |
| Muscle Mass (%) | 42.87 | 2.69 |
| Lean Body Mass (kg) | 56.95 | 10.02 |
| Lean Body Mass (%) | 79.90 | 5.18 |

### *2.2. Study Design*

A cross-sectional study was conducted over four weeks. Despite the fact that all participants were familiar with the exercises in all tests, a familiarization session was also scheduled during the first two weeks. All trials were separated by at least 48 h and performed at the same daytime to avoid the effects of circadian rhythms [36]. Participants were also advised to refrain from any strenuous physical activity in the previous 24 h of each trial. Tests performed were: (1) Anaerobic Squat Test at 60% of bodyweight (AST60); (2) Anaerobic Squat Test at 70% of bodyweight (AST70); (3) Repeated Jump Test (RJT); (4) Assault Bike Test (ABT); and (5) Wingate Anaerobic Test on a cycle ergometer (WG). Tests order execution was randomly assigned. The chronology of the tests is shown in Figure 1.

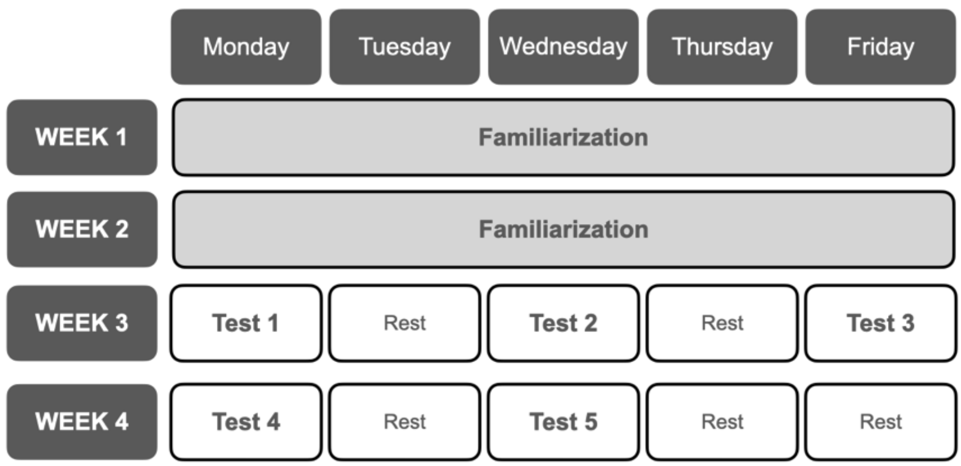


**Figure 1.** The chronology of the tests.

### *2.3. Procedures*

#### 2.3.1. Anthropometry, Body Composition and Other Physiological Variables

On the first day, to detect any possible cardiac pathology, all participants underwent an electrocardiogram assessed by a qualified physician. Furthermore, some anthropometric data were taken; height, by a wall-mounted stadiometer (SECA® 206; SECA, Hamburg, Germany) with a precision of 1 mm and body mass, by a scale with a precision of 100 gr (SECA® 803; SECA, Hamburg, Germany). Additionally, body composition was measured by a Medisystem Multifrequency Impedanciometer (Sanocare Human System SL, Madrid, Spain). Participants were asked to go fasting or without consuming any drink or food for at least 4 h, not having consumed alcohol in the last 48 h nor diuretics in the last 7 days or having performed strenuous physical activity in the previous 12 h [37]. Before the measure, they remained supine for 5 min with the upper limbs positioned about 30 degrees apart from the trunk and the lower limbs about 45 degrees apart [38]. Fat mass in kg was estimated according to Segal's formula [39], Lean body mass in kg was calculated by subtracting fat mass from total body mass and muscle mass in kg according to Janssen's formula [40]. Body composition variables were also calculated as a percentage (Table 1).

#### 2.3.2. All-Out Anaerobic Tests

Anaerobic Squat Test (AST60 and AST70)

The AST consisted of 30 s at the maximum effort of deep squats with a percentage of the participant bodyweight. The maximum number of squats had to be performed within that interval. Deep squat was established as a squat in which the iliac crest is below the highest part of the knee in its lowest position, and the leg, thigh and trunk segments are fully aligned at the highest position (Figure 2).

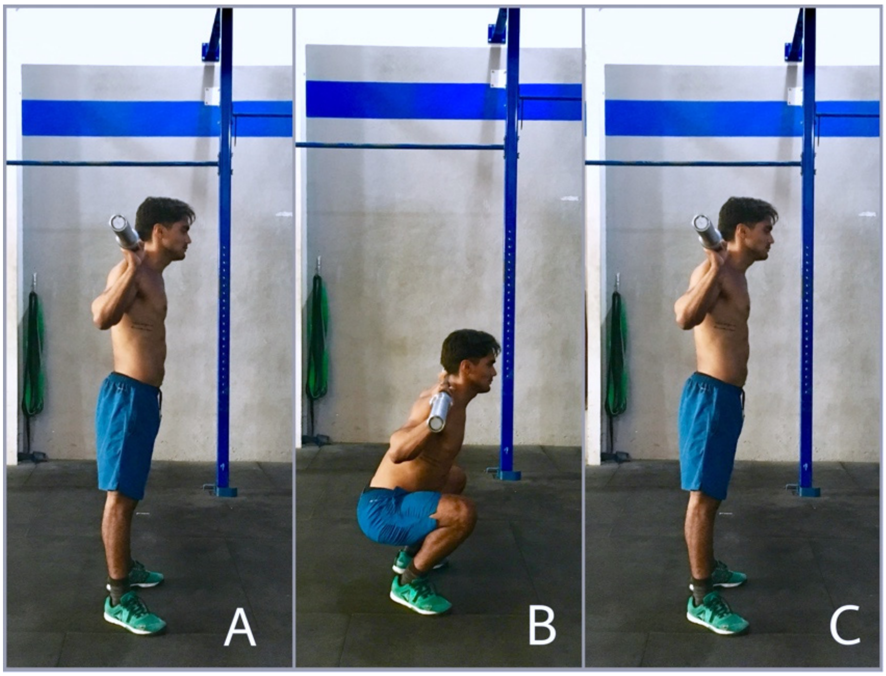


**Figure 2.** Full squat movement requirements. (**A**): start position; (**B**): lowest position; (**C**): final position.

The equipment used was a standard olympic lifting set composed of a 20 kg barbell, plates between 5 and 15 kg, with increases of 5 kg, and fractional discs from 0.5 and 2.5 kg, with 0.5 kg increments, from Xenios Usa® (Xenios Usa LLC, New York, NY, USA). The power of each repetition was registered by Beast® accelerometry sensor (Beast technologies) attached to the participant's wrist through a bracelet "ad hoc" (see Figure 3) and data processed by its smartphone application. Beast® sensor has shown to be a valid and reliable tool to measure full-squat values [41]. Two trials with different loads were executed, 60%

(AST60) and 70% (AST70) of participant bodyweight. Participants were weighed before each trial to determine the barbell load, rounded to the closest 0.5 kg. As a warm-up, they started with five minutes easy run, followed by one set of ten repetitions with an empty barbell, two more sets of ten repetitions with the assigned percentage and finished with 5 min easy run. Afterwards, a 5 min interval for recovery was established and used to set the accelerometry sensor. At the count of 3, 2, 1 . . . "Go!" the participant began to work at maximum effort, trying to execute as many squats as possible, being verbally motivated by the examiner throughout the test. To cool down, they were asked to easy walk for 5 min.

**Figure 3.** Beast sensor placement on the athlete's at right wrist.

Peak power (PP), mean power (XP) and minimal power (MP) were determined. Fatigue index (FI), understood as the loss of power during the 30 s interval, was calculated by the following formula FI (%) = (PP − PM/PP) × 100 [7].

Repeated Jump Test (RJT)

As previously described by Dal Pupo et al. [5], this test consisted of the maximum number of countermovement jumps in 30 s at the maximum height. Before the trial, participants warmed up with 5 min easy run, 3 sets of 10 forward jumps, 3 sets of 5 vertical jumps and 5 additional minutes easy run. Afterwards, a 5 min interval was established to rest and set the sensors. At the count of 3, 2, 1 . . . "Go!" the participant started to jump as high and fast as possible. In order to keep the maximum intensity, the participant was encouraged by the researchers during the whole interval. Right after the test, they were asked to easy walk for 5 min to calm down. Jumping variables were registered by a Polar® V800 with Running Bluetooth® Smart. This sensor has been shown to be valid and reliable to determine jumping variables [42]. PP, XP, MP and FI were determined.

Assault Bike Test (ABT)

This test was performed with an Assault Bike® Classic model (Assault Fitness Products; Carlsbad, CA, USA). The Assault Bike® is an air-resisted bike with the peculiarity of using both upper and lower extremities simultaneously (Figure 4). This machine has gained its popularity by being used by most CF centers and official competitions worldwide. The test consisted of 30 s at maximal effort. It began with a 15 min warm-up of cycling at 50 rpm (approximately 176 watts). Next, a 5 min recovery interval was established. The test was carried out from a static position without any inertia. To facilitate the initial start, the crank of the dominant leg was previously set to 45 degrees.

Wingate Anaerobic Test (WG)

The wingate anaerobic test is considered the gold standard when measuring the anaerobic capacity and consists of 30 s at maximum speed on a cycle ergometer with a constant resistance of 0.075 kp per kg bodyweight [7]. The test was executed with a Monark 828E cycle ergometer (Monark Exercise AB, Vansbro, Sweden) calibrated before each trial. Since trials were completed in morning-time (between 9:00 am and 2:00 pm), the warm-up was extended from 5 to 15 min, as proposed by Souissi et al. [36]. To warm up, all participants were asked to ride at 50–70 rpm at 1 kp (50–70 watts) for 15 min. Afterwards, they took a 5 min recovery interval. Straightaway, at the count of "3, 2, 1 . . . Go!" the participant started to ride as fast as possible. The researcher motivated them verbally during the whole time. A 5 min recovery ride at a warm-up pace was set to calm down. Every 5 s, power values were registered. PP, XP, MP and FI were determined.

**Figure 4.** Assault Bike® Classic.

### *2.4. Statistical Analysis*

The Statistical Package for the Social Sciences (SPSS 21, IBM Corp., Armonk, NY, USA) and MedCalc Statistical Software (MedCalc 18.6, MedCalc Software Ltd., Ostend, Belgium) were used to carry out statistical analyses. The level of significance was set at $p \leq 0.05$. Data were checked for normality by the Shapiro–Wilks analysis, and the agreement for the PP of the four methods was performed by using Bland–Altman analysis [43]. In order to evaluate the proportional error, Tau Kendall's rank correlation of the difference and mean of every method paired with WG was carried out. Previously, variables of difference and mean were computed for each pair. Furthermore, the differences among PP, XP, MP and IF of the five methods were tested for statistical significance ($p < 0.05$) using a repeated-measures analysis of variance (ANOVA). When a significant difference was found, post hoc 2-tailed paired *t*-tests to determine which values were significantly different were used. The Bonferroni adjustment was applied to keep the overall significance level at 0.05. The assumption of sphericity was tested using Mauchly's test. Additionally, the pairwise effect size was calculated by Cohen's d using G*Power 3.1.9.6 software.

## 3. Results

All variables showed a normal distribution in Shapiro–Wilks analysis ($p$ => 0.05), except for $RJT_{XP}$ ($p$ = 0.001) and $RJT_{MP}$ ($p$ = 0.022). Since the sphericity was violated, Greenhouse–Geisser corrected results are reported (ε = 0.44). The repeated-measures ANOVA showed significant differences among PP values, ($F(1.76,31.59)$ = 130.61, $p$ =< 0.001). Pairwise effect sizes are shown in Table 2. Additionally, absolute PP, XP and MP values of the AST60 and AST70 tests were slightly lower than the reference test. AST60 PP, XP and MP underestimated WG values by −110.05 (−14.12%), −101.07 (−15.20%) and −94.11 (−17.37%) watts, respectively. AST70 also underestimated WG values by −75.11 (−9.64%), −68.38 (−10.29%) and −56.16 (−10.37%) watts. In addition to the minor underestimation, the differences between AST70 and WG remained quite regular among all power values, around 10%, which was the only test that showed not statically significant differences by ANOVA test and showed the smallest effect size in all variables (Table 2).

**Table 2.** Absolute values of peak, mean, minimal power and fatigue index of the tests.

| | PP | | | XP | | | MP | | | FI | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Mean (±SD)** | ***p*** | ***d*** | **Mean (±SD)** | ***p*** | ***d*** | **Mean (±SD)** | ***p*** | ***d*** | **Mean (±SD)** | ***p*** | ***d*** |
| AST60 | 668.84 (±98.05) | 0.001 | 1.11 | 563.59 (±91.06) | 0.001 | 1.20 | 447.63 (±98.64) | 0.007 | 0.94 | 33.47 (±8.78) | 1.0 | 0.30 |
| AST70 | 703.79 (±112.94) | 0.052 | 0.73 | 596.28 (±121.61) | 0.182 | 0.60 | 485.58 (±111.84) | 0.627 | 0.46 | 31.43 (±10.03) | 1.0 | 0.13 |
| RJT | 1122.11 (±97.70) | <0.001 | 5.40 | 1057.90 (±154.65) | <0.001 | 3.56 | 921.95 (±113.29) | <0.001 | 4.69 | 17.79 (±7.25) | <0.001 | 1.39 |
| ABT | 1242.47 (±249.82) | <0.001 | 2.68 | 950.71 (±151.36) | <0.001 | 2.82 | 803.84 (±89.51) | <0.001 | 3.99 | 33.73 (±9.98) | 0.570 | 0.47 |
| WG | 778.89 (±102.30) | | | 664.66 (±73.08) | | | 541.74 (±50.42) | | | 29.71 (±8.39) | | |

AST60, anaerobic squat test at 60% of body weight; AST70, anaerobic squat test at 70% of body weight; RJT, repeated jump test, ABT, assault bike test; PP, peak power; XP, mean power; MP, minimal power; FI, fatigue index; SD, standard deviation; *p*, ANOVA *p*-values; *d*, pairwise effect sizes.

In contrast, the homologous absolute values RJT and ABT were notably higher. With an overestimation of RJT values of 343.22 (44.06%), 393.24 (59.16%) and 380.21 (70.18%), and ABT values of 463.58 (59.52%), 286.05 (43.04%) and 262.10 (48.38%) (Table 2).

In addition, Bland–Altman's analysis of agreement showed systematic bias in all field test PP values ($p$ > 0.05). The smallest difference between all PP values and $WG_{PP}$ was observed for the AST70 with an underestimation of −75.11 watts (95% CI, −124.80, −25.41). AST60 also underestimated PP by −110.05 watts (95% CI, −157.74, −62.36). Nevertheless, the other two tests, RJT and ABT, overestimated PP by 343.22 watts (95% CI, 312.63, 373.80) and 463.58 watts (95% CI, 380.18, 546.98), respectively.

Furthermore, only a significant proportional error was found in $ABT_{PP}$ by Tau Kendall's rank correlation (Table 3 and Figure 5d).

**Table 3.** Agreement analysis results.

| Methods | Bias | | | Limits of Agreement | | | | Kendall's Tau | Absolute Percentage Error | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Diff** | **95% CI** | ***p*** | **Lower** | **95% CI** | **Upper** | **95% CI** | ***p*** | **Median** | **95% CI** |
| AST60—WG | −110.05 | −157.74 to −62.36 | 0.0001 | −303.98 | −386.95 to −221.00 | 83.87 | 0.90 to 166.85 | 0.25 | 14.86% | 12.00 to 17.77 |
| AST70—WG | −75.11 | −124.80 to −25.41 | 0.0052 | −277.19 | −363.65 to −190.72 | 126.98 | 40.51 to 213.44 | 0.89 | 12.20% | 6.87 to 17.22 |
| RJT—WG | 343.22 | 312.63 to 373.80 | <0.0001 | 218.84 | 165.62 to 272.06 | 467.59 | 414.38 to 520.81 | 0.58 | 42.19% | 37.65 to 49.16 |
| ABT—WG | 463.58 | 380.18 to 546.98 | <0.0001 | 124.44 | −20.67 to 269.55 | 802.72 | 657.61 to 947.83 | <0.001 | 59.48% | 49.41 to 70.87 |

AST60, anaerobic squat test at 60% of body weight; AST70, anaerobic squat test at 70% of body weight; RJT, repeated jump test, ABT, assault bike test; CI, confidence Interval.

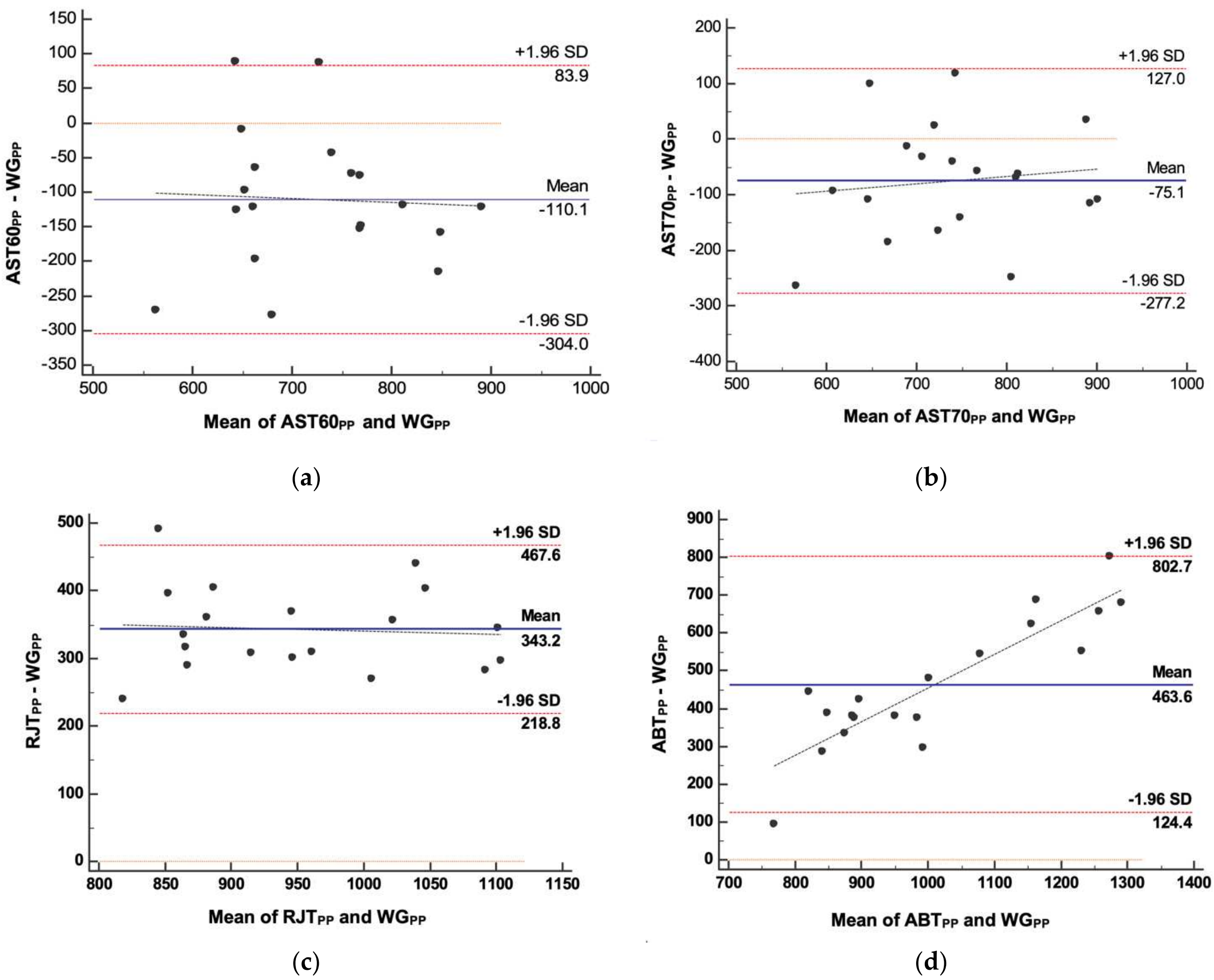


**Figure 5.** Bland–Altman's plots representing differences (Y axes) and mean (X axes) of measurements between: (**a**) AST60 and WG; (**b**) AST70 and WG; (**c**) RJT and WG; (**d**) ABT and WG.

## 4. Discussion

The main purpose of the present study was to evaluate the agreement between the five methods to assess anaerobic power in CF athletes. Since to our knowledge, this is the first study to analyze the agreement between various methods to estimate anaerobic power in CF athletes. Bland–Altman's analysis revealed a systematic bias with a mean difference that can vary between −110.05 watts ($AST60_{PP}-WG_{PP}$) and 463.58 Watts ($ABT_{PP}-WG_{PP}$). Despite the systematic bias shown by all the field tests compared with the laboratory test, the results showed good agreement between all methods ($p > 0.05$) since more than 80% of the dots on the graph were within the limits of agreement. In contrast, Tau Kendall's rank correlation analysis showed a proportional error in $ABT_{PP}$ ($p < 0.001$), where the differences were small for low PP values in the range of measurements and become higher as the true value increases. Additionally, the lowest within-subject variability in all the variables studied in the present work suggests that the AST70 is a valid field test to assess the power and anaerobic capacity in CF athletes.

Some of the field tests practiced in this study, such as AST and ABT, have not been previously used. AST is a test based on the squat exercise tested with two different percentages of the participants' body mass (60 and 70). The underestimation of PP absolute values, supported by the findings of Luebbers et al. [20], suggests that it might be interesting to replicate the study using higher percentages (75 and 80) to achieve more accurate agreement. In addition, some studies have shown underestimation of absolute values in a running test assessed in armed forces operators [21] and cycling athletes [25], as well as a kicking test studied in taekwondo athletes [44]. On the other hand, the overestimation of the RJT PP value is consistent with the findings of Sands et al. [16], where absolute power values of the Bosco test were higher than WG. In our study, overestimation was also found in ABT, and it might be due to the simultaneous use of lower and upper limbs to generate power instead of only the lower limbs as in WG. We have not found any previous study carried out with this machine that can provide data in this regard. However, the simultaneous use of the muscles of the lower limbs involved in pedaling and those of the upper limbs involved in pulling and pushing may suggest a more significant muscle mass implication and thus a greater capacity to generate power.

The results abovementioned are consistent with the $WG_{PP}$ differences reported by Gacesa et al. [45] in a comparison testing of maximum anaerobic performance on different elite athletes. Their findings suggest that the ability to generate power may be dependent on the activity since the highest values were found in anaerobic predominant sports such as volleyball, basketball, hockey, boxing, and wrestling, and lower values in soccer, rowing, and long-distance running athletes, which are predominantly aerobic types of sports. Further, some authors have found differences in power values between participants of different positions in basketball [46] and elite runners of different distances [23]. Consequently, it might be thought anaerobic power to be related to specific disciplines or attributed to some degree of specificity of the athletes tested. However, the results shown in the present study, due to the need of CF athletes to face multiple physical demands with a high level of intensity, may indicate that these athletes are able to exhibit outstanding anaerobic performance in tests of different nature (jumping, squatting, cycling, etc.).

Many comparisons or validity studies where authors studied the level of agreement between only one field test and WG were found. However, a lack of agreement works between more than one field method and the laboratory test in the literature makes it difficult to compare our results with any other. Moreover, as mentioned above, most of their results show some level of under or overestimation of field-test values which may be attributable to the biomechanical, technical or any other difference in the sporting gesture used for each test together with the intrinsic characteristic of the athlete tested. Future studies analyzing the agreement between different task tests may be of interest to find the cause of that variability and the most suitable field test for each discipline, especially in a multimodal sport as it is CF.

One limitation of the present work was not considering any other variables, such as kinematics, that could reflect the different biomechanical or lifting strategies related to performance in AST or any other test. Future research should aim to record these variables mentioned above and evaluate the interaction in the outcomes, replicating this work with other tests composed by other CF-specific exercises or in athletes of different experience/fitness levels.

In practice, the use of AST70 or RJT as a method to assess the anaerobic power in CF athletes could provide an alternative for coaches interested in assessing or monitoring their athletes at any point of the season without the need of taking them to a sports medicine laboratory.

## 5. Conclusions

Since to our knowledge, this is the first study to analyze the agreement between various methods to estimate anaerobic power in CF athletes. In conclusion, our results show a good level of agreement between all four methods and WG, being greater in AST70, which suggests that they may be used interchangeably with the exception of ABT. The proportional error found in ABT might make its use doubtful. Moreover, the results of the present study suggest that the magnitude of peak power values seems to be dependent on the type of exercise and athlete characteristics.

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**Institutional Review Board Statement:** The study was conducted according to the guidelines of the Declaration of Helsinki and approved by Ethics Committee of Universidad de Málaga (Code: CEUMA 43-2018-H).

**Informed Consent Statement:** Informed consent was obtained from all subjects involved in the study.

**Data Availability Statement:** The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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# Anthropometric Characteristics and Vertical Jump Abilities by Player Position and Performance Level of Junior Female Volleyball Players

**Suncica Pocek [1], Zoran Milosevic [1], Nemanja Lakicevic [2], Kristina Pantelic-Babic [3], Milka Imbronjev [1], Ewan Thomas [2,*], Antonino Bianco [2] and Patrik Drid [1]**

[1] Faculty of Sport and Physical Education, University of Novi Sad, 21000 Novi Sad, Serbia; suncicapocekfsfv@gmail.com (S.P.); zoranaisns29@gmail.com (Z.M.); milkaimbronjev@gmail.com (M.I.); patrikdrid@gmail.com (P.D.)
[2] Sport and Exercise Sciences Research Unit, University of Palermo, 90144 Palermo, Italy; lakinem89@gmail.com (N.L.); antonino.bianco@unipa.it (A.B.)
[3] Faculty of Physical Education and Sport, University of Banja Luka, 78000 Banja Luka, Bosnia and Herzegovina; kristina.pantelic-babic@ffvs.unibl.org
* Correspondence: ewan.thomas@unipa.it

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**Abstract:** Although absolute jump heights should be considered an important factor in judging the performance requirements of volleyball players, limited data is available on age-appropriate categories. The purpose of this study is to determine the differences in specific anthropometric characteristics and jumping performance variables in under−19 female volleyball players in relation to playing position and performance level. The sample of subjects consisted of 354 players who prepared for the U19 Women's Volleyball European Championship 2020 (17.4 ± 0.8 years, 1.81 ± 0.07 m, 67.5 ± 7.1 kg). Playing positions analyzed were setters (*n* = 55), opposites (*n* = 37), middle blockers (*n* = 82), outside hitters (*n* = 137), and liberos (*n* = 43). The results showed player position differences in every performance level group in variables of body height, spike, and block jump. Observed differences are a consequence of highly specific tasks of different positions in the composition of the team. Players of different performance levels are significantly different, with athletes of higher-ranked teams achieving better results. The acquired data could be useful for the selection and profiling of young volleyball players.

**Keywords:** spike jump; block jump; critical threshold; specialization

## 1. Introduction

Volleyball is a team sport with highly specific tasks and responsibilities for each player on the court according to player's position [1–3]. From the beginners' level and composition of 6:0, each player goes through a transition period of composition 3:3 and 4:2 to the advanced level of 5:1 team composition, with the highest level of player specialization. Based on anthropometric characteristics, the skill quality and motor abilities of players can be talent-identified and assigned to one of the player's positions [4–12]. The dominant composition played at the highest level of contemporary volleyball is the 5:1 composition. The first number denotes the number of the spikers/hitters, while the second number denotes the number of players who are in charge of the organization of the game in terms of setting. Accordingly, a contemporary volleyball team is composed of 5 hitters, namely, an opposite hitter, two outside hitters, two middle blockers, and the one and only player in charge of the organization of the game—the setter. The "7th" player on the court is a specialist defensive player—the libero—who replaces the middle blocker in serve reception and court defense responsibilities. All of them have highly specific and precise tasks.

Through the long-term process of training, talent identification, and selection, players should distinguish themselves, besides in skill level, in terms of above-average body height, upper and lower muscular power, speed, and agility [13]. Vertical jump is a fundamental part of the spike, block, and serve. At high-level volleyball, jumping is also used while setting because it reduces the flight time of the ball, speeds up the attack, and makes it harder for the first line of defense–block to read through the possibilities of the attacking team. Vertical jump assessment in volleyball is an inevitable part of training and testing procedures [1,14–21]. In a volleyball 5-set match, players in different positions perform a range of jumps that go from 65 to 136 jumps. On average, the highest number of jumps is performed by setters, followed by middle hitters, opposite hitters, and outside hitters [22]. At an elite playing level, a typical match is likely to impose the greatest stress from maximal jumping on middle players, but the setters also perform a very high number of submaximal jumps [1].

The purpose of this study is to determine the differences in anthropometric and jumping performance variables in under-19 women volleyball players in relation to playing position and performance level. This information could provide significant insight and reference values for talent identification and evaluation of the training programs applied.

## 2. Materials and Methods

### *2.1. Sample*

The Confederation European de Volleyball U19 Women's Volleyball European Championship 2020 (CEV U19W ECH 2020) was held in Bosnia & Hercegovina and Croatia from 22–30 August as the first major European competition since the outbreak of the coronavirus (COVID-19) pandemic. Out of the 12 teams initially planned for the championship, Russia, Italy, and Germany withdrew from the competition due to COVID-19 travel restrictions and specific government measures. The subject sample included 354 female volleyball players from the 12 teams planned for the competition and 3 teams that went through the 1st round of the qualification process for the U19 women's category.

### *2.2. Data Collection*

All data were retrieved from the CEV U19 Women Volleyball webpage (https://www-old.cev.eu/Competition-Area/CompetitionView.aspx?ID=1201) (accessed on 11 September 2020).

Displayed data on the official CEV cite for the abovementioned players included measures of body height, body mass, spike jump, block jump, year of birth, and player position. Body mass index was calculated based on the values of body height and body mass. Team level criteria were composed as follows: Level 1, classified 1st–4th, added by volleyball players from Russia and Italy (CEV U17W ECH 2018 1st and 2nd); Level 2, classified 5th–8th, added by volleyball players from Germany (CEV U17W ECH 2018 7th); and Level 3, which consisted of the 9th team of the final standings of the U19 competition (CEV ranking 17th), added by volleyball players from the 3 teams that played in the 1st round of qualification (CEV ranking 30th−32nd). Player position criteria were observed through the role of setter, opposite hitter, middle blocker, outside hitter, and libero (Table 1).

### *2.3. Statistical Analysis*

Descriptive and inferential analyses of the data were done using the software SPSS v.20 (SPSS Inc., Chicago, IL, USA). Multivariate analysis of variance (MANOVA) with an LSD post hoc test was used to determine the differences in jumping tests and anthropometric measures (dependent variables) between different playing positions and performance levels in volleyball (independent variables). Statistical significance was set at $p < 0.05$.

**Table 1.** Number of players in each position and each team, analyzed according to the CEV U19 Volleyball European Championship 2020 data.

| Performance Level | Setter | Opposite | Middle Blocker | Outside | Libero | ∑ |
|---|---|---|---|---|---|---|
| 1. Turkey | 5 | 2 | 7 | 15 | 3 | 32 |
| 2. Serbia | 4 | 2 | 5 | 15 | 3 | 29 |
| 3. Belarus | 3 | 2 | 5 | 5 | 3 | 18 |
| 4. France | 4 | 0 | 8 | 8 | 2 | 22 |
| * Russia | 2 | 4 | 6 | 7 | 5 | 24 |
| * Italy | 3 | 5 | 6 | 11 | 4 | 29 |
| ∑ level 1 | 21 | 15 | 37 | 61 | 20 | 154 |
| 5. Poland | 4 | 1 | 6 | 8 | 3 | 22 |
| 6. Bulgaria | 5 | 4 | 6 | 13 | 2 | 30 |
| 7. Croatia | 3 | 3 | 4 | 8 | 4 | 22 |
| 8. Slovakia | 3 | 2 | 6 | 7 | 4 | 22 |
| * Germany | 4 | 2 | 6 | 10 | 3 | 25 |
| ∑ level 2 | 19 | 12 | 28 | 46 | 16 | 121 |
| 9. Bosnia and Herzegovina | 5 | 4 | 5 | 8 | 2 | 24 |
| § Sweden | 3 | 1 | 3 | 8 | 2 | 17 |
| § Israel | 3 | 1 | 6 | 6 | 2 | 18 |
| § Montenegro | 4 | 4 | 3 | 8 | 1 | 20 |
| ∑ level 3 | 15 | 10 | 17 | 30 | 7 | 79 |
| Total | 55 | 37 | 82 | 137 | 43 | 354 |

* Teams which did non participate in the competition due to COVID restritions. § Teams which played only the 1st round of qualification.

## 3. Results

Table 2 presents mean (SD) anthropometric, physical, and age characteristics of junior female volleyball players regarding position and performance level. The MANOVAs revealed there are statistically significant differences for player position in 1st (F = 5.69, $p$ = 0.00, partial eta-squared = 0.19), 2nd (F = 3.62, $p$ = 0.00, partial eta-squared = 0.16), and 3rd performance level groups (F = 3.41, $p$ = 0.00, partial eta-squared = 0.22) for body height (1st f = 50.12, $p$ = 0.00, partial eta-squared = 0.58, 2nd f = 24.77, $p$ = 0.00, partial eta-squared = 0.46, and 3rd f = 26.90, $p$ = 0.00, partial eta-squared = 0.59), body mass (1st f = 14.68, $p$ = 0.00, partial eta-squared = 0.28, and 2nd f = 8.06, $p$ = 0.00, partial eta-squared = 0.22), body mass index (2nd f = 2.71, $p$ = 0.03, partial eta-squared = 0.09), spike jump (1st f = 23.99, $p$ = 0.00, partial eta-squared = 0.39, 2nd f = 7.70, $p$ = 0.00, partial eta-squared = 0.21, and 3rd f = 3.70, p = 0.01, partial eta-squared = 0.17), and block jump (1st f = 15.70, $p$ = 0.00, partial eta-squared = 0.30, 2nd f = 6.78, $p$ = 0.00, partial eta-squared = 0.19, and 3rd f = 3.21, $p$ = 0.02, partial eta-squared = 0.15).

Significant position-related differences in the best performance group in terms of body height are evident in all positions except between opposite and middle blocker players (post hoc LSD $p$ = 0.54), with greater values of both opposites and middles in comparison with outside hitters, after whom are setters and libero players. For spike and block jumps, there are no significant differences between players in the positions of opposite and middle blocker (post hoc LSD for spike $p$ = 0.24 and block 0.06) as well as the middle blocker and outside hitter (post hoc LSD for spike $p$ = 0.11 and block 0.42), while there are statistically significant differences between opposites and outside hitters (post hoc LSD for spike $p$ = 0.02 and block 0.01), with better results for opposite players. In all other mutual relations, there are statistically significant differences in the following order: from opposites, middles, outside hitters, setters and libero players, from best to worst results in spike and block jump. In the 2nd performance group, there are no significant differences between opposites and outside hitters in body height, spike, and block jump (post hoc LSD for body height $p$ = 0.72, spike 0.28, and block 0.32). In the lowest performance group

(3rd) of young volleyball players, differences in the abovementioned variables between positions are even less pronounced significant differences are not observed, although it was expected otherwise (for example, between setters and opposites, post hoc LSD for spike $p = 0.97$ and block 0.40).

**Table 2.** Anthropometric, physical, and age characteristics of junior female volleyball players regarding position and performance level.

| | Performance Level | Setter [1] | Opposite [2] | Middle Blocker [3] | Outside [4] | Libero [5] | ∑ |
|---|---|---|---|---|---|---|---|
| Body height (m) | 1 | 1.81 ± 0.06 [5] | 1.88 ± 0.03 [1,4,5] | 1.87 ± 0.04 [1,4,5] | 1.84 ± 0.04 [1,5] | 1.71 ± 0.05 | * 1.83 ± 0.07 |
| | 2 | 1.78 ± 0.06 [5] | 1.84 ± 0.04 [1,5] | 1.87 ± 0.05 [1,3,5] | 1.83 ± 0.05 [1,5] | 1.73 ± 0.04 | * 1.82 ± 0.07 |
| | 3 | 1.77 ± 0.03 [5] | 1.81 ± 0.06 | 1.83 ± 0.04 [1,4,5] | 1.78 ± 0.04 [5] | 1.62 ± 0.05 | * 1.78 ± 0.07 |
| | ∑ | 1.79 ± 0.05 | ‡ 1.85 ± 0.05 | ‡ 1.86 ± 0.05 | ‡ 1.82 ± 0.05 | ‡ 1.71 ± 0.06 | 1.81 ± 0.07 |
| Body mass (kg) | 1 | 68.4 ± 7.0 [5] | 72.1 ± 5.5 [5] | 73.3 ± 5.9 [4,5] | 70.3 ± 5.6 [5] | 61.5 ± 5.1 | * 69.8 ± 6.8 |
| | 2 | 63.8 ± 5.0 | 66.6 ± 7.1 [5] | 71.3 ± 7.0 [1,2,4,5] | 65.8 ± 5.5 [5] | 62.1 ± 4.3 | * 66.3 ± 6.5 |
| | 3 | 65.2 ± 6.9 | 65.9 ± 10.9 | 67.8 ± 6.3 | 64.6 ± 6.3 | 58.3 ± 5.6 | 65.0 ± 7.3 |
| | ∑ | 66.0 ± 6.5 | 68.6 ± 8.1 | ‡ 71.5 ± 6.6 | ‡ 67.5 ± 6.2 | 61.2 ± 5.1 | 67.5 ± 7.1 |
| BMI ($kg/m^{-2}$) | 1 | 21.0 ± 2.0 | 20.5 ± 1.3 | 21.0 ± 1.4 | 20.8 ± 1.6 | 20.9 ± 1.3 | 20.8 ± 1.6 |
| | 2 | 20.1 ± 1.4 | 19.7 ± 1.8 | 20.3 ± 1.6 [4] | 19.5 ± 1.2 | 20.7 ± 1.5 [4] | * 20.0 ± 1.5 |
| | 3 | 20.7 ± 1.8 | 20.1 ± 2.3 | 20.3 ± 1.6 | 20.4 ± 1.8 | 22.1 ± 1.8 | 20.6 ± 1.8 |
| | ∑ | 20.6 ± 1.8 | 20.1 ± 1.7 | 20.6 ± 1.6 | ‡ 20.3 ± 1.6 | 21.0 ± 1.5 | 20.5 ± 1.6 |
| Spike jump (m) | 1 | 2.89 ± 0.09 [5] | 3.04 ± 0.12 [1,4,5] | 3.00 ± 0.09 [1,5] | 2.97 ± 0.10 [1,5] | 2.77 ± 0.11 | * 2.95 ± 0.13 |
| | 2 | 2.87 ± 0.10 [5] | 2.90 ± 0.10 [5] | 2.95 ± 0.10 [1,5] | 2.94 ± 0.12 [1,5] | 2.78 ± 0.16 | * 2.91 ± 0.13 |
| | 3 | 2.75 ± 0.16 [5] | 2.75 ± 0.21 [5] | 2.81 ± 0.16 [5] | 2.84 ± 0.16 [5] | 2.59 ± 0.15 | * 2.78 ± 0.18 |
| | ∑ | 2.84 ± 0.13 | ‡ 2.92 ± 0.19 | ‡ 2.95 ± 0.13 | ‡ 2.93 ± 0.13 | ‡ 2.74 ± 0.15 | 2.90 ± 0.15 |
| Block jump (m) | 1 | 2.75 ± 0.09 [5] | 2.92 ± 0.11 [1,4,5] | 2.85 ± 0.16 [1,5] | 2.83 ± 0.10 [1,5] | 2.63 ± 0.14 | * 2.80 ± 0.15 |
| | 2 | 2.76 ± 0.10 [5] | 2.77 ± 0.10 [5] | 2.83 ± 0.10 [1,5] | 2.80 ± 0.11 [5] | 2.65 ± 0.16 | * 2.78 ± 0.13 |
| | 3 | 2.65 ± 0.18 [5] | 2.58 ± 0.28 | 2.70 ± 0.20 [5] | 2.71 ± 0.18 [5] | 2.44 ± 0.21 | * 2.66 ± 0.21 |
| | ∑ | 2.73 ± 0.13 | ‡ 2.78 ± 0.22 | ‡ 2.81 ± 0.16 | ‡ 2.79 ± 0.13 | ‡ 2.61 ± 0.17 | 2.76 ± 0.17 |
| Age (years) | 1 | 17.7 ± 0.6 | 17.0 ± 1.0 | 17.5 ± 0.8 | 17.3 ± 0.9 | 17.6 ± 0.7 | 17.4 ± 0.8 |
| | 2 | 17.6 ± 0.5 | 17.2 ± 0.8 | 17.4 ± 0.6 | 17.3 ± 0.9 | 17.4 ± 0.7 | 17.4 ± 0.8 |
| | 3 | 17.5 ± 0.9 | 16.9 ± 1.1 | 17.4 ± 0.7 | 17.2 ± 0.9 | 17.4 ± 0.8 | 17.3 ± 0.9 |
| | ∑ | 17.6 ± 0.7 | 17.0 ± 1.0 | 17.5 ± 0.7 | 17.3 ± 0.9 | 17.5 ± 0.7 | 17.4 ± 0.8 |

Significantly different from: [1]—Setter; [2]—Opposite; [3]—Middle blocker; [4]—Outside; [5]—Libero; *—significantly different by player position; ‡—significantly different by performance level.

The MANOVAs revealed there are statistically significant differences by performance level in the player position of opposites (F = 2.23, $p = 0.02$, partial eta-squared = 0.31), middle blockers (F = 2.87, $p = 0.00$, partial eta-squared = 0.19), outside hitters (F = 5.77, $p = 0.00$, partial eta-squared = 0.21), and libero players (F = 2.03, $p = 0.03$, partial eta-squared = 0.25). Univariate analysis showed that there are statistically significant differences in the observed variables: for opposites, in body height (f = 7.52, $p = 0.00$, partial eta-squared = 0.31), spike jump (f = 12.04, $p = 0.00$, partial eta-squared = 0.41), and block jump f = 12.22, $p = 0.00$, partial eta-squared = 0.42); for middle blockers, in body height (f = 6.13, $p = 0.00$, partial eta-squared = 0.13), body mass (f = 4.49, $p = 0.01$, partial eta-squared = 0.10), spike jump (f = 17.90, $p = 0.00$, partial eta-squared = 0.31), and block jump (f = 5.39, $p = 0.01$, partial eta-squared = 0.12); for outside hitters, in body height (f = 23.67, $p = 0.00$, partial eta-squared = 0.26), body mass (f = 13.19, $p = 0.00$, partial eta-squared = 0.17), body mass index (f = 8.93, $p = 0.00$, partial eta-squared = 0.12), spike jump (f = 10.96, $p = 0.00$, partial eta-squared = 0.14), and block jump (f = 7.65, $p = 0.00$, partial eta-squared = 0.10). Based on the post hoc LSD test, we can observe that the 1st and 2nd group of opposites, middles, outsides, and liberos, in comparison to the 3rd group, have greater values of body height and better results of spike and block jump. In the player position of opposites, there are also statistically significant differences between 1st and 2nd performance levels. Differences in the varied performance levels of setters with greater values of body height and better results of spike and block jump of the 1st performance level in comparison to 2nd and 2nd in comparison to 3rd are observed, although they are not statistically significant.

Finally, Table 3 reports position-specific normative centile values for anthropometric characteristics in terms of body height and sport-specific jumping abilities in absolute values, i.e., spike jump and block jump.

**Table 3.** Position-specific normative centile values of body height, spike jump, and block jump for junior female volleyball players.

| | | Setter | | | Opposite | | | Middle Blocker | | | Outside | | | Libero | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **Bh** | **SJ** | **BJ** | **Bh** | **SJ** | **BJ** | **Bh** | **SJ** | **BJ** | **Bh** | **SJ** | **BJ** | **Bh** | **SJ** | **BJ** |
| Percentile cut-off | 5 | 1.71 | 2.53 | 2.45 | 1.73 | 2.49 | 2.20 | 1.78 | 2.71 | 2.57 | 1.74 | 2.73 | 2.60 | 1.58 | 2.45 | 2.32 |
| | 10 | 1.73 | 2.71 | 2.58 | 1.76 | 2.63 | 2.47 | 1.80 | 2.79 | 2.68 | 1.76 | 2.79 | 2.67 | 1.64 | 2.53 | 2.40 |
| | 25 | 1.75 | 2.78 | 2.66 | 1.82 | 2.83 | 2.69 | 1.82 | 2.88 | 2.75 | 1.80 | 2.85 | 2.71 | 1.66 | 2.66 | 2.50 |
| | 50 | 1.79 | 2.85 | 2.75 | 1.85 | 2.94 | 2.83 | 1.86 | 2.97 | 2.82 | 1.82 | 2.95 | 2.80 | 1.70 | 2.74 | 2.60 |
| | 75 | 1.81 | 2.93 | 2.80 | 1.88 | 3.03 | 2.90 | 1.89 | 3.04 | 2.91 | 1.85 | 3.01 | 2.89 | 1.75 | 2.85 | 2.76 |
| | 90 | 1.86 | 3.00 | 2.88 | 1.91 | 3.09 | 3.00 | 1.92 | 3.09 | 2.98 | 1.88 | 3.09 | 2.95 | 1.78 | 2.95 | 2.82 |
| | 95 | 1.91 | 3.01 | 2.90 | 1.92 | 3.19 | 3.03 | 1.95 | 3.11 | 3.00 | 1.90 | 3.15 | 3.00 | 1.80 | 2.98 | 2.85 |

Values of body height, spike jump, and block jump are presented in meters.

## 4. Discussion

The aim of this study is to investigate the anthropometric characteristics and vertical jumping abilities of junior female volleyball players according to player position and performance level. The main results of our study are as follows:

(a) there are statistically significant differences by player position in every performance level group in the variables of body height, spike jump, and block jump.

(b) Significant position-related differences in the best performance group in terms of body height are evident in all positions except between opposite and middle blocker players, with greater values of both opposites and middles in comparison to outside hitters, followed, in order, by setters and libero players. In the variables of spike and block jumps, there are no significant differences between players in the positions of opposite and middle blocker, as well as middle blocker and outside hitters, while there are statistically significant differences between opposites and outside hitters, with better results from opposite players. In all other mutual relations, there are statistically significant differences in the following order: from opposites, middles, outside hitters, setters till the libero players, and from best to worst results in spike and block jumps. In the 2nd performance group, the same conclusions were derived with the addition that in this group, there were no significant differences between opposites and outside hitters in body height, spike jump, and block jump as a consequence of the lower values of opposites of the 2nd performance level group in comparison with the 1st performance level group, which were leveled to the values of the outside hitters. In the lowest performance group (3rd) of young volleyball players, differences in the abovementioned variables between positions were even less pronounced and non-significant.

(c) There are statistically significant differences by performance level, with greater values of body height and better results of spike and block jumps of the 1st and 2nd group of opposites, middles, outsides, and liberos in comparison to the 3rd group. In the player position of opposites, there are also statistically significant differences between 1st and 2nd performance levels. Differences in the varied performance levels of setters with greater values of body height and better results of spike and block jumps of the 1st performance level in comparison to 2nd and 2nd in comparison to 3rd are observed, although they are not statistically significant.

Based on the results of the present research, the data showed that there are statistically significant differences in body height and absolute values of spike and block jumps between positions in volleyball. These findings are in accordance with research conducted by different authors [1,3,23], and they are within expectations due to player tasks on the court.

At the same time, numerous studies that had taken into account the relative values of jumping abilities did not find any differences between player positions except for body height values [2,24–26]. Consequently, we can see on the basis of the norms of absolute values (Table 3), which is the critical height that athletes should reach. Elite volleyball players need to reach the threshold in the absolute values of spike and block jumps for specific positions. Such can be achieved either on the count of above-average body height and/or relative values of vertical jump in order to reach that threshold. Those players with a lower body height can compensate for their lack by an above-average jumping ability for the particular position that is targeted. In Table 3, we can see to which extent it should be expected. In such a manner, differences in relative jumping abilities between player positions are possible [19].

In this respect, relative vertical jumping ability is of great importance in volleyball regardless of the players' position, while absolute vertical jump values can differentiate players not only in terms of player position and performance level but in their career trajectories. However, maximum jump height performance in each and every jump, either in the spike or in the block, is neither necessary nor expedient. Due to player adaptation of their efforts to the game situation and efficacy of their performance throughout the game, the intensities of attack jumps at maximal capacity varies from 55–90% [27]. A higher contact height in the attack motion involves a better incidence angle of the opponent court [28]. Differences between the values of spike and block jumps, with the greater reach of spike jumps, are due to the type of the approach (frontal vs. lateral) and how the ball is contacted (one hand vs. both hands simultaneously). The fact that the aim of block performance is to increase the area by which we limit attacker options, the player needs to place both hands simultaneously on the ball when performing the block. Additionally, the reason for such height discrepancies between spike and block jumps is that the first is executed individually while a block must be performed by two or three players in a coordinated manner in which players need to adjust and harmonize their temporal and spatial actions.

Player specialization, i.e., determining the player's position, is a complex and long-term process. Based on the player's characteristics and abilities, coaches should assign the player a role on the court that would maximize the player's contribution to the team. Coaches may sometimes encounter resistance from players due to their affinities, but the specialization process should be approached thoroughly. Talent identification and development is a process based on an understanding of the tasks and responsibilities of the player regarding their position (Table 4) as well as a consideration of the body measures and abilities associated with sports performance. In pursuit of elite performance, it is of great importance to differentiate between the trainable and non-trainable qualities of a player [29–31].

**Table 4.** Player's role and subsequent tasks in volleyball according to their position.

| | Setter | Opposite | Middle | Outside | Libero |
|---|---|---|---|---|---|
| Serve | ✓ | | ✓ | ✓ | - |
| Serve reception | - | - | - | ✓ | ✓ |
| Setting | ✓ (II–III) | - | - ([4]) | - | - ([4]) |
| Spike | ([1] IV, III, II) | II, I ([2] R1 IV) | III | IV, VI ([2] R1 II) | - |
| Block | II | II ([3] IV) | (V, III, II) | IV ([3] II) | - |
| Backcourt defense | I | I | V | VI | V |

✓: Performed task by role, roman letters indicate the field zone in which such task can be performed. [1] Setters do not perform spikes, but are allowed in certain situations: setter positioned in Zone IV, Zone III, and Zone II. [2] R1, setter in Zone I: opposite player performs spike from Zone IV, while outside hitter performs spike from Zone II. [3] R1, setter in Zone I: as a response to an opponent's counterattack, the opposite player performs a block from Zone IV while the outside hitter performs a block from Zone II. [4] if setter is not able to perform setting due to previous contact with the ball, middle blocker or libero could help.

A spike is the most attractive and efficient way of scoring a point. The success of this action depends on height of contact, ball direction, and ball speed. The main factors that determine the height of contact are standing height reached, which consists of body height and arm length, and ability to jump and reach, which consists of the ability of a player to perform technical elements in the most efficient way in terms of the utilization of motor abilities, namely, explosive muscular power. For the height of contact, the ability to jump and reach is usually monitored in volleyball [15]. With the exception of liberos, every player may spike.

Throughout the years, as demonstrated in the European and World Championships, there has been an increase in the use of the power jump serve in both men's and women's volleyball [32]. With the change in rules and the introduction of the Rally Point System, the serve as a skill has become a mighty tool for scoring a point and not just for entering the rally in the competition of two teams. Even when a team does not score a direct or ace point, through a powerful power jump serve, it can reduce the possibilities of attack from the opponent team and facilitate the organization of a counterattack. Therefore, while performing spikes, power serves (which is very similar to the spike technique), and blocks, volleyball players should possess above average body height in combination with the power and force of lower extremities in executing simple vertical jumps.

Because of the similar requirements in spike and block jumps for opposite (main hitter) and middle blockers (main blocker), the shorter outside hitters, in order to reach the critical threshold, must make up for their lack of height and standing reach by exhibiting superior relative jump heights. In this respect, absolute jump heights of spike and block are of great importance when judging the performance requirements of outsides. Those players who did not reach these thresholds cannot play at the elite level of volleyball on the position of outsides. Hence, these players were left out during the transition from junior to senior levels of competition, which resulted in their playing career coming to an end. Because of their exquisite skillfulness in serve reception and court defense, in order to keep them in the team and improve the game, in 1998, there was a change in rules and the introduction of the libero player.

Our study was able to identify differences between various playing positions in terms of body height and absolute vertical jump for both spike and block in elite junior female volleyball players. However, the main limitation of this study is that all data were retrieved from the data displayed by the official CEV site from the competition of the U19 Women's Volleyball European Championship 2020.

## 5. Conclusions

Player specialization, i.e., determining the player's position, is a complex and long-term process. Based on the player's characteristics and abilities, coaches should assign the player a role on the court that would maximize the player's contribution to the overall quality of the team. During that process, it is important to differentiate between the trainable and non-trainable qualities of a player.

Based on the results of this research, the data shows that there are statistically significant differences in body height and absolute values of spike and block jumps between positions in volleyball. Relative vertical jumping ability is of great importance in volleyball regardless of the players' position, while absolute vertical jump values have the power to differentiate players not only in terms of player position but also in performance level. The higher the performance level of the team, the lower the intra-positional differences in terms of height, spike jump, and block jump, and some other factors become decisive (e.g., technical–tactical skill and knowledge, decision-making quality, performance under pressure).

Deficit of body height for a particular position can be compensated by jumping ability only to some extent. The relatively large sample of subjects in our study is composed of elite (1st group), good (2nd group), and lower levels of performance (3rd group) of U19 women volleyball players. In pursuit of excellence and competition on the elite senior level, they need to reach the threshold for their age and particular position in terms of absolute spike and block jumps based on the normative values presented.

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# Recovery and Fatigue Behavior of Forearm Muscles during a Repetitive Power Grip Gesture in Racing Motorcycle Riders

**Michel Marina [1,*], Priscila Torrado [1] and Raul Bescós [2]**

[1] Research Group in Physical Activity and Health (GRAFiS), Institut Nacional d'Educació Física de Catalunya (INEFC), Universitat de Barcelona (UB), 08038 Barcelona, Spain; priscilatorradopineda@gmail.com
[2] Plymouth Institute of Health and Care Research (PIHR), University of Plymouth, Plymouth PL4 8AA, UK; raulbescos@gmail.com
* Correspondence: michel.marina.1964@gmail.com; Tel.: +34-616-845-407

**Abstract:** Despite a reduction in the maximal voluntary isometric contraction ($MVC_{isom}$) observed systematically in intermittent fatigue protocols (IFP), decrements of the median frequency, assessed by surface electromyography (sEMG), has not been consistently verified. This study aimed to determine whether recovery periods of 60 s were too long to induce a reduction in the normalized median frequency ($MF_{EMG}$) of the flexor digitorum superficialis and carpi radialis muscles. Twenty-one road racing motorcycle riders performed an IFP that simulated the posture and braking gesture on a motorcycle. The $MVC_{isom}$ was reduced by 53% ($p < 0.001$). A positive and significant relationship ($p < 0.005$) was found between $MF_{EMG}$ and duration of the fatiguing task when 5 s contractions at 30% $MVC_{isom}$ were interspersed by 5 s recovery in both muscles. In contrast, no relationship was found ($p > 0.133$) when 10 s contractions at 50% MVC were interspersed by 1 min recovery. Comparative analysis of variance (ANOVA) confirmed a decrement of $MF_{EMG}$ in the IFP at 30% $MVC_{isom}$ including short recovery periods with a duty cycle of 100% (5 s/5 s = 1), whereas no differences were observed in the IFP at 50% $MVC_{isom}$ and longer recovery periods, with a duty cycle of 16%. These findings show that recovery periods during IFP are more relevant than the intensity of $MVC_{isom}$. Thus, we recommend the use of short recovery periods between 5 and 10 s after submaximal muscle contractions for specific forearm muscle training and testing purposes in motorcycle riders.

**Keywords:** handgrip; carpi radialis; flexor digitorum superficialis; neuromuscular fatigue; motorcycle; recovery

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## 1. Introduction

Simulation of highly repetitive intermittent muscle contractions present during motorcycle competitions is currently under investigation because of their relationship with the development of clinically significant conditions, especially in the hand/forearm. These conditions, characterized by pain and loss of the hand or forearm function, are defined as exertional compartment syndrome [1–4]. They frequently lead to long periods of illness in motorcycle riders, especially in those participating in endurance competitions such as 24 h races, where they must brake more than 4000 times and make 10,000 gear changes [5]. Similar pathological patterns can also occur among workers in the manufacturing industry [6]. The fact that many athletes, manual workers, and musicians must endure their mechanical work over long periods of time, muscle contraction intensities that characterize each activity explains the large number of studies focused on neurophysiological fatigue of the forearm muscles [7–11]. These muscles are involved in a great variety of repetitive grip tasks that can lead to neuromuscular fatigue and functional impairment when these tasks become chronic. Thus, it is important to obtain better knowledge and understanding of the mechanisms involved in these physiological situations to prevent forearm syndrome.

When assessing human muscle fatigue with superficial electromyography (sEMG), the power spectrum displacement towards lower frequencies has been extensively documented in continuous fatiguing protocols (CFP), in which submaximal voluntary contractions are maintained until exhaustion [9,12–16]. Intermittent fatiguing protocols (IFP) have also been extensively studied because intermittent contractions at different intensities are very common in the everyday life of the majority of workers and athletes [17,18]. Consequently, when comparing both types of fatiguing tasks (CFP versus IFP) specifically adapted to motorcycle riders [9], IFP showed a stronger relationship with the level of motorcyclist forearm discomfort compared to CFP [9].

The relative intensity of the contraction with respect to maximal voluntary isometric contraction ($MVC_{isom}$) registered in a non-fatigued condition ($\%MVC_{isom}$) is a key factor that modulates muscle fatigue. Studies looking at CFP confirmed that the higher the intensity of the effort, the shorter the time to task failure [14,16,19], obviously because of the lack of recovery periods. Moreover, it has been generally observed that $\%MVC_{isom}$ and the time to task failure (also called time limit) have a significant effect on the decrement of sEMG frequency ($MF_{EMG}$) and increment of the sEMG amplitude ($RMS_{EMG}$) [14,15,20]. A reduction in $MF_{EMG}$ was observed during CFPs at 10% MVC [21,22], 25% MVC [22–24], 30% [21], 40% [9,21,24], 60% [25], 55, 70, 80, and 90% of MVC [24]. Nevertheless, some caution is recommended in regard to $MF_{EMG}$ because $\%MVC_{isom}$ should not be considered as a definitive factor explaining the absence of a reduction in $MF_{EMG}$ during fatiguing protocols [24,25].

A second factor that is necessary to consider when measuring fatigue is the duration of the effort or exertion time. It is known that the duration of fatiguing tasks at a constant relative submaximal $\%MVC_{isom}$ is negatively associated with $MVC_{isom}$ decrements, reaching the maximal point at time to task failure [26]. Duration of the effort induces a linear decrement of $MF_{EMG}$ [14,24,27] whose slope may differ slightly depending on the muscle group and type of movement [15,16,20,21]. With $\%MVC_{isom}$ and duration of the effort as the main triggers of fatigue in CFPs, the greatest $MF_{EMG}$ decrements were observed at longer durations due to lower %MVCs [28].

A third factor must be taken into account in IFP: the duration of the recovery interspersed between muscle contractions. Controversial $MF_{EMG}$ results have been observed when applying IFPs, despite the lower $MVC_{isom}$ recorded at the end of such fatigue protocols. For example, some authors, but not all [29,30], reported a reduction in $MF_{EMG}$ during an IFP [31,32]. $MF_{EMG}$ was similar to pre-fatigue values with different work–rest cycles, whatever the intensity used in the IFP, [22]. These results are consistent with the findings of Mundale [28], who also studied the factors that lengthen the endurance time of an IFP. It seems that the duration of the recovery period could be one of the key factors explaining the disparity in $MF_{EMG}$ results, particularly among IFPs. Looking at motorcycle riders, we [5] observed no significant $MF_{EMG}$ decrement throughout a 24-h motorcycle endurance race despite the significant decrease in $MVC_{isom}$. Following the recommendation of previous studies [33–35], we took care not to exceed an interval of 4–5 min between the end of each relay and the handgrip assessment. The lack of $MF_{EMG}$ decrement led to conclude that this interval was too long. According to these findings, we decided to compare an IFP and CFP specifically adapted to motorcycle riders [9]. The lack of a reduction in $MF_{EMG}$ in the IFP suggested that rest cycles were too long, achieving basal values of $MF_{EMG}$ between the work cycles. These findings are in agreement with another study by Krogh-Lund and Jorgensen [23] that compared two pairs of fatiguing sustained isometric contractions at 40% $MVC_{isom}$ separated by different rest intervals. They found that the $MF_{EMG}$ at the start of the second contraction did not recover to pre-fatigued values when the rest interval was less than 1 min, [23]. Other studies reached similar conclusions when they used intermittent contractions [24,25,36], suggesting that a $MF_{EMG}$ shift toward the pre-fatigue state occurs independently of the contraction intensity (25–50%) [36].

Some authors [37] suggest that the validity of the spectral shift of the sEMG signal in assessments of fatigue must be taken with caution because a clear MVC decrement is sometimes weakly reflected in the sEMG signal [38]. This is supported by studies that used IFP to assess muscle fatigue [29,30,39,40]. In contrast, the usefulness of the sEMG signal for studying muscle fatigue in occupational field studies [41] is supported by other studies that reported a reduction in $MF_{EMG}$ with IFP [31,32]. These overall discrepancies between studies suggest that the combination of different, contraction–relaxation periods, effort intensities (%$MVC_{isom}$), muscle groups, and other non-controlled or non-reported factors, are critical to understanding muscle fatigue in IFPs [18,22,42].

Therefore, this study aimed to verify in road racing motorcycle riders whether the recovery period performing an IFP matching the braking movement was more relevant than the contraction intensity and effort duration in two forearm muscles (flexor digitorum superficialis and carpi radialis). We hypothesized that $MF_{EMG}$ will not decrease during the contractions performed at 50% $MVC_{isom}$ because they are preceded by long recovery periods. On the contrary, $MF_{EMG}$ recorded at 30% $MVC_{isom}$ and during a shorter exertion time (5 s) may decrease due to short recovery periods (5 s).

## 2. Methods

### 2.1. Subjects

Twenty-one road racing motorcycle riders aged 29.1 ± 8.0 years (body mass: 72.1 ± 5.5 kg; height: 176.2 ± 4.9 cm) participated in this study. Of these riders, 48% were winners within the Spanish and/or World Championships and 24% were on the podium of the Championship at the end of the season over the previous 6 years. The remaining 28% participated in races at the regional level with at least 5 years of racing experience. The study was approved by the Clinical Research of the Ethics Committee for Clinical Sport Research of Catalonia (Ref. number 15/2018/CEICEGC) and written consent was given by all the participants. The data were analyzed anonymously, and the clinical investigation followed the principles of the Declaration of Helsinki.

### 2.2. Procedures

Before the assessment, the brake lever to handgrip distance was adjusted to the participant's hand size to ensure that hand placement in relation to the brake was similar across all subjects. Afterwards, during the familiarization period, the subject practiced six to ten submaximal non-stationary contractions while watching the dynamometric feedback displayed on the PC screen, while the researcher provided feedback about how to interpret the auditory and visual information. A continuous linear feedback and a columnar and numerical display showed the subject the magnitude of the force they exerted against the brake lever. In addition, a different tone was provided depending on the force level. Dynamometric and sEMG signals were recorded and these signals were synchronized with an external trigger. Five minutes before the beginning of the intermittent fatigue protocol (IFP), two $MVC_{isom}$ trials separated by a 1-min rest were performed to provide a baseline value of $MVC_{isom}$. The 1-min resting period between the two $MVC_{isom}$s was considered sufficient to avoid fatigue from the previous contraction [43,44]. The higher $MVC_{isom}$ was recorded as the basal value of that day and used to calculate the submaximal efforts (50% and 30% of the maximum). During the IFP, the subject adopted the "rider position" with both hands on the handlebar.

### 2.3. Sequence and Structure of the IFP

The intermittent protocol comprised a succession of a maximum of 25 rounds. Each round comprised two sections (Figure 1A). Section one consisted of six 5-s voluntary contractions of 30% $MVC_{isom}$, with a resting period of 5 s between each contraction. Section two comprised a 3-s $MVC_{isom}$ followed by a 1-min resting period and a 50% $MVC_{isom}$ maintained for 10 s. During the 1-min resting period subjects were in the seated position with their hands resting on their thighs.

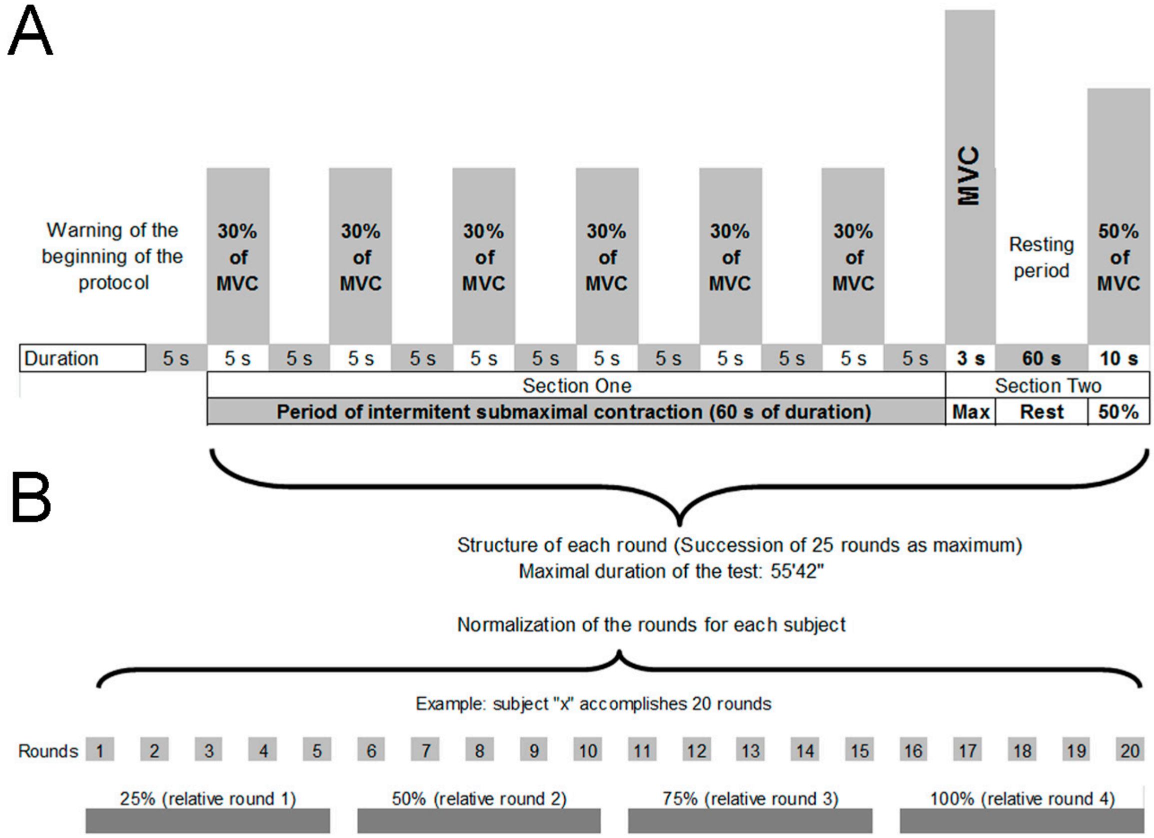


**Figure 1.** (**A**): Description of the sequence and structure of the intermittent protocol. Auditory feedback was provided to ensure the exact duration of each contraction and resting period. (**B**): Represents an illustration of a subject who performed 20 rounds, which means that each one of the four successive relative rounds is composed of five rounds.

Intensities ranging from 10% to 40% of MVC have previously been used to carry out a continuous or intermittent fatigue protocol [18,22,45]. A sequence of 30% of $MVC_{isom}$ was finally adopted after consulting with expert riders (exclusively, winners of races at the national and world level) who agreed about the perception of applying approximately this percentage of force during very strong braking in real situations.

Section two was designed to replicate an experimental protocol from one of our previous studies of motorcycle riders [5]. The test stopped when the subject was unable to maintain the established 50% of $MVC_{isom}$ for 10 s, or the concurrent $MVC_{isom}$ was 10% lower than 50% of the $MVC_{isom}$ value. The number of rounds achieved by each subject was used as a performance measure.

### *2.4. Dynamometric Assessment*

To simulate the overall position of a rider on a 600–1000-cc racing motorcycle, a static structure was built to preserve the distances between the seat, stirrups, and particularly the combined system of shanks, forks, handlebar, brake and clutch levers, and gas (Figure 2). As it happens in a road race motorcycle, levers tilt, distances between levers and handle gas, and distance between the handlebar and seat were modified according to the ergonomic requirements of the rider (Figure 2).

The subjects were asked to exert a force against the brake lever (always the right hand) using the second and third finger to hold the lever half way, and the thumb and other fingers grasping the handgrip at the same time, which is the most common way of braking of road racing motorcycle riders (Figure 2). Both arms had a slight elbow flexion (angle 150–160°), forearms half-pronated, wrist in neutral abduction/adduction position and alienated with respect to the forearm, dorsal flexion of the wrist no bigger than 10°, and legs flexed with feet above the footrests; in short, the typical overall position of a rider piloting a motorcycle in a straight line.

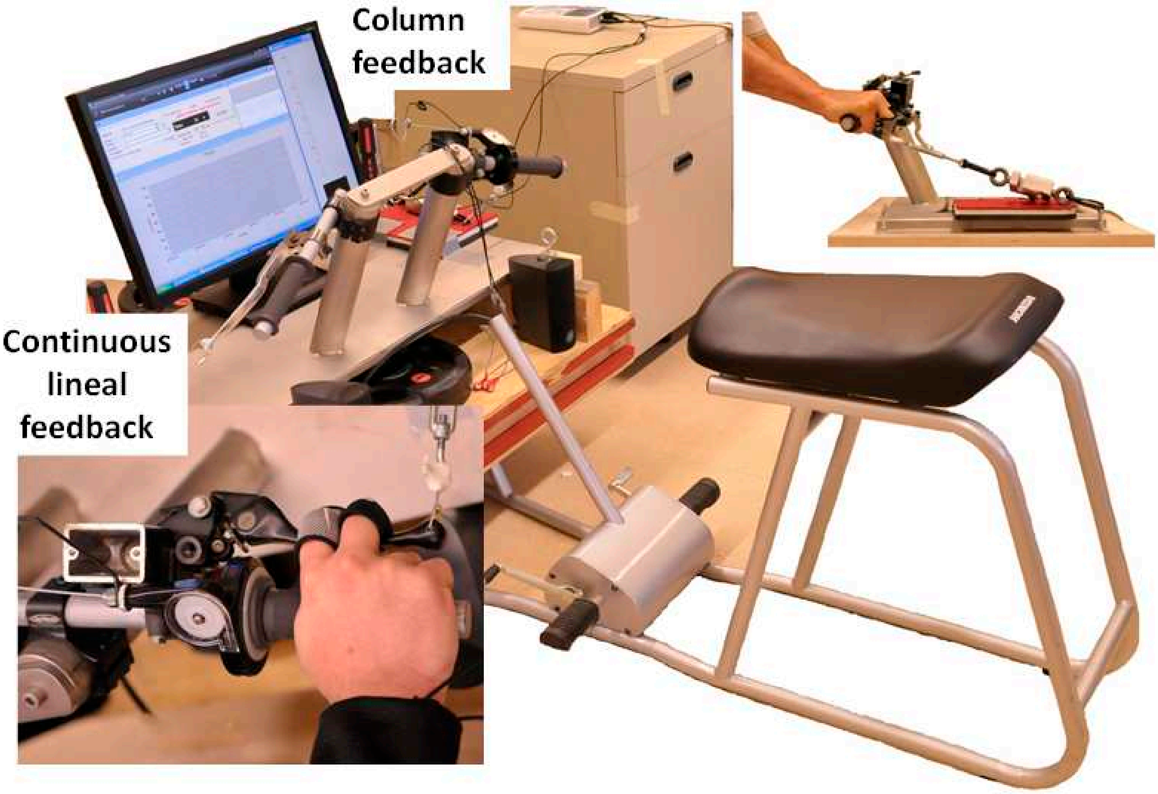


**Figure 2.** Simulation of the overall position of a rider above a motorcycle race from 600 cc to 1000 cc. A static structure was built to preserve the distances between seat, stirrups, and particularly the combined system of shanks, forks, handlebar, brake and clutch levers, and gas.

Special attention was given to controlling the handgrip position, and the wrist, elbow, and trunk angles to avoid any modification of the initial overall body position during the test. One experimenter supervised the recording of force and sEMG signals, and another continuously checked the maintenance of body position. It has been reported that variations in body posture [46] and wrist angles [47] alter the behavior of the forearm muscles during handgrip force generation.

To measure the force exerted against the brake lever we used a unidirectional gauge connected to the MuscleLab$^{TM}$ system 4000e (Ergotest Innovation AS, Stathelle, Norway). The frequency of measurement was 400 Hz, and the loading range was from 0 to 4000 N. The gauge (Ergotest Innovation AS, Norway), with a linearity and hysteresis of 0.2%, and 0.1 N sensibility, was attached to the free end of the brake lever in such a way that the brake lever system and the gauge system laid over the same plane and formed a 90° angle approximately when the subject was exerting force. The MVC at the end of the IFP was compared to the MVC in the pre-fatigued state. The 30% and 50% MVC contractions were used for sEMG analysis.

### 2.5. Electromyography

A ME6000 electromyography system (Mega Electronics, Kuopio, Finland) was used to register flexor digitorum superficialis (FS) and carpi radialis (CR) EMG signals. Adhesive surface electrodes (Ambu Blue Sensor, M-00-S, Ballerup, Denmark) were placed 2 cm apart (from center to center) according to the anatomical recommendations of the SENIAM Project [48,49]. The raw signal was recorded at a sampling frequency of 1000 Hz. Data were amplified with a gain of 1000 using an analog differential amplifier and a common-mode rejection ratio of 110 dB. The input impedance was 10 GΩ. A Butterworth bandpass filter of 8–500 Hz (–3 dB points) was used. To compute the median frequency ($MF_{EMG}$, Hz), Fast Fourier Transform was used with a frame width at 1024, a shift method of 30% of the frame width, and the "flat-topped" windowing function. The power spectrum densities were computed and averaged afterwards to obtain one mean or median for each submaximal contraction of 30% $MVC_{isom}$ (5 s duration) and 50% $MVC_{isom}$ (10 s duration). Afterwards, the median frequency ($MF_{EMG}$) was normalized with respect to the basal condition during the $MVC_{isom}$.

In order to obtain the same number of $MF_{EMG}$ values from the IFP of each individual, and for each round and $MVC_{isom}$ intensity, the six 30% $MVC_{isom}$s of the first section (Figure 1A) were averaged to obtain one $MF_{EMG}$ ($MF_{EMG30}$). Each $MF_{EMG30}$ was paired with the only $MF_{EMG}$ of the second section (Figure 1A) obtained from the 50% $MVC_{isom}$ ($MF_{EMG50}$).

### *2.6. Statistics*

Parametric statistics were used after confirming the normal distribution of the normalized parameters used in this study ($MVC_{isom}$, $MF_{EMG30}$, and $MF_{EMG50}$) with the Shapiro-Wilk test. Descriptive results were reported as the mean and standard deviation. A paired sample t-test was used to compare the $MVC_{isom}$ in the pre-fatigued state and at the end of the IFP. Two methodological approaches were used to verify the study's hypothesis. First, we used regression analysis for each individual, to study the strength of the relation and detect possible trends between the number of rounds accomplished (independent variable) and the $MF_{EMG30}$ (dependent variable). Second, we used a 2 (time points: $T_1$ and $T_2$) × 2 (muscles: FS and CR) × 2 (%$MVC_{isom}$: 30 and 50) ANOVA of repeated measures to compare all $MF_{EMG}$ values at the beginning and the end of the IFP, and to study potential interactions with the two muscle groups analyzed (CR and FS) and the two intensities that were preceded by distinct recovery periods (5 s for 30% $MVC_{isom}$ and 1 min for 50% $MVC_{isom}$). When necessary, the Greenhouse-Geisser's correction was used if the sphericity test to study matrix proportionality of the dependent variable was significant ($p < 0.05$). Then, when a significant effect was found, a post-hoc analysis was carried out conducting multiple comparisons between the normalized rounds with Sidak's adjustment. Partial Eta squared ($\eta^2 p$) was used to report effect sizes (0.01 ≈ small, 0.06 ≈ medium, >0.14 ≈ large). Statistical analysis was performed using the PASW Statistics for Windows, Version 18.0 (SPSS, Inc., Chicago, IL, USA). The level of significance was set at 0.05.

## 3. Results

At baseline conditions, $MVC_{isom}$ (276 ± 46.6) was 53% lower than the $MVC_{isom}$ at the end of the IFP (147 ± 46.3; $p < 0.001$).

Individual regression analysis (Table 1, Figure 3) was conducted to verify possible trends between the NMF of the CR and FS and the number of rounds accomplished by the motorcycle riders during an intermittent fatigue protocol (IFP) at two different intensities (30% and 50% of $MVC_{isom}$). The overall individual regression analysis showed a significant linear relationship ($p < 0.005$) between the $MF_{EMG}$ and the number of rounds accomplished by both muscles when they were exercised at 30% $MVC_{isom}$ ($CR_{30}$ and $FS_{30}$), with pauses of 5 s between each contraction. In contrast, when both muscles were exerted at 50% $MVC_{isom}$ ($CR_{50}$ and $FS_{50}$), after 1 min of recovery, no significant relationship was observed ($p > 0.133$). The higher correlation observed in $CR_{30}$ and $FS_{30}$ ($r \geq -0.71$) in comparison to $CR_{50}$ and $FS_{50}$ ($r \leq 0.59$) supports the hypothesis of a weaker relationship between the $MF_{EMG50}$ and the number of rounds when both muscles had the opportunity to recover for longer (1 min for $CR_{50}$ and $FS_{50}$). Similarly, the overall individual regression analysis showed that the fraction of $MF_{EMG}$ variance, explained by the number of rounds attained during the intermittent protocol, was bigger with $CR_{30}$ and $FS_{30}$ ($r^2 \geq 0.50$) in comparison to $CR_{50}$ and $FS_{50}$ ($r^2 \leq 0.40$) (Table 1).

**Table 1.** Regression analysis of normalized median frequency ($MF_{EMG}$, dependent variable), against the number of rounds (independent variable) accomplished by each rider ($n$ = 21). Muscles analyzed are the carpi radialis (CR) and flexor digitorum superficialis (FS) at 30% and 50% of MVC.

| ***n* = 21** | | ***r*** | ***r*²** | **Error of Estimate** | ***F*** | ***p*** |
|---|---|---|---|---|---|---|
| $CR_{30}$ | Mean | −0.756 | 0.580 | 0.026 | 54.163 | 0.005 |
| | sd | ± 0.176 | ± 0.266 | ± 0.012 | ± 57.827 | ± 0.009 |
| | $CI_{sup}$ | 0.758 | 0.583 | 0.027 | 54.954 | 0.006 |
| | $CI_{inf}$ | 0.753 | 0.576 | 0.026 | 53.372 | 0.005 |
| $CR_{50}$ | Mean | 0.594 | 0.397 | 0.045 | 28.046 | 0.133 |
| | sd | ± 0.284 | ± 0.302 | ± 0.019 | ± 43.913 | ± 0.295 |
| | $CI_{sup}$ | 0.598 | 0.401 | 0.045 | 28.647 | 0.137 |
| | $CI_{inf}$ | 0.590 | 0.393 | 0.045 | 27.445 | 0.129 |
| $FS_{30}$ | Mean | −0.711 | 0.504 | 0.022 | 27.659 | 0.005 |
| | sd | ± 0.152 | ± 0.214 | ± 0.008 | ± 23.267 | ± 0.007 |
| | $CI_{sup}$ | 0.713 | 0.507 | 0.022 | 27.977 | 0.005 |
| | $CI_{inf}$ | 0.709 | 0.501 | 0.002 | 27.341 | 0.004 |
| $FS_{50}$ | Mean | −0.542 | 0.338 | 0.033 | 20.524 | 0.158 |
| | sd | ± 0.283 | ± 0.290 | ± 0.016 | ± 31.906 | ± 0.288 |
| | $CI_{sup}$ | 0.546 | 0.342 | 0.033 | 20.960 | 0.161 |
| | $CI_{inf}$ | 0.539 | 0.334 | 0.033 | 20.087 | 0.154 |

Pearson coefficient correlation ($r$), R squared ($r^2$), error of the estimate, F-statistics ($F$), level of significance ($p$), degree of freedom (df: 1, 10–23). The minor number of accomplished rounds was 10. Five riders succeeded to perform all 25 rounds of the intermittent protocol.

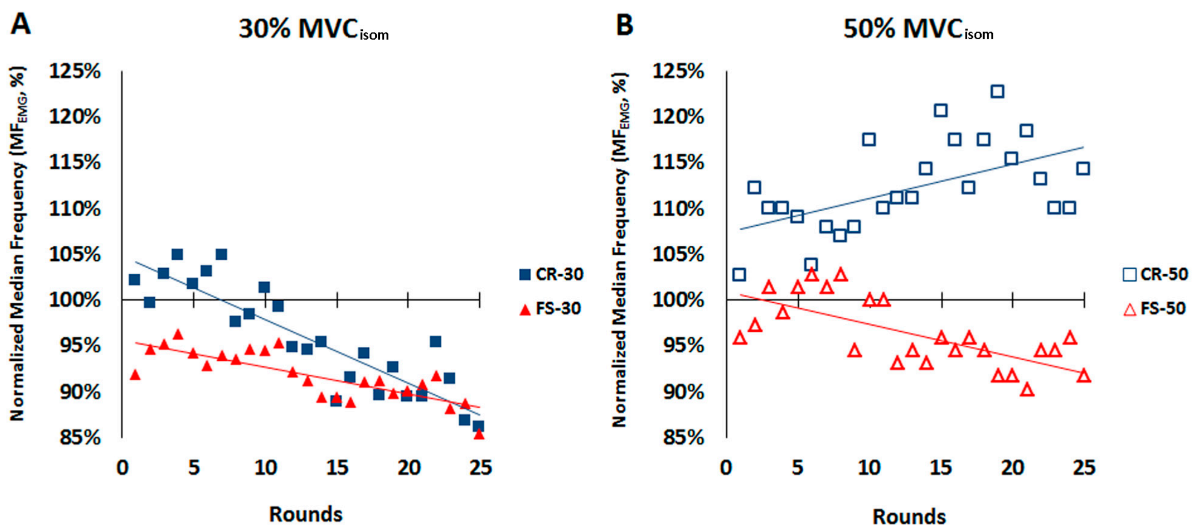


**Figure 3.** Example of a comparative regression analysis of an individual. Regression of the carpi radialis (CR) and flexor superficialis digitorum (FS) at the two intensities: (**A**) is 30% of $MVC_{isom}$, and (**B**) is 50% of $MVC_{isom}$; both used in the intermittent protocol.

In addition to the regression analysis performed for each individual, Table 2 reveals that a greater number of riders satisfied better levels of statistical condition in $CR_{30}$ and $FS_{30}$ in comparison to $CR_{50}$ and $FS_{50}$. Moreover, the higher correlation values ($r > 0.70$) and higher levels of significance ($p < 0.001$) were associated with higher frequency values in $CR_{30}$ and $FS_{30}$, while lower correlation values ($r < 0.39$) and lower levels of significance ($p > 0.05$) were associated with a higher number of riders in $CR_{50}$ and $FS_{50}$.

**Table 2.** Frequency table. Number of motorcycle riders who match the condition reported in the individual linear regression analysis. Normalized median frequency ($MF_{EMG}$) was the variable taken for analysis against the number of rounds accomplished during the intermittent fatigue protocol.

| ***n* = 21** | ***r*** | | | ***p*** | | |
|---|---|---|---|---|---|---|
| | **>0.70** | **0.40–0.69** | **<0.39** | **<0.001** | **0.001–0.05** | **ns** |
| $CR_{30}$ | 13 | 8 | 0 | 14 | 7 | 0 |
| $CR_{50}$ | 10 | 7 | 4 | 10 | 7 | 4 |
| $FS_{30}$ | 13 | 8 | 0 | 12 | 9 | 0 |
| $FS_{50}$ | 7 | 7 | 7 | 9 | 5 | 7 |

Figure 3 is an example of the regression analysis carried out in one subject showing higher $MF_{EMG}$ values for the CR in comparison to the FS. Moreover, at 50% MVC, the $MF_{EMG}$ of the CR never dropped below the $MF_{EMG}$ level established during the basal assessment (Figure 3B), which is consistent with the comparative results (Table 3).

**Table 3.** 2 (Time) × 2 (Muscles) × 2 (% $MVC_{isom}$) ANOVA of repeated measures between the beginning ($T_1$) and the end ($T_2$) of the intermittent fatiguing protocol (IFP). The parameter of analysis is the normalized median frequency ($MF_{EMG}$) of the Carpi Radialis (CR) and Flexor Digitorum Superficialis (FS).

| **Effect** | ***F*** | ***df*** | ***p*** | **$\eta^2$p** | **Paired Comparisons** | ***p*** |
|---|---|---|---|---|---|---|
| T × In × M | 20.04 | 1, 20 | <0.001 | 0.5 | $T_1$ & $T_2$: $FS_{30} < CR_{30}$; $FS_{50} < CR_{50}$ | <0.001 |
| | | | | | $T_1$: $CR_{30} > CR_{50}$; $T_2$: $CR_{30} < CR_{50}$ | <0.002 |
| | | | | | $CR_{30}$: $T_1 > T_2$; $CR_{50}$: $T_1 < T_2$ | <0.001 |
| T × In | 33.6 | 1, 20 | <0.001 | 0.63 | $In_{30}$: $T_1 > T_2$ | <0.001 |
| | | | | | $In_{50}$: $T_1 < T_2$ | <0.024 |
| T × M | 0.74 | 1, 20 | ns | 0.04 | | |
| In × M | 3.02 | 1, 20 | ns | 0.13 | | |
| T | 1.43 | 1, 20 | ns | 0.07 | | |
| In | 28.58 | 1, 20 | <0.001 | 0.59 | | |
| M | 42.43 | 1, 20 | <0.001 | 0.68 | | |

Time (T), Intensity (In) of 30% $MVC_{isom}$ ($In_{30}$) and 50% $MVC_{isom}$ ($In_{50}$), Muscle (M).

The second methodological approach was used to determine whether less intense and shorter muscle contractions (30% $MVC_{isom}$ instead of 50%; 5 s instead of 10 s) could induce bigger $MF_{EMG}$ decrements in the CR and FS. The second objective was to determine whether the two muscles (CR and FS) had a similar $MF_{EMG}$ decrement due to fatigue. Thus, we compared two times of measurement ($T_1$ and $T_2$), two muscles (CR and FS) and two contraction intensities (30% and 50% of $MVC_{isom}$) (Table 3).

A significant three-way interaction was found ($p < 0.001$) with a large effect size ($\eta^2$p = 0.5) (Table 3). Paired comparisons found lower values for the FS than the CR at both times and both intensities. Moreover, we observed a higher $MF_{EMG}$ in the CR muscle at 30% $MVC_{isom}$ ($CR_{30}$) than at 50% $MVC_{isom}$ ($CR_{50}$) at the beginning of the IFP, but the opposite response was observed at the end. Finally, regarding the CR, while $MF_{EMG}$ was lower at the end than at the beginning of the IFP at the 30% $MVC_{isom}$ ($CR_{30}$), the opposite was observed at the 50% $MVC_{isom}$ exertion ($CR_{50}$) (Table 3).

In addition, a significant two-way interaction was found between the time and $MVC_{isom}$ intensity (time per intensity) with a large effect size ($\eta^2$p = 0.63), but not for the other interactions (time per muscle, and intensity per muscle) with a small and medium effect size, respectively (Table 3). The $MF_{EMG}$ was higher at the beginning than at the end of the IFP when both muscles were exerted at 30% $MVC_{isom}$, but no significant differences were observed when they were exerted at 50% $MVC_{isom}$. Finally, we observed a significant main effect for intensity and muscle factor (Table 3).

## 4. Discussion

The $MVC_{isom}$ decrement observed in our IFP confirmed the occurrence of muscle fatigue as this physiological phenomenon is commonly defined as the "loss of the maximal force-generating capacity" [37,50]. From a functional and neurophysiological point of view, and according to the literature, the decrement of the sEMG power spectrum is related, among other factors, to: (1) a reduction in the conduction velocity of the active fibers [35]; (2) impairment of the excitation–contraction coupling [27] related to metabolic changes that occur during fatigue [51]; (3) the recruitment of new units [52], based on the knowledge that subjects with a high relative number of fast twitch fibers may have higher sEMG frequency values [53], and that during fatigue, they show a greater shift towards lower $MF_{EMG}$ compared to subjects with a low relative number of fast twitch fibers [54]; (4) structural damage to muscle cells when muscle soreness is reported by the subjects [18]; (5) other reactions taking place beyond the muscle cell membrane [55], based on observations that short resting periods between each muscle activation are sufficient to maintain the neuromuscular excitability at normal levels during IFP. It must be highlighted that this study did not intend to explain the changes in $MF_{EMG}$ induced by fatigue from a physiological perspective, we were focused on the relationship between the $MF_{EMG}$ and the two factors controlled in our IFP: the load intensity and the work–rest cycle.

High variability of $MF_{EMG}$ values at low loads has been attributed to the influence of the number of recruited muscle fibers and the synchronism and firing rate [56]. According to this, it could be more difficult to find a significant pattern at 30% $MVC_{isom}$ rather than 50% $MVC_{isom}$, but we found that the $MF_{EMG}$ of the CR and FS decreased more consistently throughout the IFP when the muscles were exerted at 30% $MVC_{isom}$ in comparison to 50% $MVC_{isom}$. The regression analysis of each individual revealed systematically stronger correlations, coefficients of determination, and statistical significance with $CR_{30}$ and $FS_{30}$ in comparison with $CR_{50}$ and $FS_{50}$. Moreover, participants reported a stronger relationship between the number of rounds accomplished and the $MF_{EMG}$ at 30% $MVC_{isom}$, rather than 50% $MVC_{isom}$, in both muscles that were assessed. In agreement with this, we found a higher and more significant $MF_{EMG}$ decrement when the participants performed the IFP at 30% $MVC_{isom}$, which may suggest different neuromuscular fatigue patterns between the $CR_{50}$ and $FS_{50}$ during the IFP [9]. If force intensity was the only one factor explaining these differences, it would be difficult to argue that time to exhaustion of any fatigue protocol would be longer when muscles work at higher intensities. As expected, other studies proved the opposite [22,23,57]. Moreover, when studying the magnitude of fatigue in two different IFPs at two different intensities (25 and 50% $MVC_{isom}$), Seghers and Spaepen [42] observed very similar relative $MF_{EMG}$ decrements in the two muscles analyzed (IFP at 25% $MVC_{isom}$: 29%, and 30%; IFP at 50% $MVC_{isom}$: 29%, and 28%), when sustaining an isometric contraction at 75% of prefatigued $MVC_{isom}$ at the end of both protocols [42]. On the other hand, whereas the same authors observed a significant negative slope of the $MF_{EMG}$ during the IFP at 25% $MVC_{isom}$, during the IFP at 50% $MVC_{isom}$ the slope did not differ significantly from zero. It is possible that the differences in $MF_{EMG}$ changes during the two IFPs could be more related to differences in their work–rest cycles (10 + 10 s in 25% $MVC_{isom}$ and 5 + 15 s in 50% $MVC_{isom}$) than in the contraction intensity. In rock climbers, the significant reduction in the $MF_{EMG}$ observed during an intense IFP (80% $MVC_{isom}$) [58], with a work–rest cycle of 5 + 5 s (same cycle as in our IFP for the 30% $MVC_{isom}$), indicates that the majority of the frequency components of the $MF_{EMG}$ are unaffected by tension [24]. Thus, we believe that the key point for understanding the different $MF_{EMG}$ patterns during our IFP must be the resting period before the two intensities. Only 5 s of recovery were interspersed between braking muscle contractions of the forearm at 30% $MVC_{isom}$ compared to the 60 s (1 min) at 50% $MVC_{isom.}$ This clearly indicates that $MF_{EMG}$ can be explained to a greater extent when the riders have a very short recovery time despite a smaller contraction intensity (30% $MVC_{isom}$ instead of 50% $MVC_{isom}$) and a shorter contraction time (5 s for 30% $MVC_{isom}$ instead of 10 s for 50% $MVC_{isom}$). Similar results were reported by Nagata et al. [25].

Nevertheless, it is important to highlight that these authors used a continuous fatigue protocol in which the force was maintained at an intensity of 60% $MVC_{isom}$ until exhaustion, which substantially differs to the IFP in our study.

Before undertaking this study, it was not evident that 1 min of recovery before the 50% $MVC_{isom}$ could be long enough to allow a systematic recovery of the $MF_{EMG}$ towards baseline levels (pre-fatigued). The $MF_{EMG}$ recovery curve towards pre-fatigued values can be characterized by an exponential function [59–61], as well as a logarithmic course characterized by large inter-individual variations [61,62]. Therefore, a large proportion of the $MF_{EMG}$ spectrum recovery corresponds to the first 1 min of the exponential recovery curve [21,23,43,44,59–63]. However, depending on the fatigue protocol, this does not mean full restoration comparable to pre-fatigued or basal $MF_{EMG}$ values. Following the completion of ten cycles of work/rest (10 s/10 s) at $MVC_{isom}$, Mills [59] observed that the mean power frequency of a compound muscle action potential evoked by supramaximal nerve stimulation required 3 min to recover 50% of its initial values. Three to six minutes, depending on age, are sometimes necessary to recover the pre-fatigued $MF_{EMG}$ values of the abductor digiti-minimi muscle after a $MVC_{isom}$ exertion maintained until 50% $MVC_{isom}$ [64]. Other studies [62,65,66] have confirmed that the majority of the $MF_{EMG}$ spectrum is re-established after 1 and 3 min of recovery, but full recovery it may take until the fifth minute [23,62]. Interestingly, Krogh-Lund and Jorgensen [23] observed that the restoration of $MF_{EMG}$ paralleled that of conduction velocity for the last 4 min of recovery. Regarding the first part of the exponential recovery curve, 35 s were sufficient to allow restoration of 50% of the decline in $MF_{EMG}$ during the previous fatigue protocol [61], but a longer interval (1.4 min) was required to reach 50% of pre-fatigued values for the biceps brachii [67]. Faster $MF_{EMG}$ recovery (up to 85% of the pre-fatigued state during the first minute) was found by Krogh-Lund [21] in the brachioradialis and biceps brachii muscles. Nevertheless, the standard error of the measurement (about 60 s) reported by Elfving et al. [61], which was much larger than the average recovery, reflects the large between-subject variability of the $MF_{EMG}$ parameter when studying the recovery phase. The inconclusive results reported in the literature combined with the accepted large variability that characterizes this type of analysis, support the idea that different combinations of IFP (contraction intensities and durations of contraction and relaxation) to assess muscle fatigue can provide different results [42]. Thus, although it is difficult to compare sEMG data from different studies it is even more complicated when the protocol involves voluntary exercise [37]. The fact that the physiological mechanisms causing muscle fatigue are specific to the task [68], should encourage future studies looking at road racing motorcycle riders to focus on the specific conditions of the forearm muscles, in order to understand better pathologies such as exercise-induced compartment syndrome.

The main limitations of this study were that effort duration, contraction intensity, and recovery time were not separated in different IFPs. Ideally, swapping these three factors would mean that riders had to attend the laboratory on at least six occasions to undertake different IFPs and following a randomized protocol. However, this approach was not feasible in the current study due to the busy racing and training schedules and other commitments of the population of this study.

## 5. Conclusions

This study reproduced, in the most accurate way and under laboratory conditions, the braking action in road racing motorcycle riders to investigate different work–rest cycles during an IFP. For training purposes, we recommend using short recovery periods between 5 and 10 s after submaximal muscle contractions as the most effective way to induce muscle fatigue than intermittent tasks performed at higher intensities and with longer recovery periods. That is, much less than 1 min for the resting time (no more than 30 s) according to the results of previous studies [21,23,43,44,60,61,63]. Furthermore, contraction intensities above 50% $MVC_{isom}$ may not be useful for road racing motorcycle riders since only around 30% $MVC_{isom}$ is required to break in real conditions when they have to slow down at high speed (more than 270 km/h) to connect a straight line with a slow curve [9]. Muscle contraction times longer than 10 s are not useful either to match road racing requirements, so protocols involving this type of contraction are not recommended for these individuals. Finally, accelerations with the right hand promote hand dorsal flexion and the assessment of both movements (braking and acceleration) have not been combined in a single IFP. This must be taken into account in future studies to match the real conditions of road motorcycle racing in laboratory settings. This knowledge is needed to enhance our understanding of the most appropriate stimulus (muscle contraction intensities and recovery periods) to be applied within the training programs of road racing motorcycle riders in order to mimic racing conditions and to reduce the risk of muscle pathologies such as the forearm chronic exertional compartmental syndrome.

**Author Contributions:** Conceptualization, M.M.; methodology, M.M.; software, P.T.; validation, M.M. and P.T.; formal analysis, P.T.; investigation, M.M., P.T. and R.B.; resources, M.M.; data curation, P.T. and R.B.; writing—original draft preparation, M.M.; writing—review and editing, M.M., P.T. and R.B.; visualization P.T. and R.B.; supervision, M.M.; project administration, M.M.; funding acquisition, M.M. All authors have read and agreed to the published version of the manuscript.

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**Institutional Review Board Statement:** This study was conducted according the guidelines of the Declaration of Helsinki, and approved by the Ethics Committee for Clinical Research of the Catalan Sports Council (protocol code 15/2018/CEICEGC, date 10 February 2018).

**Informed Consent Statement:** Informed consent was obtained from all subjects involved in the study.

**Data Availability Statement:** The data presented in this study is not available.

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*Review*

# The Effects of Interval Training and Continuous Training on Cardiopulmonary Fitness and Exercise Tolerance of Patients with Heart Failure—A Systematic Review and Meta-Analysis

**Daxin Li, Ping Chen and Junying Zhu ***

Department of Physical Education, Ocean University of China-Laoshan Campus, Qingdao 266100, China; lidaxin@stu.ouc.edu.cn (D.L.); qdchping@126.com (P.C.)
* Correspondence: zhujy10018@163.com

**Abstract:** Purpose: To investigate the effects of interval training (IT) as compared with continuous training (CT) on cardiorespiratory fitness and exercise tolerance of patients with heart failure (HF), with the aim to provide reasonable exercise prescriptions for patients with HF. Methods: Through searching electronic databases, randomized controlled studies were collected. The included studies were evaluated for methodological quality using the Cochrane risk of bias assessment tool, and statistical analyses were carried out using Review Manager 5.3 and Stata MP 15.1 software. Results: A total of seventeen randomized controlled trials (i.e., studies) with 617 patients were included. The meta-analysis showed that IT can improve a patient's peak oxygen uptake (VO2peak) (MD = 2.08, 95% CI 1.16 to 2.99, $p < 0.00001$), left ventricular ejection fraction (LVEF) (MD =1.32, 95% CI 0.60 to 2.03, $p = 0.0003$), and 6-minute walk distance (6MWD) (MD = 25.67, 95% CI 12.87 to 38.47, $p < 0.0001$) as compared with CT. However, for respiratory exchange ratio (RER) (MD = 0.00, 95% CI −0.02 to 0.03, $p = 0.81$), $CO_2$ ventilation equivalent slope (VE/VCO2 slope) (SMD = 0.04, 95% CI −0.23 to 0.31, $p = 0.75$), and resting heart rate (HRrest) (MD = 0.15, 95% CI −3.00 to 3.29, $p = 0.93$) there were no statistical significance. Conclusions: The evidence shows that IT is better than CT for improving the cardiorespiratory fitness and exercise tolerance of patients with HF. Moreover, an intensity of 60–80% peak heart rate of IT is the optimal choice for patients. It is hoped that, in the future, more well-designed studies would further expand the meta-analysis results.

**Keywords:** interval training; continuous training; heart failure; meta-analysis

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## 1. Introduction

Heart failure (HF) is a common disease with an increasing prevalence worldwide and it is characterized by a low five-year survival of 35–55% [1], which affects cardiac function, exercise tolerance, and the daily life of patients [2,3]. Cardiac rehabilitation is defined as a set of activities that aims to provide patients with heart disease with the best physical, mental, and social conditions, therefore, reducing the risk of death and acute events related to their illness [4]. Previous studies have demonstrated that cardiac rehabilitation with physical exercise was beneficial to physical fitness, cardiac function, and quality of life in HF patients [5,6]. At present, various exercise programs are widely applied to cardiac rehabilitation, in which continuous training (CT) and interval training (IT) are the main forms of exercise [7,8]. CT is defined as continuous training with low and moderate intensity exercises that are performed for more than 20 min without resting intervals. IT is characterized by relatively high-intensity repetitions of physical activity with periods of rest for recovery [9]. It has been widely demonstrated that CT improves aerobic capacity, skeletal muscle function, and quality of life. In addition, it can change peripheral blood flow and decrease mortality rate [10–12]. However, CT as an exercise program can be tedious for the patients, which results in the exercise effect being unsustainable [13]. Therefore, IT has been increasingly used in cardiac rehabilitation for HF patients [7,14]. IT leads to greater improvements in aerobic capacity, left ventricular function, endothelial function, and quality of life [15,16]. In addition, IT for patients with HF appears to be more effective than CT for improving functional capacity [17]. However, there continues to be disagreement on whether or not IT and CT can significantly improve the cardiac function and functional capacity of patients with cardiovascular disease; the effectiveness between the two exercise programs is similar and it cannot be distinguished which exercise program is better [18,19].

Some previous studies have shown that the two exercise programs were effective in cardiac rehabilitation of HF patients [4,20]. However, due to differences in subjects and intervention programs, the conclusions were still controversial. Neil compared the effect of IT and CT in patients with HF, and showed that IT elicited superior improvements in peak oxygen uptake (VO2peak) and $CO_2$ ventilation equivalent slope (VE/VCO2 slope) as compared with CT in HF patients [20]. VO2peak has been considered to be the best predictor of survival in cardiovascular diseases and it has been used in many previous studies to measure patients' cardiorespiratory fitness [17–21]. The VE/VCO2 slope is inversely related to cardiac output at peak exercise and is at least partly explained by a decrease in pulmonary perfusion [22]. This prognostic parameter related to cardiac function has been chosen consistently in HF patients [18,20,23–27]. Bruna (2019) suggested that high intensity interval training was more effective than moderate continuous interval training for improving VO2peak, while the effect was not significant for improving left ventricular ejection fraction (LVEF) between the two exercise programs [4]. LVEF is a sensitive index that directly reflects the left ventricular ejection efficiency and indirectly reflects myocardial contractility [19,28]. Because of its close association with HF, the prognostic value that the LVEF consistently demonstrates is not surprising [19,20,23,26,27,29,30]. The number of included studies was inadequate (only five studies) in the above two studies, which were not enough for them to state whether IT was superior to CT. Mansueto (2018) suggested that high intensity interval training was superior to moderate continuous interval training for improving VO2peak in HF patients with reduced ejection fraction but the superiority disappeared when they performed a subanalysis [31]. The aim of this systematic literature review with meta-analysis was to synthesize the most up-to-date evidence to explore the effects of IT and CT on cardiorespiratory fitness and exercise tolerance of patients with HF. The specific objectives were:

1. To compare the effects of IT and CT on cardiorespiratory fitness and exercise tolerance of patients with HF (subanalysis with different durations and isocaloric consumption).
2. To compare difference high or moderate intensities of IT on cardiorespiratory fitness and exercise tolerance, to provide an optimal exercise prescription for patients with HF.
3. To collect rehabilitation recommendations for future research on this topic.

## 2. Methods

### *2.1. Literature Search*

A systematic literature review was conducted in Pubmed, Embase, Cochrane library, Web of Science, China Biomedical Literature Database, China National Knowledge Infrastructure, VIP Database, and Wanfang Data. The randomized controlled trials were collected between the earliest available date and April 2021 using the following terms: (high intensity interval training OR high-intensity intermittent exercise OR sprint interval training OR aerobic interval training OR interval training) AND (heart failure OR congestive heart failure OR myocardial failure OR heart decompensation OR cardiac insufficiency). In addition, the references of articles included in other systematic reviews with meta-analyses were searched to identify other possible eligible studies.

### *2.2. Study Selection*

The inclusion criteria for this meta-analysis were full-text research articles published in peer-reviewed academic journals in Chinese or English language. The exclusion criteria were: (1) patients with unstable HF, (2) non-randomized controlled trials, (3) outcome measurements that did not meet the requirements, (4) a significant difference between the baseline values of the two groups ($p < 0.05$), (5) patients who had no medical supervision during the exercise intervention.

Two researchers independently screened the literature by reading the titles and abstracts and excluded irrelevant studies. Then, they independently collected and downloaded the studies that met the standards and excluded the unqualified studies by reading the full text. Differences in the assessment of study eligibility were resolved by discussion.

### *2.3. Measured Outcomes*

The primary outcome measurement was changes in VO2peak (mL/kg/min). Secondary outcomes included cardiorespiratory fitness parameters (i.e., respiratory exchange ratio (RER), LVEF, and resting heart rate (HRrest)) and exercise tolerance parameters (i.e., VE/VCO2 and 6-minute walk distance (6MWD)).

### *2.4. Data Extraction and Analysis*

All data were independently extracted by an investigator and checked for accuracy by another reviewer. The collected data included authors' names, year of publication, country in which the study was conducted, characteristics of participants, intervention description, outcome, and quality assessment.

### *2.5. Quality Assessment*

The study quality was assessed by two authors using *Cochrane Handbook for Systematic Reviews of Interventions* 5.0.1 which included selection bias, performance bias, detection bias, attrition bias, reporting bias, and other biases. Disagreements were resolved by consensus [32].

### *2.6. Statistical Analysis*

Statistical analyses were performed using Review Manager 5.3 (Nordic Cochrane Centre, Copenhagen, Denmark) and Stata MP 15.0 (StataCorp, Pyrmont, Australia). Effect sizes for continuous variables were expressed as either mean difference (MD) or standardized mean difference (SMD), each with 95% confidence interval (95% CI). The heterogeneity among studies was examined with Cochrane's Q and $I^2$ statistics, in which values greater than 50% indicated significant heterogeneity and random-effects model was chosen [33]. The overall effects were considered to be significant when *p*-values ($p$) were $\leq 0.05$. A sensitivity analysis with one-by-one removal of studies was conducted to investigate possible effects of each study on heterogeneity and overall effect. Finally, Egger's regression model was used to assess publication bias.

## 3. Results

### *3.1. Identified Studies*

The initial research resulted in 1356 references. After duplicates were removed, the titles and abstracts of 726 studies were reviewed. Following a screening of potential studies, 672 studies were excluded, and 54 studies were retrieved in full text, 37 studies of which did not match the eligibility criteria. The final seventeen studies were included in the meta-analysis (Figure 1).

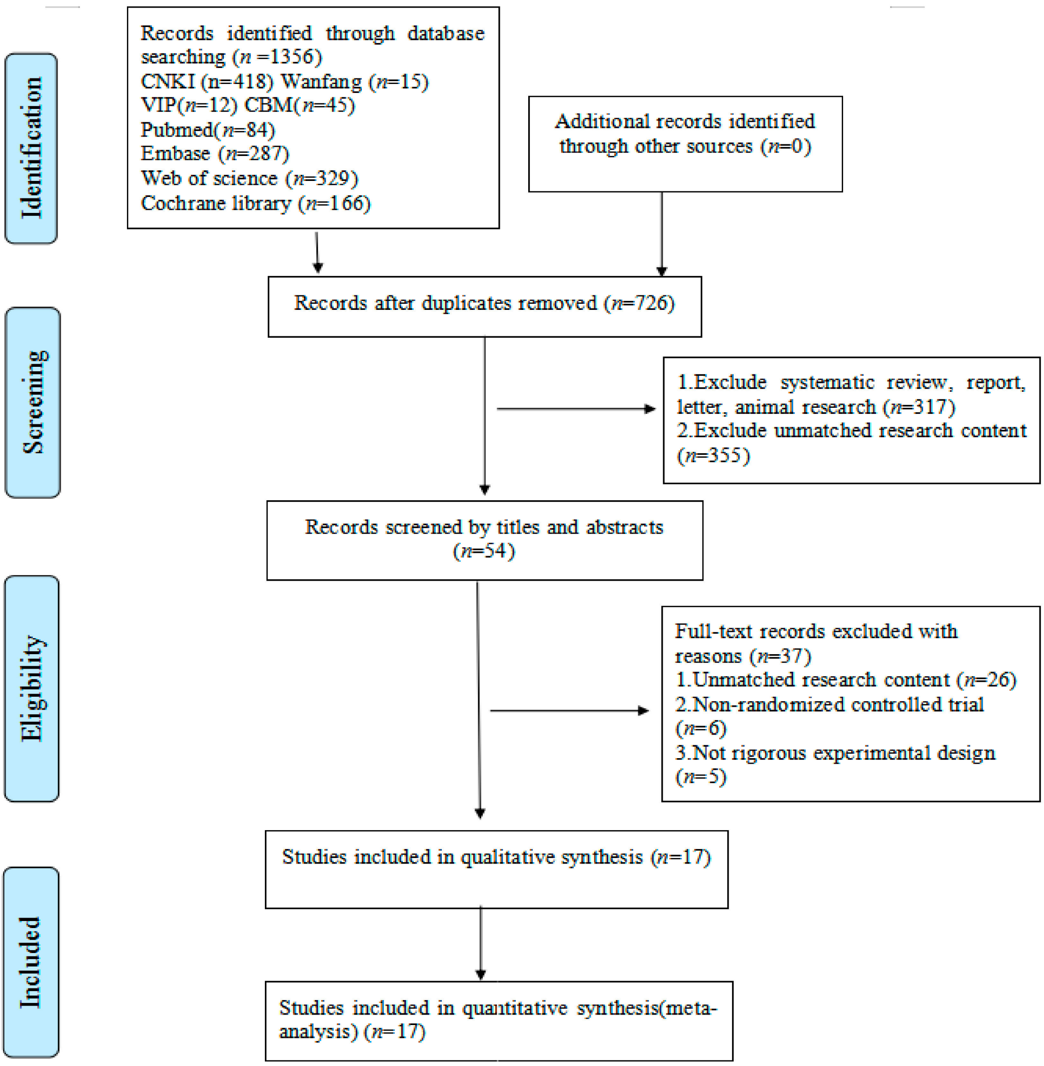


**Figure 1.** Flow diagram of literature selection.

### *3.2. Study Characteristics*

The characteristics of included studies are shown in Tables 1 and 2 and the methodological quality of each study is shown in Figure 2. The seventeen studies involved a total of 617 patients (316 IT and 301 CT) with HF [17–20,23–27,29,30,34–39]. Among these studies, two studies each were conducted in Brazil [19,27], France [17,26], Greece [40,41], Italy [18,24]. Norway [34,37] and Turkey [25,36], one study each was conducted in the America [29], Australia [20], Bulgaria [27], China/Taiwan [35] and England [29]. Intervention duration ranged from 3 to 24 weeks with a frequency of exercise training ranging from 2 to 5 days per week.

**Table 1.** Characteristics of the studies included in the meta-analysis.

| Study | Country | Characteristics of Patients | | | | Outcome | Quality Assessment |
|---|---|---|---|---|---|---|---|
| | | Sample Size (IT/CT) | Gender (M/F) | Age (years) (Mean ± SD) | Diagnosis Standard of HF | | |
| Dimopoulos 2006 [34] | Greece | 24 (14/10) | IT (9/1)<br>CT (14/0) | IT (59.2 ± 12.2)<br>CT (61.5 ± 7.1) | HFrEF<br>HFmrEF<br>HFpEF | VO2peak, VE/VCO2 Slope, HRrest | 4 |
| Roditis 2007 [35] | Greece | 21 (11/10) | IT (10/1)<br>CT (9/1) | IT (63 ± 2)<br>CT (61 ± 3) | HFrEF<br>HFmrEF | VO2peak, VE/VCO2 Slope, HRrest | 4 |
| Wisloff 2007 [29] | Norway | 18 (9/9) | IT (7/2)<br>CT (7/2) | IT (76.5 ± 9)<br>CT (74.4 ± 12) | HFrEF | VO2peak, RER, LVEF, HRrest | 3 |
| Smart 2011 [20] | Australia | 23 (10/13) | IT (8/2)<br>CT (13/0) | IT (59.1 ± 11)<br>CT (62.9 ± 9.3) | HFrEF | VO2peak, RER, VE/VCO2 slope, LVEF | 5 |
| Freyssin 2012 [17] | France | 26 (12/14) | IT (6/6)<br>CT (7/7) | IT (54 ± 9)<br>CT(55 ± 12) | HFrEF | VO2peak, 6WMT | 4 |
| Iellamo 2012 [18] | Italy | 16 (8/8) dropout 20% | NI | IT(62.2 ± 8)<br>CT (62.6 ± 9) | HFrEF | VO2peak, RER, VE/VCO2 slope | 3 |
| Fu 2013 [23] | Taiwan | 30 (15/15) dropout 10% | IT (10/5)<br>CT (9/6) | IT (67.5 ± 1.8)<br>CT (66.3 ± 2.1) | HFrEF<br>HFmrEF | VO2peak, LVEF | 2 |
| Koufaki 2014 [24] | England | 33 (16/17) dropout 48% | IT (14/2)<br>CT (13/4) | IT (59.8 ± 7.4)<br>CT (59.7 ± 10.8) | HFrEF<br>HFmrEF | VO2peak | 3 |
| Angadi 2014 [36] | America | 15 (9/6) | IT (8/1)<br>CT (4/2) | IT (69 ± 6.1)<br>CT (71.5 ± 11.7) | HFpEF | VO2peak, RER, VE/VCO2 slope, LVEF | 3 |
| Iellamo 2014 [25] | Italy | 36 (18/18) dropout 8% | IT (16/2)<br>CT (15/3) | IT (67.2 ± 6)<br>CT (68.4 ± 8) | HFrEF | VO2peak, RER, VE/VCO2 slope | 3 |
| Tolga 2015 [37] | Turkey | 30 (17/13) | IT (13/4)<br>CT (13/0) | IT (63.7 ± 8.8)<br>CT (59.6 ± 6.8) | HFrEF<br>HFmrEF | VO2peak, HRrest | 5 |
| Sibel 2015 [26] | Turkey | 30 (15/15) | IT (13/2)<br>CT (13/2) | IT (63.7 ± 8.8)<br>CT (59.6 ± 6.9) | HFrEF<br>HFmrEF<br>HFpEF | VO2peak, VE/VCO2 slope, LVEF, HRrest, 6WMT | 4 |
| Ulbrich 2016 [19] | Brazil | 22 (12/10) | IT (12/0)<br>CT (10/0) | IT (53.15 ± 7)<br>CT (54.02 ± 9.9) | HFrEF<br>HFmrEF | VO2peak, LVEF, HRrest, 6WMT | 6 |
| Ellingsen 2017 [30] | Norway | 142 (77/65) | IT (59/18)<br>CT (53/12) | IT (63 ± 22.4)<br>CT (61.5 ± 14.4) | HFrEF | VO2peak, LVEF | 5 |
| Florent 2019 [27] | France | 31 (16/15) | IT (11/5)<br>CT (11/4) | IT (59 ± 13)<br>CT (59.5 ± 12) | HFrEF<br>HFmrEF | VO2peak, RER, VE/VCO2 slope, LVEF, HRrest | 6 |
| Jannis 2020 [38] | Bulgaria | 120 (60/60) | IT (35/25)<br>CT (35/25) | IT (63.7 ± 6.7)<br>CT (63.8 ± 6.7) | HFrEF | VO2peak, LVEF, 6WMT | 5 |
| Silveira 2020 [39] | Brazil | 19 (10/9) | IT (3/7)<br>CT (4/5) | IT (60 ± 10)<br>CT (60 ± 9) | HFpEF | VO2peak, RER, VE/VCO2 slope, LVEF | 6 |

**Table 2.** Characteristics of the studies included in the meta-analysis (intervention program).

| Study | Intervention | | | |
|---|---|---|---|---|
| | Mode | Duration | Exercise Program | |
| | | | IT | CT |
| Dimopoulos 2006 [34] | Cycle ergometer | 12 weeks, 3 d/week | Total: 40 min<br>① 40 × 30 s interval (100–120% WR peak)<br>② 40 × 30 s recovery | Total: 40 min<br>40 min cycling (50–70% WR peak) |
| Roditis 2007 [35] | Cycle ergometer | 12 weeks, 3 d/week | Total: 40 min<br>① 40 × 30 s interval (100–120% WR peak)<br>② 40 × 30 s recovery | Total: 40 min<br>40 min cycling (50–60% WR peak) |
| Wisloff 2007 [29] | Treadmill | 12 weeks, 3 d/week | Total: 38 min<br>① 10 min warm-up (60–70% HRpeak)<br>② 4 × 4 min interval (90–95% HRmax)<br>③ 3 × 3 min recovery (50–70% HRmax)<br>④ 3 min cool-down | Total: 47 min<br>47 min running (70–75% HRmax) |
| Smart 2011 [20] | Cycle ergometer | 16 weeks, 3 d/week | Total: 60 min<br>① 30 × 60 s interval (70% VO2peak)<br>②3 0 × 60 s recovery | Total: 30 min<br>30 min cycling (70% VO2peak) |
| Freyssin 2012 [17] | Cycle ergometer/Treadmill | 8 weeks, 5 d/week | Total: 74 min<br>① 10 min warm-up (5 W)<br>② (12 repetitions of 30 s of exercise and 60 s of recovery)*3 (50–80 W), separated by 5 min recovery | Total: 60 min<br>① 10 min warm-up<br>② 45 min running/cycling ($HR_{VT1}$)<br>③ 5 min cool-down |
| Iellamo 2012 [18] | Treadmill | 12 weeks,<br>2 d/1–3 weeks,<br>3 d/4–6 weeks,<br>4 d/7–9 weeks,<br>5 d/10–12 weeks | Total: 37 min<br>① 9 min warm-up<br>② 4 × 4 min interval (75–80% HRR)<br>③ 4 × 3 min recovery (45–50% HRR) | Total: 30–45 min<br>30–45 min running (45–60% HRR) |
| Fu 2013 [23] | Cycle ergometer | 12 weeks, 3 d/week | Total: 60 min<br>① 30 × 60 s interval (60–70% VO2peak)<br>② 30 × 60 s recovery | Total: 30 min<br>30 min cycling (60–70% VO2peak) |
| Koufaki 2014 [24] | Cycle ergometer | 24 weeks, 3 d/week | Total: 30 min<br>(30 s × 10 interval (100% WR peak)<br>60 s × 10 recovery (20–30% WR peak) × 2 | Total: 40 min<br>40 min cycling (40–60% VO2peak) |

**Table 2.** *Cont.*

| Study | Intervention | | | |
|---|---|---|---|---|
| | Mode | Duration | Exercise Program | |
| | | | IT | CT |
| Angadi 2014 [36] | Treadmill | 4 weeks,<br>3 d/week | Total: 31–43 min<br>① 10 min warm-up (50% HR peak)<br>② 4 × 2–4 min interval (80–90% HRpeak)<br>③ 4 × 2–3 min recovery (50% HR peak)<br>④ 5 min cool-down (50% HR peak) | Total: 30–45 min<br>① 10 min warm-up (50% HRpeak)<br>② 15–30 min running (60–70% HR peak)<br>③ 5 min cool-down (50% HRpeak) |
| Iellamo 2014 [25] | Treadmill | 12 weeks,<br>3 d/week | Total: 48 min<br>① 10 min warm-up<br>② 4 × 4 min interval (75–80% HRR)<br>③ 4 × 3 min recovery (45–50% HRR)<br>④ 10 min cool-down | Total: 55–60 min<br>① 10 min warm-up<br>② 30–45 min running (45–60% HRR)<br>③ 10 min cool-down |
| Tolga 2015 [37] | Cycle ergometer | 12 weeks,<br>3 d/week | ① 5 min warm-up<br>② 30 s interval (50–75% HRR) with 30 s recovery (50–75% HRR)<br>③ 5 min cool-down | Total: 40 min<br>① 5 min warm-up<br>② 30 min cycling (50–75% HRR)<br>③ 5 min cool-down |
| Sibel 2015 [26] | Cycle ergometer | 10 weeks,<br>3 d/week | Total: 35 min<br>① 10 min warm-up/cool-down (20 W)<br>② 17 × 60 s interval (50–75% VO2peak)<br>③ 17 × 30 s recovery (30 W) | Total: 35 min<br>① 10 min warm-up/cool-down (20 W)<br>② 25 min cycling (50–75% VO2peak) |
| Ulbrich 2016 [19] | Treadmill | 12 weeks,<br>3 d/week | Total: 36–51 min<br>① 7–10 min warm-up (70% HR peak)<br>② 4–6 × 3 min interval (95% HR peak)<br>③ 4–6 × 3 min recovery (70% HRpeak)<br>④ 5 min cool-down (50% VO2peak) | Total: 42–45 min<br>① 7–10 min warm-up (70% HRpeak)<br>② 30 min Running (75% HRpeak)<br>③ 5 min cool-down (50% VO2peak) |
| Ellingsen 2017 [30] | Cycle ergometer/treadmill | 12 weeks,<br>3 d/week | Total: 38 min<br>① 5 min warm-up<br>② 4 × 4 min interval (90–95% HRpeak)<br>③ 4 × 3 min recovery<br>④ 5 min cool-down | Total: 47 min<br>47 min cycling or running<br>(60–70% HRpeak) |

**Table 2.** *Cont.*

| Study | Intervention | | | |
|---|---|---|---|---|
| | Mode | Duration | Exercise Program | |
| | | | IT | CT |
| Florent 2019 [27] | Cycle ergometer | 3 weeks, 5 d/week | Total: 30 min<br>① 5 min warm-up (30% WR peak)<br>② 2 × (30 s interval following 30 s recovery × 8)(100% WR peak), seperated by 4 min recovery<br>③ 5 min cool-down (30% WR peak) | Total: 40 min<br>① 5 min warm-up (30% WR peak)<br>② 30 min cycling (60% WR peak)<br>③ 5 min cool-down (30% WRpeak) |
| Jannis 2020 [38] | Cycle ergometer | 12 weeks, 2 d/week | Total: 40 min<br>① Warm-up<br>② 3 bouts of interval (90% HRpeak)<br>③ 2 bouts of recovery (70% HRpeak)<br>④ Cool-down | Total: 40 min<br>40 min cycling (70% HRpeak) |
| Silveira 2020 [39] | Treadmill | 12 weeks, 3 d/week | Total: 38 min<br>① 10 min warm-up<br>② 4 × 4 min interval (85–95% HRpeak)<br>③ 3 × 3 min recovery<br>④ 3 min cool-down | Total: 47 min<br>47 min running (60–70% HRpeak) |

Abbreviations: IT, interval training; CT, continuous training; M/F, male/female; HRpeak, heart rate peak; HRmax, maximal heart rate; VO2peak, peak oxygen uptake; VO2res, reserve oxygen uptake; HRres/HRR, reserve heart rate; $HR_{VT1}$, the first ventilatory threshold; WRpeak, peak work rate; NI, not informed; HFrEF, heart failure with reduced ejection fraction; HFmrEF, heart failure with mid-range ejection fraction; HFpEF, heart failure with preserved ejection fraction.

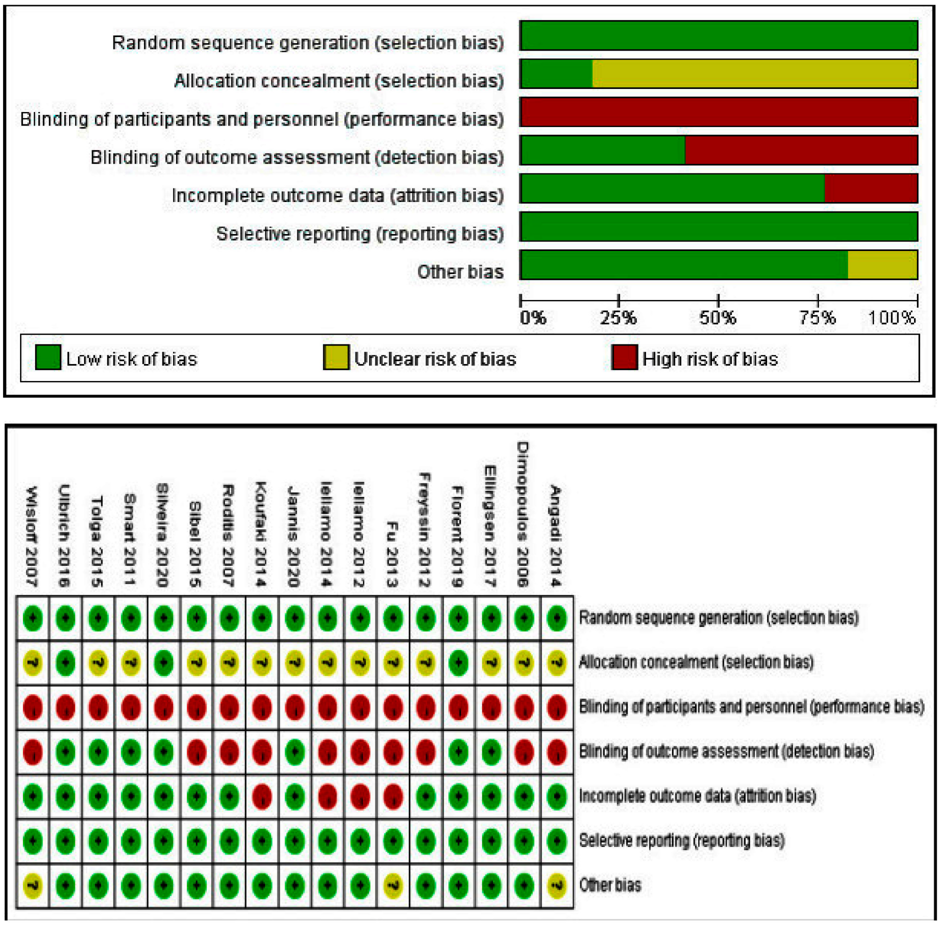


**Figure 2.** Analysis of the risk of bias in accordance with the Cochrane collaboration guidelines.

Randomization was adopted in each study, of which nine studies described specific randomization [20,25–27,29,30,34,35,38]. Because the patients were older, which could lead to adverse accidents, all patients needed to have signed informed consent forms and only seven studies implemented blinding and all of them were blind to the assessor [19,20,27,30,37–39]. Four studies reported the dropout of patients and the reasons for dropout were indicated in the study [18,23–25].

### *3.3. Effects of the Intervention*

#### 3.3.1. VO2peak

VO2peak was reported by seventeen studies including 617 participants with HF. The aggregate results of these studies showed that IT was associated with a significantly improved VO2peak (random effects model, MD = 2.08, 95% CI 1.16 to 2.99, $p < 0.00001$) (Figure 3). The test for heterogeneity was significant ($p = 0.008$ and $I^2 = 51\%$). Subgroup analyses based on intervention duration, exercise intensity of IT, and isocaloric consumption were performed. The results of subgroup analyses (Table 3) showed that intervention duration, exercise intensity of IT, and isocaloric consumption were not the potential factors that led to heterogeneity. Sensitivity analyses were conducted to explore potential sources of heterogeneity, exclusion of individual studies did not substantially alter heterogeneity.

#### 3.3.2. RER

Seven studies with a total of 158 participants reported no significant difference in the RER between IT and CT (fixed-effects model, MD = 0.00, 95% CI −0.02 to 0.03, $p = 0.81$) (Figure 4). The test for heterogeneity was not significant ($p = 0.23$ and $I^2 = 25\%$).

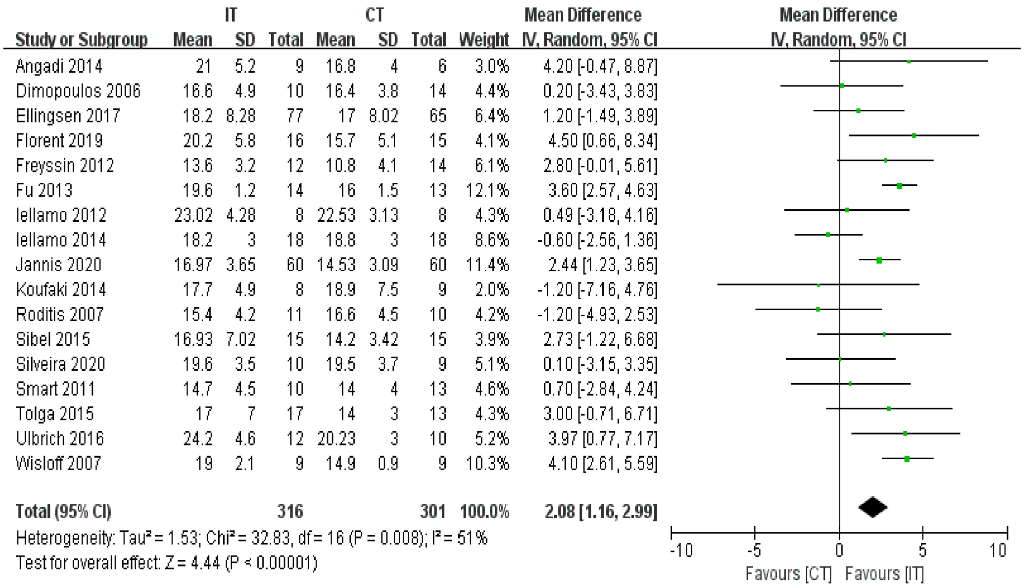


**Figure 3.** Forest plot: Effects of VO2peak.

**Table 3.** Subgroup analyses of effects of IT vs. CT on VO2peak in HF patients.

| Outcome | Subgroup | Potential Factors | Included Studies | Sample Size | 95% Confidence Intervals | Heterogeneity | *p*-Value |
|---|---|---|---|---|---|---|---|
| $VO_2$ peak | Intervention duration | Duration < 12 weeks | 4 | 102 | 3.38 (1.56, 5.19) | $I^2$ = 0% *p* = 0.87 | *p* = 0.0003 |
| | | Duration ≥ 12 weeks | 13 | 515 | 1.73 (0.65, 2.82) | $I^2$ = 62% *p* = 0.002 | *p* = 0.002 |
| | Exercise intensity of IT | Intensity of 60–80% HRpeak | 5 | 136 | 3.26 (2.38, 4.15) | $I^2$ = 0% *p* = 0.62 | *p* < 0.00001 |
| | | Intensity of 80–100% HRpeak | 12 | 481 | 1.70 (0.47, 2.92) | $I^2$ =58% *p* = 0.007 | *p* = 0.007 |
| | Isocaloric consumption | Yes | 7 | 267 | 1.80 (0.28, 3.31) | $I^2$ = 65% *p* = 0.009 | *p* = 0.02 |
| | | No | 10 | 350 | 2.14 (0.99, 3.29) | $I^2$ = 33% *p* = 0.14 | *p* = 0.0003 |

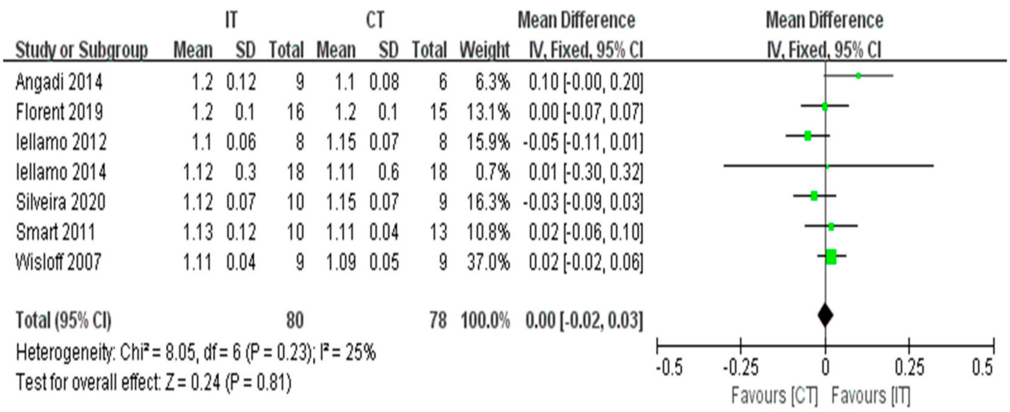


**Figure 4.** Forest plot: Effects of the RER.

#### 3.3.3. VE/VCO2 Slope

Nine studies with a total of 215 participants reported no difference in the VE/VCO2 slope between IT and CT (fixed-effects model, SMD = 0.04, 95% CI −0.23 to 0.31, $p$ = 0.75) (Figure 5). The test for heterogeneity was not significant ($p$ = 0.70 and $I^2$ = 0%).

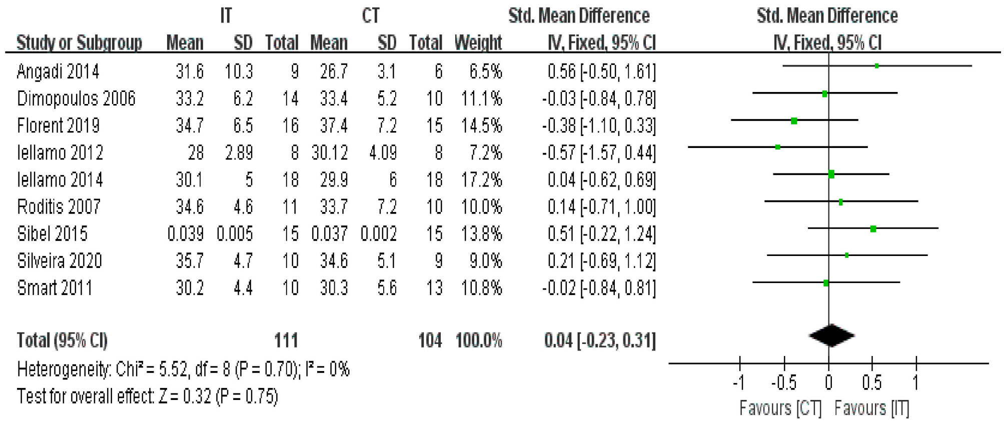


**Figure 5.** Forest plot: Effects of VE/VCO2 slope.

#### 3.3.4. LVEF

The LVEF was reported by ten studies that included a total of 447 participants with HF Figure 6). The meta-analysis showed a significant improvement for participants in the IT group as compared with the CT group (fixed-effects model, MD = 1.32, 95% CI 0.60 to 2.03, $p$ = 0.0003) (Figure 6). The test for heterogeneity was not significant ($p$ = 0.35 and $I^2$ = 10%).

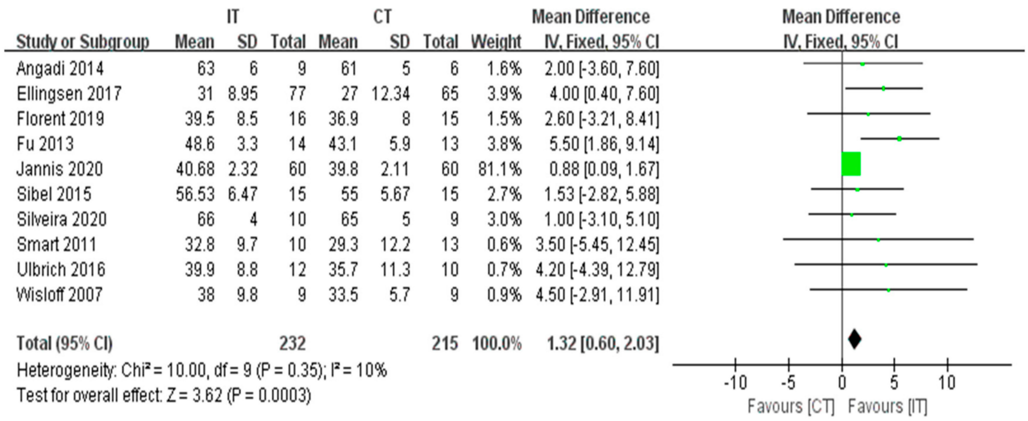


**Figure 6.** Forest plot: Effects of LVEF.

#### 3.3.5. HRrest

Six studies with a total of 154 participants reported no difference in HRrest between IT and CT (fixed-effects model, MD = 0.15, 95% CI −3.00 to 3.29, $p$ = 0.93) (Figure 7). The test for heterogeneity was not significant ($p$ = 0.19 and $I^2$ = 33%).

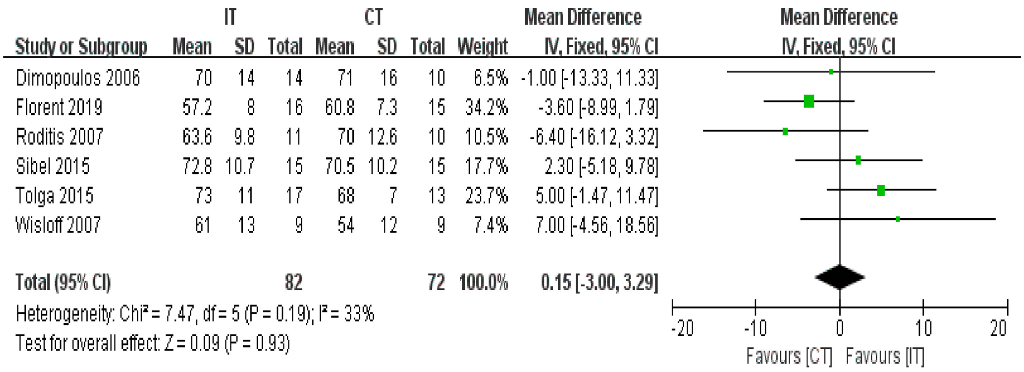


**Figure 7.** Forest plot: Effects of HRrest.

### 3.3.6. MWD

Four studies with a total of 198 participants reported a significant difference in 6MWD between IT and CT (fixed-effects model, MD = 25.67, 95% CI 12.87 to 38.47, $p < 0.0001$) (Figure 8). The test for heterogeneity was not significant ($p = 0.94$ and $I^2 = 0\%$).

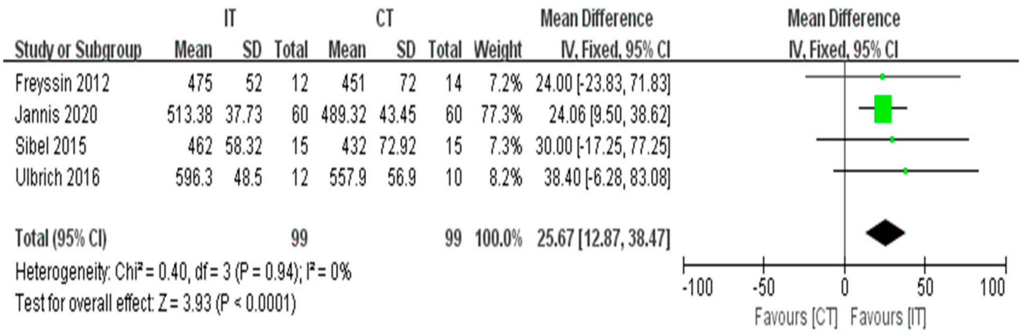


**Figure 8.** Forest plot: Effects of 6MWD.

### 3.3.7. Publication Bias

Egger's test was applied for the six outcomes (Table 4). There were no significant publication biases for VO2peak, RER, VE/VCO2 slope, HRrest, and 6MWD. However, there was publication bias for LVEF (asymmetry test, $p = 0.022$). Therefore, the trim-and-fill method which conservatively imputes hypothetical negative unpublished studies to mirror the positive studies that cause funnel plot asymmetry was performed. The imputed studies produced a symmetrical funnel plot (Figure 9). Combined with the funnel chart, the five studies need to be included, in the future, to ensure the symmetry of the funnel chart and eliminate publication bias.

**Table 4.** Egger's test of the included studies.

| Outcomes | *n* | Std. Err | t | $p > \lvert t \rvert$ | 95% CI | Interval |
|---|---|---|---|---|---|---|
| VO2peak | 17 | 0.656 | −1.87 | 0.081 | −2.625 | 0.170 |
| VE/VCO2 slope | 9 | 2.093 | 0.18 | 0.862 | −4.570 | 5.326 |
| LVEF | 10 | 0.340 | 2.84 | 0.022 | 0.182 | 1.746 |
| HRrest | 6 | 1.890 | 0.35 | 0.745 | −4.590 | 5.905 |

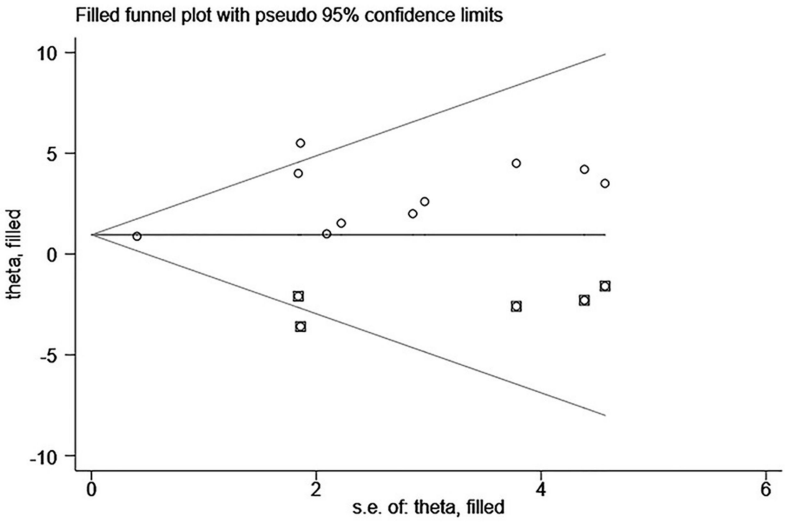


**Figure 9.** O: previous studies; □: filled studies. A funnel plot with trim and fill for the effect size of LVEF.

## 4. Discussion

This systematic literature review with meta-analysis suggests that IT elicits greater improvements in VO2peak, LVEF, and 6MWD than CT, which is similar to previous meta-analyses comparing IT with CT in HF [4,42] and coronary heart disease patients [43,44]. The strengths of this study as compared with previous studies is that more studies were retrieved to compare the effects on cardiorespiratory fitness and exercise tolerance in HF patients between IT and CT. In addition, several indispensable outcomes for HF patients were adopted to measure the effects between the two exercise programs, and therefore provided enough basis for cardiac rehabilitation.

The VO2peak is considered to be the best predictor of survival in cardiovascular diseases [45,46]. Previous studies have indicated that a peak aerobic power ≤10 mL/kg/min is a strong predictor of a poor prognosis in patients with HF [47,48]. The meta-analysis showed that IT significantly improved VO2peak of 2.08 mL/kg/min in patients with HF than CT. In addition, the results of the subgroup analyses suggested that IT as compared with CT was more significant for improving patients' VO2peak with "intervention duration <12 weeks" than "intervention duration ≥12 weeks". Meanwhile, the intensity of 60–80% HRpeak can gain better exercise effects than the intensity of 80–100% HRpeak for HF patients. The reason why a lower intensity gained a better effect may be that maximal intensity of IT has a deeper impact on patients' hearts than a relatively lower intensity, which may not be beneficial to recovery. Previous clinical studies have shown that every 1 mL/kg/min increment in VO2peak leads to the mortality of male and female patients with cardiovascular diseases reducing by 16% and 14%, respectively [21]. The mechanism of IT improving VO2peak may be reflected in the following aspects: (1) the intensity of IT is relatively higher than CT, which may result in an increase in plasma volume and erythrocyte volume [49,50]. (2) IT improves venous drainage and increases stroke output as well as decreases the resistance of blood flow [51]. (3) IT can increase activation of peroxisome proliferator-activated receptor-$\gamma$ coactivator (PGC-1a), which accelerates the mitochondrial biosynthesis process, which is essential to enhance the metabolism ability of skeletal muscle. Mitochondrial function is associated with aerobic physical fitness and plays an important pathophysiological role in cardiac patients [43,52]. Some previous studies have explored the potential physiological mechanism of IT for improving patients' cardiorespiratory fitness, but there was still no clear explanation. It may be influenced by intervention duration, exercise intensity, and individual physical capacity. Therefore, the physiological mechanism of IT for improving cardiorespiratory fitness needs further exploration.

The LVEF is a sensitive index that reflects the function of the left ventricular pump. It is more sensitive and reliable than stroke volume and cardiac index. It directly reflects the left ventricular ejection efficiency and indirectly reflects myocardial contractility [28]. The meta-analysis suggested that there was a significant difference in the LVEF between IT and CT (MD = 1.32, 95% CI 0.60 to 2.03, $p = 0.0003$). The mechanisms responsible for an increment in LVEF may be the following: (1) A higher exercise heart rate during IT increases the magnitude of the post-exercise alteration in left ventricular diastolic filling [53]. (2) Potential mechanisms responsible for altered left ventricular relaxation, in addition to prolonged elevated heart rate, include downregulation of cardiac β-adrenoceptors mediated by elevated catecholamines during exercise. In fact, circulating catecholamines are responsible for maintaining tachycardia during exercise [54]. (3) Exercise training leads to a partial correction of peripheral endothelial dysfunction in patients with HF [55].

The 6MWD is an indicator of the ability to perform daily life activities, which measures exercise tolerance. Improvement in the 6MWD has also been equated with improved quality of life in patients [56]. The meta-analysis suggested that IT significantly increased 6MWD more than CT in HF patients (MD = 25.67, 95% CI 12.87 to 38.47, $p < 0.0001$). The mechanism of IT responsible for increased 6MWD is that a high-intensity IT effort culminating near VO2max, requires that mitochondrial oxidative phosphorylation is fueled by carbohydrate substrates and operates at or near maximal capacity for several consecutive minutes. This type of effort might also represent a greater metabolic challenge for the mitochondria than CT, during which anaerobic metabolism (glycolysis and phosphocreatine) contributes significantly to ATP production [57]. Finally, the acute effects on mitochondrial respiratory function of a relatively high-intensity IT that ultimately yields VO2max and elicits improvements in muscle aerobic capacity [52].

The RER is the ratio of carbon dioxide emission to oxygen uptake. A value of RER equal to at least 1.0 is commonly used to describe adequate effort and motivation in HF patients [58]. The result suggested that there was no significance in RER between IT and CT (MD = 0.00, 95% CI −0.02 to 0.03, $p = 0.81$). The VE/VCO2 slope is an important indicator reflecting exercise tolerance, and it is also an important predictor of death in patients with HF [59]. Risk of mortality is thought to increase when the value of the VE/VCO2 slope is greater than 34 [40]. The non-significance of our result (SMD = 0.04, 95% CI −0.23 to 0.31, $p = 0.75$) between IT and CT is in agreement with previous studies [43,44]. HRrest is a useful clinical marker for cardiovascular disease assessment. Previous studies have shown that for every 10 beats per minute (bpm) increment in HRrest, there is a 14% increased risk for a clinical cardiovascular disease event [41]. The meta-analysis result showed that there was no significance in HRrest between the two exercise programs (MD = 0.15, 95% CI −3.00 to 3.29, $p = 0.93$). These outcomes still need to be further elucidated in large and well-designed studies.

There are some limitations to the meta-analysis as follows: (1) There are no previous studies that have explored the impact of different intensities of IT on HF patients, which makes the division of intensity difficult. In addition, in all the included studies, all patients were in the New York Heart Association (NYHA) functional class I–III, but there was no literature to provide detailed class information. In the future, different intensities of IT could be classified to investigate which one is the optimal intensity for HF patients with different NYHA classes. (2) There is significant heterogeneity with respect to the outcome of VO2peak. Although various subgroups (i.e., exercise duration, exercise intensity of IT, and isocaloric consumption) were performed to explore heterogeneity, unwanted heterogeneity was still obvious, and the relatively small number of studies included in each subgroup could not effectively account for the heterogeneity underlying the various studies. (3) This meta-analysis is not registered and some outcomes are based on small sample sizes, which may affect the stability of the results. In addition, our results may be affected by publication bias. It is hoped that, in the future, more well-designed studies would further expand the meta-analysis results.

## 5. Conclusions

The evidence shows that interval training is better than continuous training for improving cardiorespiratory fitness and exercise tolerance of patients with heart failure. Moreover, the intensity of 60–80% peak heart rate of interval training is the optimal choice for patients. It is hoped that, in the future, more well-designed studies would further expand the meta-analysis results.

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# Strength and Power Characteristics in National Amateur Rugby Players

**Diego Alexandre Alonso-Aubin [1,*], Moisés Picón-Martínez [1] and Iván Chulvi-Medrano [2]**

[1] Wingsport Management SL, 28850 Madrid, Spain; moi_beneixama@hotmail.com
[2] UIRFIDE (Sport Performance and Physical Fitness Research Group), Department of Physical and Sports Education, University of Valencia, 46010 Valencia, Spain; ivan.chulvi@uv.es
* Correspondence: diego@wingsport.es; Tel.: +34-690-093-962

**Abstract:** Rugby players need muscular strength and power to meet the demands of the sport; therefore, a proper assessment of the performance in rugby players should include both variables. The purpose of this study was to examine the strength and power characteristics (SPC) during the squat (SQ) and bench press (BP) in national amateur rugby players and to analyze gender- and position-related differences. A total of 47 players (30 males and 17 females; age: 25.56 ± 1.14 and 23.16 ± 1.38 years, respectively) participated in the study. The one repetition-maximum (1-RM) and SPC in SQ and BP were obtained using a Smith Machine. Then, subjects performed one set of five repetitions on the SQ and BP against six relative loads (30–40–50–60–70–80% 1-RM) using a linear transducer. Differences between genders were found in 1-RM for maximal power, kilograms lifted at maximal power, maximal power, maximal strength and maximal speed in BP ($p < 0.00$) and 1-RM, kilograms lifted at maximal power, maximal power, maximal strength and maximal speed in SQ ($p < 0.00$). Comparisons between variables in SQ and BP present a significant relationship ($p < 0.01$) in SQ and BP 1-RM with kilograms lifted at maximal power ($r = 0.86$ and r = 0.84), maximal strength ($r = 0.53$ and $r = 0.92$) and maximal power ($r = 0.76$ and $r = 0.93$). This study confirms the importance of the SPC assessment for training prescription in rugby amateur players.

**Keywords:** squat; bench press; training; strength; speed

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## 1. Introduction

Rugby is a collision sport that involves high-intensity bouts of exercise including sprint and agility activities and contact and tackling separated by short bouts of low-intensity activity [1,2]. Rugby players need speed, agility, muscular strength and power to meet the demands on the sport and these factors distinguish high- and low-level players [3,4]. Indeed, muscular strength and power are directly associated with performance, whereby the elite players demonstrate the highest muscle power values [5,6]. For example, high-speed running demands are influenced by strength and power and, consequently, by the force–power–velocity profile (FVP) characterizing the maximal mechanical capabilities of the neuromuscular system [7]. Moreover, due to the tactical and movement patterns of rugby, players should have agility skills for avoiding contact and collisions [8–11]. In the case of rugby, there are two general player positions, backs and forwards, with different physical demands [12,13]. Forwards are involved in more collisions, whereas backs are involved in more high-speed running (>5 $m \cdot s^{-1}$) [14]. In addition, previous studies identified that forwards are stronger and more powerful than backs [15]. Backs are reportedly faster and more agile than forwards [16,17].

Muscular strength and power are key attributes for rugby players due to the contact and collision element of the sport, alongside its relationship with those for other physical qualities [18]. Maximal strength is the vehicle that drives the development of the strength and power and allows athletes to develop greater performance on speed and agility activities [19,20]. Thereby, when considering the ability to develop power, it is clear that high levels of muscular strength are a key factor to reach high levels of power [21,22].

Assessing the physical demands could assist in athlete development, guiding athletes' training and assisting coaches. For example, training studies that incorporate maximal or explosive strength exercises have found improvements in the sprinting speed of athletes [21]. In addition, there are several studies presenting strength and power data via Wattbike peak power output, countermovement jump or isoinertial highlighting the importance on strength and power characteristics (SPC) understanding [23].

However, studies on SPC in females are limited, which causes a gap in the knowledge about SPC in females and if there are differences in comparison to males. We hypothesize that males are stronger and more powerful than females because they are heavier and bigger [24,25]. It seems that at the elite level in females, forwards were heavier and displayed greater upper-body strength, whereas backs showed greater acceleration and maximal speed abilities [26]. Recently, similar data were reported in other studies comparing backs and forwards where high-speed demands were different, suggesting that maximal velocity running and strength and power training are important [27]. These facts highlight the importance of assessing SPC and maximizing long-term adaptation of muscle force and power via resistance training [28]. Consequently, a proper assessment of the performance in rugby players should include maximal strength and power. However, there is a gap in the research on the study of these two capacities and their relationship for rugby performance and how strength and conditioning programs should be individualized attending to position demands and gender differences. In order to assess SPC, exercises should be selected that provide a transfer to the sport in skill movement and strength. Thus, the squat (SQ) and the bench press (BP) are two of the most used and effective exercises in resistance training for strengthening the lower and the upper body for improving athletic performance [29,30].

Therefore, the purpose of this study was to examine the strength and power characteristics (SPC) on the SQ and BP in national amateur rugby players and to analyze sex- and position-related differences for better strength and conditioning program designs. We hypothesize that there are differences in SPC between backs and forwards and males and females.

## 2. Materials and Methods

### *2.1. Participants*

A total of 47 rugby players, with at least 5 years of experience in practice in rugby and resistance training performing parallel SQ and BP exercises, volunteered to participate in this study. Exclusion criteria included a musculoskeletal injury over the past six months, any medical condition that could limit the exercise performance, and taking steroids, drugs, medications or dietary supplements for enhancing sport performance. Subjects were national amateur rugby players and included 30 males (age 26.56 $\pm$ 1.14 years; height 1.78 $\pm$ 0.16 m; and body mass 86.85 $\pm$ 1.88 kg) and 17 females (age 23.16 $\pm$ 1.38 years; height 1.63 $\pm$ 0.16 m; and body mass 66.46 $\pm$ 2.39 kg). Then, for comparing player positions we split in forwards (age 25.57 $\pm$ 1.25 years; height 1.74 $\pm$ 0.15 m; and body mass 84.11 $\pm$ 2.43 kg; 20 males and 10 females) and backs (age 25.07 $\pm$ 1.27 years; height 1.71 $\pm$ 0.25 m; and body mass 72.23 $\pm$ 3.04 kg; 10 males and 7 females). Their average weekly training volume was 13 h*wk$^{-1}$ including three days of rugby-specific training, three days of resistance training and competition. All procedures followed ethical principles for medical research involving human subjects by the World Medical Association Declaration of Helsinki (General Assembly of the World Medical Association. 2014). The study was approved by the University of Alicante Institution Ethics Committee UA-2018-06-20. All subjects were informed of the purpose of the study, and experimental procedures and potential risks of the study. They were given the opportunity to ask any questions related to the procedures. After being informed, they signed the informed consent form.

### 2.2. Procedures

The present research was performed in 3 different sessions, all separated by 3 days. The first visit to the laboratory was dedicated to informing the subjects about the procedures, familiarization with tests and anthropometric measurements. Maximum strength tests (1-RM) in parallel SQ and parallel BP were performed in the second session and power assessment in the third in randomized order. For the strength assessments, we used a Smith Machine (Multipower, Line Selection; Technogym, Gambettola, Italy). All the sessions were performed at the same time, between 5 p.m. and 8 p.m. All tests were supervised by a Certified Strength and Conditioning Specialist (CSCS) who has 10 years' experience in testing and training rugby athletes. Subjects were instructed to avoid any strenuous physical activity 24 h prior to each assessment and not to eat and drink water ad libitum 45 min before the assessments. Before testing, players performed a standardized 15 min warm-up that consisted of 5 min of pedaling on a cycle ergometer at an intensity of 50 watts followed by 1 set of 15 repetitions on either SQ or BP exercise at an increasing velocity with a 20-kg barbell.

#### 2.2.1. Squat and Bench Press Techniques

To standardize exercise performance during the testing sessions, an analogic goniometer was used to measure 90° of knee flexion (parallel-squat) and ensure a consistent stance distance during the SQ and 90° of elbow flexion and biacromial distance of the grip width during the BP.

To ensure the correct range of motion, straps were used to limit a greater displacement than 90° of knee flexion on the SQ and 90° of elbow flexion on the BP.

During the SQ, the load was lifted without lifting heels off the ground, keeping the back straight, eyes focused forward and feet slightly wider than shoulder-width apart with toes pointing slightly outward.

During the BP, the load was lifted without lifting the hips off the bench, with the neck and the back lying on the bench and the feet on the ground [31,32].

#### 2.2.2. Maximal Strength

Subjects completed the squat assessment first and then the bench press assessment. Subjects performed 1 set of 3–4 repetitions on the SQ and BP exercises with 4 relative loads calculated according to their previous 1-RM performed 2 weeks ago in a training-test session (60–70–80–90% 1-RM) for warming up. After the specific 15 min warm-up previously mentioned, subjects performed a 1-RM attempt by increasing progressively (by 10–20% in the SQ and 5–10% in the BP) the load used in 100% 1-RM. If the subject failed the 1-RM attempt, we decreased the load by 5–10% in the squat and 2.5–5% in the BP. The subjects' 1-RMs were achieved within five attempts. Subjects were given 3 min of recovery between each set and 5 min between exercises.

#### 2.2.3. Power Strength

After 72 h from the maximal strength assessment, subjects returned to the testing facility to perform 1 set of 5 repetitions on the SQ and BP exercises on 6 relative loads with an increasing intensity calculated from the data recorded in the first session (30–40–50–60–70–80% 1-RM). Subjects were given a 3 min recovery between each set and 5 min between exercises.

Participants were told the importance of performing the concentric phase at the highest speed and effort possible. During the performance, they were not given any kind of feedback.

#### 2.2.4. Measurement Equipment and Data Analysis

The bar was properly instrumented with a linear position transducer (T-Force System, Ergotech, Murcia, Spain) that has a precision in 1000 N and a sampling frequency on 1000 Hz for maximal power recording. This device has been used to assess kinetic and kinematic variables in resistance exercises. The system consists of a linear velocity transducer extension cable in interface with a personal computer that obtains data with an analogic–digital resolution of 14 bits. The specific software (TFDMS Version 2.35) calculates the kinematic and kinetic parameters of each repetition, and stores and provides all information from the results obtained in real time [33]. The system's software automatically calculated the bar velocity of every repetition, providing auditory and visual feedback in the same moment of realization.

The concentric phase or positive work was as fast as the subject could perform. The eccentric or negative work, and recovery phase had a duration of 3.5 s [34]. Additionally, all the measurement data were stored on a virtual disk.

Subsequently, the software analyzed the data, obtaining the following variables for both exercises: maximal power at a given percentage (Max. Power at 1-RM%), kilograms used to achieve the highest power value (Max. Power kg), maximal power (Max. Power in W), maximal strength (Max. Strength in N), maximal speed (Max. Speed), time spent reaching maximal power (Time to Max. Power), time spent reaching maximal speed (Time to Max. Speed).

### 2.3. Statistical Analysis

The normality of the data for each group was checked using the Shapiro–Wilk test. Due to the normal distribution, data are described as mean and standard deviation (SD). One-way ANOVA was used to determine differences between backs and forwards, and men and females. Pearson correlations were performed to determine the significance of the association between variables (0.00 to 0.30: negligible correlation; 0.30 to 0.50: low positive correlation, 0.50 to 0.70: moderate positive correlation, 0.70 to 0.90: high positive correlation, 0.90 to 1.00: very high positive correlation) [35]. Significance was set at $p < 0.05$. To assess effect size d, the Cohen test was used. The effect size indices were 0.2 = small; 0.5 = medium; 0.8 = large and 1.3 = very large [36]. Analyses were performed using SPSS® v25.0 for Mac (SPSS, Inc., Chicago, IL, USA).

## 3. Results

Table 1 shows differences by gender and rugby position in 1-RM for both exercises, maximal power at a given percentage (Max. Power at 1-RM%), kilograms used to achieve the highest power value (Max. Power kg), maximal power (Max. Power in W), maximal strength (Max. Strength in N), maximal speed (Max. Speed), time spent reaching maximal power (Time to Max. Power), time spent reaching maximal speed (Time to Max. Speed).

**Table 1.** Differences between genders and positions.

| | Males | Females | Significance | Effect Size | Forwards | Backs | Significance | Effect Size |
|---|---|---|---|---|---|---|---|---|
| | Mean ± SD | Mean ± SD | *p* | d | Mean ± SD | Mean ± SD | *p* | d |
| 1-RM Bench Press (kg) | 96.83 ± 3.40 | 37.81 ± 2.13 | 0.001 ** | 14.67 | 76.37 ± 5.99 | 76.17 ± 8.21 | 0.89 | 0.01 |
| Max. Power BP (1-RM%) | 61.33 ± 2.47 | 69.37 ± 2.49 | 0.02 * | −2.61 | 62.41 ± 2.74 | 67.05 ± 2.05 | 0.30 | −1.58 |
| Max. Power BP (kg) | 58.93 ± 2.66 | 25.87 ± 1.37 | 0.001 ** | 14.77 | 46.27 ± 3.88 | 49.41 ± 4.56 | 0.53 | −0.35 |
| Max. Power BP (W) | 713.28 ± 27.84 | 241.51 ± 15.90 | 0.001 ** | 1.84 | 560.96 ± 51.34 | 529.11 ± 57.71 | 0.80 | 0.02 |
| Max.Strength BP (N) | 777.38 ± 27.16 | 343.64 ± 25.26 | 0.001 ** | 1.26 | 613.69 ± 48.68 | 652.17 ± 54.16 | 0.51 | −0.03 |
| Max.Speed BP (m/s) | 1.06 ± 0.3 | 0.78 ± 0.42 | 0.001 ** | 4.20 | 1.02 ± 0.04 | 0.86 ± 0.05 | 0.04 * | 0.10 |
| Time to Max. Power BP (ms) | 512.36 ± 23.84 | 522 ± 42.06 | 0.82 | −0.02 | 518.13 ± 25.34 | 499.17 ± 38.33 | 0.55 | 0.04 |
| Time to Max. Speed BP (ms) | 555.26 ± 22.85 | 560 ± 44.35 | 0.90 | −0.01 | 561.41 ± 24.09 | 536.88 ± 51.09 | 0.47 | 0.03 |
| 1-RM Squat (kg) | 199.83 ± 6.97 | 125.31 ± 8.23 | 0.001 ** | 2.56 | 170 ± 10.34 | 180.58 ± 10.23 | 0.41 | −0.20 |
| Max. Power SQ (1-RM%) | 68.33 ± 1.92 | 66.87 ± 3.50 | 0.85 | 0.37 | 67.58 ± 2.30 | 68.23 ± 2.60 | 0.94 | −0.22 |
| Max. Power SQ (kg) | 136.66 ± 6.08 | 82.00 ± 6.07 | 0.001 ** | 2.96 | 114.58 ± 8.09 | 122.88 ± 8.19 | 0.50 | −0.25 |
| Max. Power SQ (W) | 1472.94 ± 66.57 | 656.60 ± 45.75 | 0.001 ** | 0.50 | 1154.19 ± 92.54 | 1248.39 ± 125.19 | 0.48 | −0.02 |
| Max.Strength SQ (N) | 1784.16 ± 71.47 | 1366.42 ± 242.53 | 0.04 * | 0.03 | 1569.60 ± 106.77 | 1794.44 ± 207.45 | 0.23 | −0.02 |
| Max.Speed SQ (m/s) | 0.95 ± 0.31 | 0.67 ± 0.43 | 0.001 ** | 3.99 | 0.85 ± 0.04 | 0.84 ± 0.05 | 0.78 | 9.76 |
| Time to Max. Power SQ (ms) | 626 ± 37.31 | 514.23 ± 46.64 | 0.07 | 0.13 | 598.34 ± 39.26 | 574.11 ± 49.19 | 0.76 | 0.02 |
| Time to Max. Speed SQ (ms) | 668.50 ± 37.56 | 572.11 ± 47.14 | 0.12 | 0.11 | 650.03 ± 38.79 | 615.11 ± 49.69 | 0.64 | 0.04 |

BP: Bench Press; SQ: Squat; s: seconds; 1-RM: one maximum repetition; kg: kilograms; W: watts; N: newtons; ms: milliseconds; * $p < 0.05$; ** $p < 0.01$; d: d Cohen.

Significant differences ($p < 0.01$) were found between males and females in the BP in 1-RM (d = 14.67), kilograms used to achieve the highest power value (d = 14.77), maximal power (d = 1.84), maximal strength (d = 1.26) and maximal speed (d = 4.20) and in the SQ in kilograms used to achieve the highest power value (d = 2.96), maximal power (d = 0.50) and maximal speed (d = 3.99).

Tables 2 and 3 show the comparisons between positions by gender among variables in SQ and BP. We found significant differences ($p < 0.01$) in the BP in females in kilograms to achieve the higher power values (d = 0.76) and maximal strength (d = 0.81).

Tables 4 and 5 show the correlations among variables in SQ and BP.

**Table 2.** Squat comparisons between positions by gender.

| | Gender | Position | Mean ± SD | Significance (*p*) | Effect Size (d) |
|---|---|---|---|---|---|
| 1-RM Squat (kg) | Males | Forwards | 195.25 ± 44.7 | 0.362 | 0.14 |
| | | Backs | 209 ± 18.52 | | |
| | Females | Forwards | 113.88 ± 31.2 | 0.11 | 0.34 |
| | | Backs | 140 ± 31.09 | | |
| Max. Power SQ (1-RM%) | Males | Forwards | 68.5 ± 10.89 | 0.9 | 0.05 |
| | | Backs | 68 ± 10.32 | | |
| | Females | Forwards | 65.55 ± 15.89 | 0.68 | 0.06 |
| | | Backs | 68.57 ± 12.14 | | |
| Max. Power SQ (kg) | Males | Forwards | 133.6 ± 36.91 | 0.48 | 0.1 |
| | | Backs | 142.8 ± 25.24 | | |
| | Females | Forwards | 72.33 ± 22.48 | 0.69 | 0.45 |
| | | Backs | 94.42 ± 21.95 | | |
| Max. Power SQ (W) | Males | Forwards | 1404.15 ± 383.06 | 0.14 | 0.3 |
| | | Backs | 1610.54 ± 295.24 | | |
| | Females | Forwards | 598.72 ± 132.39 | 0.15 | 0.28 |
| | | Backs | 731.03 ± 221.09 | | |
| Max.Strength SQ (N) | Males | Forwards | 1722.93 ± 417.43 | 0.232 | 0.21 |
| | | Backs | 1906.62 ± 317.81 | | |
| | Females | Forwards | 1228.86 ± 744.22 | 0.44 | 0.11 |
| | | Backs | 1634.19 ± 1322.35 | | |
| Max.Speed SQ (m/s) | Males | Forwards | 0.93 ± 0.18 | 0.14 | 0.3 |
| | | Backs | 0.98 ± 0.13 | | |
| | Females | Forwards | 0.69 ± 0.18 | 0.51 | 0.09 |
| | | Backs | 0.63 ± 0.15 | | |
| Time to Max. Power SQ (ms) | Males | Forwards | 616.2 ± 218.95 | 0.69 | 0.67 |
| | | Backs | 648 ± 180.57 | | |
| | Females | Forwards | 558.66 ± 200.2 | 0.38 | 0.13 |
| | | Backs | 468.57 ± 196.73 | | |
| Time to Max. Speed SQ (ms) | Males | Forwards | 656.9 ± 219.81 | 0.67 | 0.07 |
| | | Backs | 691.7 ± 183.11 | | |
| | Females | Forwards | 634.77 ± 193.98 | 0.2 | 0.23 |
| | | Backs | 460.71 ± 189.43 | | |

BP: Bench Press; s: seconds; 1-RM: one maximum repetition; kg: kilograms; W: watts; N: newtons; ms: milliseconds; d Cohen.

**Table 3.** Bench Press comparisons between positions by gender.

| | Gender | Position | Mean ± SD | Significance (*p*) | Effect Size (d) |
|---|---|---|---|---|---|
| 1-RM Bench Press (kg) | Males | Forwards | 95 ± 17.84 | 0.456 | 0.113 |
| | | Backs | 100.50 ± 20.60 | | |
| | Females | Forwards | 35 ± 9.68 | 0.14 | 0.3 |
| | | Backs | 41.42 ± 5.56 | | |
| Max. Power BP (1-RM%) | Males | Forwards | 60 ± 15.55 | 0.457 | 0.113 |
| | | Backs | 64 ± 8.43 | | |
| | Females | Forwards | 67.77 ± 12.01 | 0.48 | 0.1 |
| | | Backs | 71.42 ± 6.90 | | |

**Table 3.** *Cont.*

| | Gender | Position | Mean ± SD | Significance (*p*) | Effect Size (d) |
|---|---|---|---|---|---|
| Max. Power BP (kg) | Males | Forwards<br>Backs | 56.75 ± 16.23<br>63.30 ± 9.77 | 0.253 | 0.204 |
| | Females | Forwards<br>Backs | 23 ± 4.78<br>29.57 ± 4.64 | 0.01 * | 0.76 |
| Max. Power BP (W) | Males | Forwards<br>Backs | 716.99 ± 169.97<br>705.88 ± 117.85 | 0.855 | 0.054 |
| | Females | Forwards<br>Backs | 214.23 ± 53.89<br>276.58 ± 60.83 | 0.04 * | 0.52 |
| Max.Strength BP (N) | Males | Forwards<br>Backs | 759.36 ± 167.47<br>813.44 ± 99.85 | 0.357 | 0.148 |
| | Females | Forwards<br>Backs | 289.98 ± 55.03<br>421.79 ± 113.02 | 0.008 ** | 0.817 |
| Max.Speed BP (m/s) | Males | Forwards<br>Backs | 1.10 ± 0.23<br>0.99 ± 0.17 | 0.196 | 0.248 |
| | Females | Forwards<br>Backs | 0.85 ± 0.14<br>0.69 ± 0.19 | 0.07 | 0.42 |
| Time to Max. Power BP (ms) | Males | Forwards<br>Backs | 493.45 ± 126.67<br>550.2 ± 136.49 | 0.269 | 0.193 |
| | Females | Forwards<br>Backs | 573 ± 148.95<br>426.28 ± 167.47 | 0.08 | 0.04 |
| Time to Max. Speed BP (ms) | Males | Forwards<br>Backs | 537.8 ± 117.21<br>590.2 ± 139.48 | 0.288 | 0.192 |
| | Females | Forwards<br>Backs | 613.88 ± 147.65<br>460.71 ± 189.43 | 0.09 | 0.04 |

BP: Bench Press; s: seconds; 1-RM: one maximum repetition; kg: kilograms; W: watts; N: newtons; ms: milliseconds; * $p < 0.05$; ** $p < 0.01$; d: d Cohen.

**Table 4.** Correlation among squat variables.

| | 1-RM Squat (kg) | Max. Power SQ (kg) | Max. Power SQ (1-RM%) | Max. Strength SQ (N) | Max. Power SQ (W) | Max. Speed SQ (m/s) |
|---|---|---|---|---|---|---|
| 1-RM Squat (kg) | | | | | | |
| Max. Power SQ (kg) | 0.867 ** | | | | | |
| Max. Power SQ (1-RM%) | −0.082 | 0.436 ** | | | | |
| Max.Strength SQ (N) | 0.530 ** | 0.634 ** | 0.332 * | | | |
| Max. Power SQ (W) | 0.764 ** | 0.808 ** | 0.228 | 0.533 ** | | |
| Max.Speed SQ (m/s) | 0.269 | 0.165 | −0.186 | −0.183 | 0.628 ** | |
| Time to Max. Power SQ (ms) | 0.262 | 0.399 ** | 0.304 * | 0.105 | 0.367 * | 0.22 |
| Time to Max. Speed SQ (ms) | 0.208 | 0.361 * | 0.344 * | 0.152 | 0.344 * | 0.175 |

SQ: Squat; s: seconds; 1-RM: one maximum repetition; kg: kilograms; W: watts; N: newtons; ms: milliseconds; * $p < 0.05$; ** $p < 0.01$.

**Table 5.** Correlation among bench press variables.

| | 1-RM Bench Press (kg) | Max. Power BP (kg) | Max. Power BP (1-RM%) | Max. Strength BP (N) | Max. Power BP (W) | Max. Speed BP (m/s) |
|---|---|---|---|---|---|---|
| 1-RM Bench Press (kg) | | | | | | |
| Max. Power BP (kg) | 0.843 ** | | | | | |
| Max. Power BP (1-RM%) | −0.444 ** | 0.078 | | | | |
| Max.Strength BP (N) | 0.921 ** | 0.956 ** | −0.124 | | | |
| Max. Power BP (W) | 0.938 ** | 0.821 ** | −0.363 * | 0.921 ** | | |
| Max.Speed BP (m/s) | 0.539 ** | 0.15 | −0.747 ** | 0.303 * | 0.621 ** | |
| Time to Max. Power BP (ms) | −0.158 | 0.168 | 0.607 ** | −0.081 | −0.213 | |
| Time to Max. Speed BP (ms) | −0.138 | 0.161 | 0.568 ** | −0.083 | −0.2 | −0.302 * |

BP: Bench Press; s: seconds; 1-RM: one maximum repetition; kg: kilograms; W: watts; N: newtons; ms: milliseconds; * $p < 0.05$; ** $p < 0.01$.

## 4. Discussion

The purpose of this study was to examine SPC on the SQ and BP in national amateur rugby players, analyzing possible differences in performance between genders and playing positions. One finding of this study was that the assessment of the SPC could be a useful tool for resistance-training prescription, adding the ability for coaches to prescribe training according the role demands. In addition, our study could provide the opportunity for other studies to recruit samples from multiple clubs, thus increasing sample sizes, generalizability of results and statistical power of subcategory comparisons (e.g., position, playing level or gender). This objective is one of the goals proposed in the most recent scientific literature [37].

First, there is a scarcity in the literature comparing SPC in males and females, and we found strong differences between BP and SQ in males and females, in both absolute and relative values of the different variables of the SPC, especially in 1-RM, maximal power and maximal speed in SQ and BP. These results are similar to those found in previous research conducted with adolescent rugby players where there were also differences between genders in both exercises [38,39]. These findings could be attributed to the prevalence of slower type-I and II-A fibers in females compared with males that parallels the lower contractile velocity in females compared with males and differences in thyroid hormone, estrogen and testosterone levels [40]. Supporting this, one study previously demonstrated that with different maturation status SPC could be different in males and females, as in adolescent age females could demonstrate greater power values than males [38].

Secondly, comparing different sports disciplines also shows that the variables that make up the SPC are specific not only to sports but also individually [41]. In the case of rugby, the player's role may have an important implication for the training design since the specific techniques of the sport as well as the movements associated with their playing positions may have a direct relationship with the training method to be applied [42]. Supporting this evidence, other findings confirm the influence of training and sport activity on the force and velocity capacity balance for power-oriented sports [43]. Due to these differences and the scarce studies carried on rugby it is important to determine the SPC in these players. One of the objectives of the SPC studies is to determine if there are differences between athletes based on their role during the game. We did not find strong differences between backs and forwards in our study in the SPC variables, even when we compared positions by gender, excepting in maximal speed in the BP exercise when we compared all the subjects together, and maximal power and strength in females. This could be explained by their amateur level, as other studies found differences in strength and maximal force production in BP in rugby union players because of the physical demands of these respective positions [6]. In the literature there are few studies that determine differences related to the athletes' roles [44,45]. The SPC assessment could be important to determine the factors that have an influence on performance individually on rugby players. Our data show that SQ and BP present a significant strong relationship in 1-RM and maximal power and BP and kilograms lifted at maximal power, maximal strength and maximal power. The sport position could have an influence in the performance showing differences between forwards and backs in maximal speed in BP exercise.

Our study found high correlations in SQ and BP between maximal power and maximal strength, and kilograms lifted at maximal power, suggesting that strength performance is critical for greater power values. Similar conclusions were reported in previous studies in SQ [46–48] and in BP [49,50]. Knowing the SPC of the players can also be decisive to know the level and potential of future performance of the players since the strength and power values are considered indicators of the level of development [51]. We analyzed the data and the relationships that exist between the variables of the SPC in order to determine which are the most significant in power performance to prescribe more specific training according to the objectives and for enhancing players' performance by their roles. Based on our data, maximal power in SQ and BP is strongly related to maximal strength. In this sense, the training contents can be manipulated by the coaches to make rugby players improve their performance through increased production of strength [52].

In the same way, the relationship between the force–velocity profile (FVP) and performance in sprint and jump tests has also been studied, determining that there is a high correlation between some of the FVP variables such as maximum power, speed and strength, especially in the first one [53].

Therefore, it is necessary to develop new research to understand different training protocols in order to improve the performance of the FVP associated with the specific context of rugby, including also the assessment of speed and agility since it will allow determining the possibilities of improvement in movement during game situations. In the case of trying to improve rugby performance, it is suggested that resistance training must be adjusted using SPC values close to the rugby role playing reported in high performance players. This will optimize the SPC in the different positions in rugby forwards or backs.

This is the first study analyzing the SPC in national amateur rugby players by comparing the SPC variables between gender and positions and providing SPC data in females by positions. However, some limitations should be acknowledged. Research in SPC in national amateur rugby players is a field with gaps in the literature and we need more studies for a better understanding. In our study, we only had access to 47 rugby players, but we know that a greater number of subjects would be better for improved inferences. In this sense, we have not assessed the muscle mass, and this could give a better perspective about the SPC and its relationship with the body composition. Finally, we have not included a rugby-specific test to correlate with the SPC.

## 5. Conclusions

This study confirms the importance of the SPC assessment for training prescription in national amateur rugby players for enhancing performance by player position or gender. In addition, this study provides data so that other investigations can compare their results and thus establish a database to make inferences about the performance of rugby players. It is confirmed that there are differences between males and females in both absolute and relative values of the different variables of the SPC, especially in 1-RM, maximal power and maximal speed in SQ and BP. These variables are also critical for sport performance and should be considered for a proper assessment and training in rugby performance.

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# The Biomechanical Characterization of the Turning Phase during a 180° Change of Direction

**Enrico Santoro [1], Antonio Tessitore [1], Chiang Liu [2], Chi-Hsien Chen [2], Chutimon Khemtong [3], Mauro Mandorino [1], Yi-Hua Lee [4] and Giancarlo Condello [3,*]**

1 Department of Movement, Human and Health Sciences, University of Rome Foro Italico, Piazza Lauro De Bosis 6, 00135 Roma, Italy; enry9521@gmail.com (E.S.); antonio.tessitore@uniroma4.it (A.T.); mauromandorino@gmail.com (M.M.)
2 Institute of Sports Equipment Technology, University of Taipei, 101 Zhongcheng Rd. Section 2, Shilin District, Taipei 111, Taiwan; chiangliu1974@yahoo.com.tw (C.L.); s840410s@gmail.com (C.-H.C.)
3 Graduate Institute of Sports Training, Institute of Sports Sciences, University of Taipei, 101 Zhongcheng Rd. Section 2, Shilin District, Taipei 111, Taiwan; tmedmet.md_sci3@hotmail.com
4 Department of Ball Sports, University of Taipei, 101 Zhongcheng Rd. Section 2, Shilin District, Taipei 111, Taiwan; lykllyy@utaipei.edu.tw
* Correspondence: giancarlo.condello@gmail.com

**Abstract:** The aim of this study was to characterize the turning phase during a modified 505 test. Forty collegiate basketball students, divided into faster and slower performers and high-playing-level and low-playing-level groups, were evaluated for the force-time characteristics (braking and/or propulsive phase) of the penultimate foot contact (PFC), final foot contact (FFC), and first accelerating foot contact (AFC), and for completion time and approach velocity. Based on the composition of the AFC, trials were classified as braking/propulsive or only propulsive. Regression analysis for the prediction of completion time was performed. The AFC contributed to reacceleration through shorter contact times and step length, and lower braking force production ($p < 0.05$). Faster performers and the high-playing-level group demonstrated ($p < 0.05$): lower completion times, higher approach velocities, longer steps length in the PFC and FFC, greater braking forces and impulses in the PFC; greater braking and propulsive forces, braking impulses, lower contact times in the FFC; greater braking and propulsive horizontal forces, horizontal impulses, lower contact times and vertical impulses in the AFC. Kinetic variables from only the FFC and AFC and approach velocity predicted 75% (braking/propulsive trials) and 76.2% (only-propulsive trials) of completion times. The characterization of the turning phase demonstrated the specific contribution of each foot contact and the possible implications for training prescription.

**Keywords:** modified 505 test; kinetic variables; completion time; foot contact; predictors

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## 1. Introduction

Change-of-direction (COD) ability is a preplanned, multidirectional action and an important physical quality for many team sports [1–3]. It can be defined as the ability to decelerate (i.e., eccentric action) in the shortest time and quickly reaccelerate (i.e., concentric action) in a new direction while running or sprinting [1–4]. This coupling of an eccentric and concentric action also refers to the ability to properly use the stretch-shortening cycle (SSC) [5].

A COD can be performed with or without a stimulus to which to respond. Specifically, when a directional change occurs in response to a stimulus, it is referred to as agility, while it is only referred to as COD speed if the response to a stimulus is not required [1–3]. Focusing solely on the preplanned action during training and competitions, CODs are executed at different directions, speeds, and with different cutting angles. In particular, a 180° COD action frequently occurs during competitions (i.e., basketball, soccer, netball, cricket) [6–8]. For this reason, it is widely included in fitness testing batteries for either COD speed tests (i.e., 505 test) or endurance field-based cardiorespiratory tests (i.e., Yo-Yo test, 30–15 Intermittent Fitness Test). In this context, the test's completion time is mainly used as the performance outcome. However, an exhaustive evaluation of the COD ability requires technical and biomechanical assessments [9–12], hence focusing on the "how" (i.e., quality) and not only on the "what" (i.e., time) of the COD performance to better address training prescription [13]. Therefore, the investigation of the "how" has been consistently addressed through the assessment of kinetic and kinematic variables during the critical foot contacts of COD performance [14].

Focusing solely on the 180° COD speed tests, the kinetic and kinematic variables of the penultimate foot contact (PFC) and final foot contact (FFC) are commonly evaluated during traditional and modified 505 tests to investigate the differences between faster and slower performers [15–17]. Recently, new research investigated for the first time the antepenultimate foot contact, demonstrating its role in facilitating the deceleration phase during a traditional 505 test [18]. However, it would be interesting to also consider the analysis of the first step after turning, henceforth called the first accelerating foot contact (AFC). However, to the best of our knowledge, previous studies did not include the analysis of this foot contact during traditional or modified 505 tests.

The available evidence demonstrates the differences between faster and slower performers (based on the completion time) during the 505 test. Faster performers showed greater horizontal braking forces for the PFC, greater horizontal propulsive forces, vertical impact forces, and shorter contact times for the FFC compared with slower performers during the modified 505 test [15]. Furthermore, faster performers demonstrated greater vertical braking and propulsive forces compared with slower performers in the COD-only step analyzed during the traditional 505 test [16]. Moreover, faster performers showed greater peak and average horizontal propulsive forces for the FFC than slower performers during the traditional and modified 505 test [17]. Finally, associations have recently been demonstrated between greater antepenultimate foot contact peak vertical, horizontal, and resultant braking forces, mean vertical, horizontal, and resultant GRFs, and horizontal total impulses in comparison with faster performers during the traditional 505 test [18].

Furthermore, the possible influence of limb asymmetries and directional dominance might exist in the traditional or modified 505 test in female and male team sports players [19,20]; however, it has not been largely confirmed in a further investigation of only female soccer players [21]. Nonetheless, contradictory results also emerged considering limb dominance as a factor associated with injury risk during COD actions [22].

Playing level might be considered a critical issue in sports performance. However, it has been demonstrated that COD speed tests are not able to discriminate between higher-skilled groups [3]. In fact, previous investigations did not report significant differences between higher- and lower-performance groups in Australian football [23–25] and rugby league [26,27] players when the completion time was measured. However, there is a paucity of evidence regarding the effect of the playing level on spatial–temporal and kinetic variables during a 505 test.

Similarly, considering that several determinants (spatial–temporal and kinetic variables) may influence the performance outcome (i.e., completion time) of a 505 test, limited evidence is available for the predictors of completion time.

Taken together, the current knowledge on the 505 test can still be expanded through the inclusion of other foot contacts with those already investigated in order to define the entire turning phase, as well as in relation to several factors, such as leg dominance, COD performance, and playing level. Therefore, the objective of this study was to investigate the modified 505 test, providing an analysis of the three foot contacts (PFC, FFC, AFC) that characterize the turning phase. In particular, the purpose of this study was to examine the effects of leg preference, COD performance, and playing level on spatial–temporal and kinetic variables for each foot contact and to evaluate the prediction of the completion time from the spatial–temporal and kinetic variables. We hypothesized the existence of differences between legs and superior performance for faster performers and the high-playing-level group during the modified 505 test.

## 2. Materials and Methods

### 2.1. Study Design

A cross-sectional study design was applied to investigate the effect of leg preference, COD performance (i.e., completion time), and playing level on spatial–temporal and kinetic variables during the modified 505 test. Furthermore, the predictors of COD performance were examined.

This study was approved by the University of Taipei Institutional Review Board (Taipei, Taiwan, reference number: IRB-2018-093). All participants gave their informed written consent, and all the experimental procedures were conducted in accordance with the Declaration of Helsinki [28].

### 2.2. Participants

A minimum sample size of 34 participants was determined from an a priori power analysis performed by G*Power (version 3.1.9.2 University of Dusseldorf, Dusseldorf, Germany), considering an ANOVA test with a power of 0.95, an effect size of 0.65, and $\alpha = 0.05$. Accordingly, 40 male and female collegiate students (32 males: age = 20.9 ± 2.0 years, height = 179 ± 7.3 cm, body mass = 76.1 ± 9.6 kg; 8 females: age = 21.5 ± 1.8 years, height = 164 ± 8.4 cm, body mass = 58 ± 8.6 kg) were recruited to participate in this study and were eligible in accordance with the following inclusion criteria: (a) age 18–25 years; (b) absence of known cardiovascular, pulmonary, metabolic, bone, or joint diseases; (c) no smoking; (d) no muscle and joint injuries during the last six months. Participants were asked to identify their preferred leg used to kick a ball, which was then identified as the kicking leg (KL). Consequently, the opposite leg was ascertained to be the leg used to jump off when performing a right-handed running basketball layup and was identified as the stance leg (SL) [29]. Participants were divided into faster (top 33%, $n = 13$) and slower (bottom 33%, $n = 13$) performers based on their completion time [17] to test the hypothesis of the effect of COD performance. In addition, participants were divided into a high-playing-level group ($n = 17$), engaged in basketball training and competitions at collegiate and national levels (>3 training sessions per week; >5 years of basketball experience), and a low-playing-level group ($n = 23$), engaged in basketball as a recreational activity (<3 sessions per week), to test the hypothesis of the effect of playing level.

### 2.3. Procedures

Participants reported to the laboratory on two occasions separated by a 72 h resting period at the same time of the day (10:00 ± 30 min), with temperature and humidity kept consistent at 24 ± 1 °C and 55 ± 5%, respectively. They were required to abstain from exercise during the 72 h prior to each experimental session and to abstain from alcohol and caffeine consumption during the 12 h prior.

After ascertaining the inclusion criteria, participants were familiarized with all the experimental procedures during the first experimental session. Moreover, height (cm) and body mass (kg) were measured to the nearest decimal using a Jenix DS-102 stadiometer (Dong Sahn Jenix Co., Ltd., Seoul, South Korea). During the second experimental session, participants performed the modified 505 test (Mod505) [26], in which they were required to sprint forward for 5 m, make a 180° COD while on the force plates, and sprint back for another 5 m. Participants were instructed: (a) to start 0.5 m from the start line with their preferred foot forward in a two-point stance; (b) to have a straight trajectory toward the force plates; (c) to make the COD with the external leg on a visual target (X) highlighted on the middle of the second force plate; (d) to exert maximal effort during the entire course of the test. Participants performed several trials (5 to 7) for each leg (alternating one trial for each leg) with a 2 min resting period in between. A trial was included in the analysis if the participants had a straight trajectory toward the force plates without prior stuttering or prematurely turning prior to final contact and made full contact with the force plates during the three foot-contacts of the turning phase [30]. Inspection of full contacts was performed at the end of each trial using two video cameras synchronized with the Optojump photoelectric system and the force plate software showing the pushing area of the foot. The fastest four trials were considered suitable for analysis and the average value for each investigated variable was used for the statistical analysis.

Participants used the same model of basketball shoes (Adidas Pro Bounce 2019, Herzogenaurach, Germany) to reduce the variability given by the use of different types of sports shoes. Before the experimental session, they completed a standardized warmup involving 3 min of jogging on a treadmill followed by dynamic stretching, squats, frontal and lateral lunges, short accelerations, directional changes, and submaximal trials of the test.

The experimental protocol was executed in a laboratory setting (Figure S1) with the simultaneous use of two adjacent embedded force plates with a sampling rate of 2400 Hz (60 cm $\times$ 90 cm; BMS 600900 OPTIMA™ Biomechanics Measurement Series, AMTI, Watertown, MA, USA) and an Optojump photoelectric system (OptojumpNext, Microgate, Bolzano, Italy) placed beside the force plates, covering the entire 5 m course. The transmitter and receiver bars were placed 2 m apart. Force plates were covered with anti-slip tape to prevent slippage. Moreover, a set of a timing lights system (SMARTSPEED; Fusion Sports, Queensland, Australia) was placed in correspondence with the start/stop line at the hip height of participants to avoid other body parts (unless the lower torso) activating the infrared light.

### 2.4. Data Processing

Due to the use of two adjacent force plates, the definition of the turning phase from one direction to the new direction was achieved, consisting of three consecutive foot contacts: (1) the PFC, defined as the second last foot contact with the first force plate before moving towards a new intended direction [17]; (2) the FFC, defined as the turning foot while in contact with the second force plate to initiate the movement towards a new intended direction [17]; and (3) the AFC, defined as the first accelerating foot contact with the first force plate moving in the new intended direction. The PFC and FFC have been previously investigated [14,17,19], whilst the AFC was first evaluated in this study. A preliminary analysis was completed to verify the composition of each foot contact, using the resultant GRF. Accordingly, the PFC consisted only of a braking phase, whilst the FFC consisted of both the braking and propulsive phases, as already demonstrated in previous research [14,17,19]. In contrast, two executions have been identified for the AFC, with some trials characterized by both braking and propulsive phases and some trials encompassing only a propulsive phase. Therefore, considering the execution of the AFC, each trial for every participant was categorized as a braking/propulsive trial or only-propulsive trial and was included in the analysis in an attempt to explain possible differences for the investigated variables.

Data from force plates were collected using Cortex software (version 3.6.0; Motion Analysis Corp., Santa Rosa, CA, USA), digitally filtered at 25 Hz using a Butterworth low-pass filter, and imported and analyzed with Microsoft Excel (Microsoft Corp, Redmond, WA). The three components of the GRF were vertical (Fz), anterior-posterior (horizontal; Fx), and mediolateral (Fy). Foot contact was defined from the initial contact (touchdown), when the vertical GRF was above a threshold of 10 N, to the final contact (takeoff), when the vertical GRF was below a threshold of 10 N [10,31]. The identification of the braking and propulsive phases was based on the bimodal resultant GRF profile. The braking phase spans from the initial contact to the minimal value between the two peaks, while the propulsive phase spans from the minimal value between the two peaks to the takeoff. Therefore, for AFC classification, the braking/propulsive trials were characterized by a bimodal GRF profile with two peaks, whilst the only-propulsive trials were characterized by a unimodal GRF profile with a single peak (Figure 1).

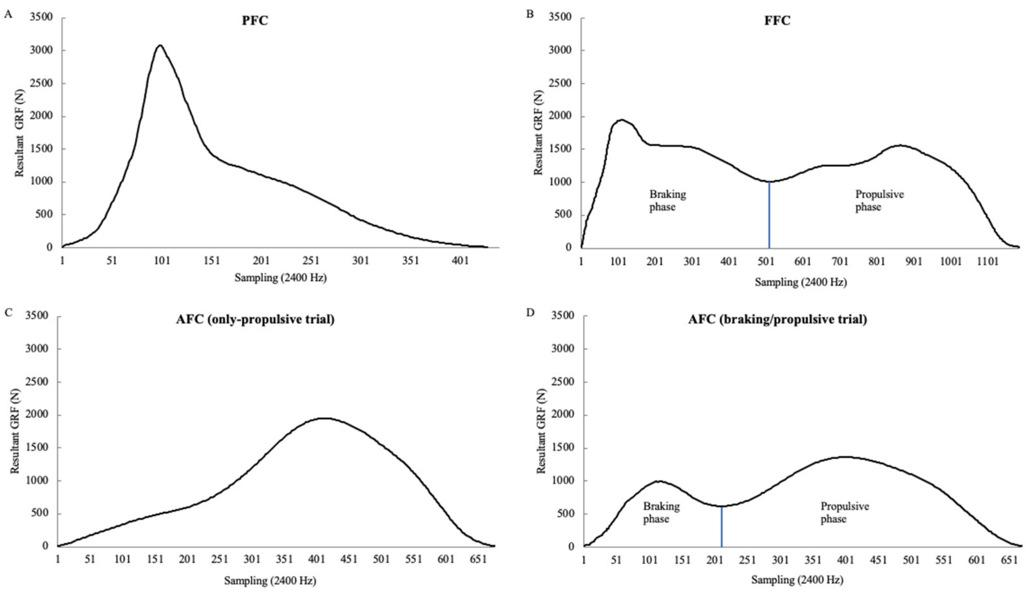


**Figure 1.** Example of vertical ground reaction force (GRF) profiles for (**A**) penultimate foot contact (PFC), (**B**) final foot contact (FFC), and first accelerating foot contact (AFC) in case of (**C**) only-propulsive trials and (**D**) braking/propulsive trials, used for the identification of the braking and propulsive phases.

The variables obtained from the force plates for each foot contact (for either braking, propulsive, or both phases) included: braking, propulsive, and total contact time (CT); peak relative braking and propulsive GRF for both vertical and horizontal components (VGRF and HGRF); relative braking, propulsive, and total impulse for both vertical and horizontal components (VImp and HImp). All GRF and impulse variables were normalized by body mass. Moreover, peak braking and propulsive resultant GRFs were calculated using the Pythagorean theorem [17]:

$$\text{resultant force} = \sqrt{\left(\text{vertical force}^2\right) + \left(\text{horizontal force}^2\right)}$$

The variables derived from the Optojump system (directly provided by the dedicated software, version 1.12.15, OptojumpNext, Microgate, Bolzano, Italy) were step length and approach velocity. Step length was calculated as the tip-to-tip distance from one foot to the next (i.e., right–left, left–right). According to the manufacturer's instructions, velocity was calculated as V = L/(Tc + Tf), where L is step distance, Tc is contact time, and Tf is flight time; all parameters were previously investigated for their reliability in gait analysis [32]. Therefore, approach velocity referred to the velocity at the last foot contact before the turning phase. A preliminary assessment of the data among trials revealed that approach velocity at the last foot contact before the turning phase was the last one with increasing velocity, then the PFC (i.e., the first foot contact of turning phase) consistently showed a decrease in velocity.

Finally, the completion time was measured to the nearest 0.01 s and used as the outcome of COD performance.

The measurement of the investigated variables demonstrated "moderate" to "excellent" internal consistency reliability, ascertained by intraclass correlation coefficients (two-way mixed effects, average measures, absolute agreement). Intraclass correlation coefficients with the 95% confidence intervals are reported in Table S1 in the Supplementary Materials. Furthermore, a recent investigation demonstrated the concurrent validity and internal consistency reliability for the use of the force plate and Optojump system in evaluating the sprint test with a 180° COD [31].

### *2.5. Statistical Analysis*

Data were analyzed using the Statistical Package for the Social Sciences, version 25.0 (SPSS Inc., Chicago, IL, USA). The level of statistical significance was set at $p < 0.05$ for all computations. The normality assumption for each variable was verified using the Shapiro–Wilk test, which confirmed the normal distribution of data.

Since prior analysis showed no gender differences for the investigated variables, data from male and female participants were pooled. Moreover, since the analysis for the stance and kicking legs did not reveal differences, the data were pooled to further increase the sample size. Statistics are provided in Table S2 of the Supplementary Materials.

Differences between braking/propulsive and only-propulsive trials were investigated with paired *t*-test. Cohen's *d* effect sizes (ESs) were calculated and interpreted as trivial (<0.19), small (0.20–0.59), moderate (0.60–1.19), large (1.20–1.99), very large (2.0–4.0), and extremely large effects (>4.0) [33].

Independent sample *t*-tests were applied to ascertain differences between faster and slower performers and between the high-playing-level and low-playing-level groups for both braking/propulsive and only-propulsive trials. Hedges' *g* effect sizes (ESs) were calculated and interpreted as trivial (<0.19), small (0.20–0.59), moderate (0.60–1.19), large (1.20–1.99), very large (2.0–4.0), and extremely large effects (>4.0) [33].

A stepwise multiple regression analysis was separately executed for the braking/propulsive and only-propulsive trials to create a model able to explain the prediction of the completion time from the spatial–temporal and kinetic variables. For braking/propulsive trials, the predictors included in the model were: step length, CT, braking VGRF, HGRF, VImp, and HImp for the PFC; step length, total, braking, and propulsive CT, braking and propulsive VGRF and HGRF, total, braking, and propulsive VImp and HImp for the FFC; step length, total, braking, and propulsive CT, braking and propulsive VGRF and HGRF, total, braking, and propulsive VImp and HImp for the AFC; approach velocity.

For only-propulsive trials, the predictors included in the model were: step length, CT, braking VGRF, HGRF, VImp, and HImp for the PFC; step length, total, braking, and propulsive CT, braking and propulsive VGRF and HGRF, total, braking, and propulsive VImp and HImp for the FFC; step length, CT, propulsive VGRF and HGRF, VImp, and HImp for the AFC; approach velocity. Multicollinearity was ascertained using tolerance and the variation inflation factor (VIF) to verify the degree of correlations among the included predictors. Values lower than 0.20 for tolerance and higher than 10 for VIF denoted the presence of multicollinearity.

## 3. Results

### *3.1. Characterization of the Mod505 Performance and Turning Phase*

A descriptive analysis of the entire course of the Mod505 revealed a total number of between 8 and 10 steps to complete the test. The shortest step length was for the AFC (80.6 ± 9.9 cm), whilst the last step was the longest (154.4 ± 23.4 cm). The approach velocity at the last foot contact before the turning phase was 5.40 ± 0.47 m/s. The turning phase lasted an average of 1.22 ± 0.17 s considering all the trials, representing 44.2% of the average completion time (2.77 ± 0.14 s).

### *3.2. Analysis of Different Executions*

Based on the execution of the AFC, the trials of every participant have been classified as braking/propulsive (65.8%) or only propulsive (34.2%). No differences emerged for completion time (braking/propulsive trials: 2.71 ± 0.13 s; only-propulsive trials: 2.73 ± 0.12 s), approach velocity (braking/propulsive trials: 5.46 ± 0.51 m/s; only-propulsive trials: 5.52 ± 0.46 m/s), and turning phase (braking/propulsive trials: 1.22 ± 0.17 s; only-propulsive trials: 1.23 ± 0.21 s). Significant differences ($p < 0.05$) between trials emerged for braking VGRF and resultant GRF in the PFC, braking and total VImp and braking HImp in the FFC, and propulsive VGRF and HGRF, total VImp, propulsive resultant GRF, and step length in the AFC (Table 1).

**Table 1.** Comparisons of spatial–temporal and kinetic variables during the turning phase between braking/propulsive and only-propulsive trials (mean ± SD).

| | Variables | Braking/Propulsive Trials | Only-Propulsive Trials | *p* (ES) |
|---|---|---|---|---|
| Penultimate Foot Contact | Total CT (s) | 0.385 ± 0.103 | 0.391 ± 0.13 | 0.677 (0.07) |
| | Braking VGRF (N/kg) | 27.0 ± 7.3 | 28.0 ± 7.4 | 0.018 (0.41) |
| | Braking HGRF (N/kg) | 15.1 ± 4.1 | 15.5 ± 4.1 | 0.137 (0.25) |
| | Braking VImp (N·s/kg) | 2.3 ± 0.5 | 2.3 ± 0.4 | 0.654 (0.08) |
| | Braking HImp (N·s/kg) | 1.4 ± 0.3 | 1.4 ± 0.3 | 0.935 (0.01) |
| | Braking resultant GRF (N/kg) | 30.5 ± 8 | 31.6 ± 8.1 | 0.012 (0.44) |
| | Step length (cm) | 113.7 ± 33.9 | 116.7 ± 34.2 | 0.145 (0.24) |
| Final Foot Contact | Braking CT (s) | 0.223 ± 0.036 | 0.230 ± 0.047 | 0.297 (0.18) |
| | Propulsive CT (s) | 0.300 ± 0.055 | 0.301 ± 0.069 | 0.937 (0.01) |
| | Total CT (s) | 0.524 ± 0.07 | 0.534 ± 0.083 | 0.303 (0.17) |
| | Braking VGRF (N/kg) | 21.5 ± 4.9 | 21.9 ± 4.3 | 0.510 (0.11) |
| | Propulsive VGRF (N/kg) | 14.3 ± 1.1 | 14.4 ± 1.3 | 0.260 (0.19) |
| | Braking HGRF (N/kg) | 16.3 ± 3 | 16.7 ± 2.5 | 0.148 (0.24) |
| | Propulsive HGRF (N/kg) | 11.1 ± 1.6 | 10.9 ± 1.4 | 0.177 (0.23) |
| | Braking VImp (N·s/kg) | 2.7 ± 0.4 | 2.8 ± 0.5 | 0.023 (0.40) |
| | Propulsive VImp (N·s/kg) | 3.0 ± 0.5 | 3.1 ± 0.6 | 0.490 (0.12) |
| | Total VImp (N·s/kg) | 5.7 ± 0.6 | 5.9 ± 0.7 | 0.021 (0.40) |
| | Braking HImp (N·s/kg) | 2.2 ± 0.4 | 2.3 ± 0.4 | 0.013 (0.41) |
| | Propulsive HImp (N·s/kg) | 2.3 ± 0.3 | 2.2 ± 0.4 | 0.316 (0.17) |
| | Total HImp (N·s/kg) | 4.4 ± 0.5 | 4.5 ± 0.5 | 0.184 (0.22) |
| | Braking resultant GRF (N/kg) | 27.0 ± 5.4 | 27.3 ± 4.8 | 0.632 (0.08) |
| | Propulsive resultant GRF (N/kg) | 18.1 ± 1.7 | 18.7 ± 4 | 0.312 (0.17) |
| | Step length (cm) | 91.0 ± 13.5 | 92.3 ± 11.9 | 0.425 (0.13) |
| First Accelerating Foot Contact | Braking CT (s) | 0.089 ± 0.032 | N/A | N/A |
| | Propulsive CT (s) | 0.224 ± 0.048 | N/A | N/A |
| | Total CT (s) | 0.313 ± 0.065 | 0.301 ± 0.06 | 0.219 (0.21) |
| | Braking HGRF (N/kg) | 8.9 ± 2.8 | N/A | N/A |
| | Propulsive VGRF (N/kg) | 16.1 ± 1.9 | 16.7 ± 1.9 | 0.007 (0.48) |
| | Braking HGRF (N/kg) | 4.6 ± 1.6 | N/A | N/A |
| | Propulsive HGRF (N/kg) | 9.0 ± 1.4 | 9.3 ± 1.3 | 0.016 (0.42) |
| | Braking VImp (N·s/kg) | 0.5 ± 0.2 | N/A | N/A |
| | Propulsive VImp (N·s/kg) | 2.2 ± 0.4 | N/A | N/A |
| | Total VImp (N·s/kg) | 2.7 ± 0.3 | 2.6 ± 0.3 | 0.005 (0.50) |
| | Braking HImp (N·s/kg) | 0.2 ± 0.1 | N/A | N/A |
| | Propulsive HImp (N·s/kg) | 1.2 ± 0.2 | N/A | N/A |
| | Total HImp (N·s/kg) | 1.4 ± 0.1 | 1.4 ± 0.2 | 0.162 (0.02) |
| | Braking resultant GRF (N/kg) | 9.6 ± 3.2 | N/A | N/A |
| | Propulsive resultant GRF (N/kg) | 18.4 ± 2.2 | 19.0 ± 2 | 0.020 (0.41) |
| | Step length (cm) | 81.8 ± 9.6 | 77.9 ± 10.8 | 0.024 (0.38) |

Note: AU = arbitrary unit; CT = contact time; ES = effect size; HGRF = horizontal ground reaction force; HImp = horizontal impulse; N/A = not available; VGRF = vertical ground reaction force; VImp = vertical impulse.

### *3.3. Analysis of COD Performance*

Faster performers (completion time = 2.61 ± 0.07 s) revealed higher values for approach velocity (faster: 5.72 ± 0.42 m/s; slower: 5.13 ± 0.36 m/s; $p < 0.001$, ES = 1.51) compared with slower performers (completion time = 2.92 ± 0.06 s). For step length, differences between faster and slower performers emerged in the PFC (faster: 126 ± 32.2 cm; slower: 96.8 ± 31.4 cm; $p = 0.005$, ES = 0.92) and the FFC (faster: 95 ± 9.3 cm; slower: 85.2 ± 14.6 cm; $p = 0.011$, ES = 0.82) for the braking/propulsive trials, whilst only in the PFC (faster: 123.3 ± 31.2 cm; slower: 97.9 ± 37.6 cm; $p = 0.042$, ES = 0.75) for the only-propulsive trials, compared with slower performers A similar time for turning phase emerged for both braking/propulsive (faster: 1.19 ± 0.11 s; slower: 1.22 ± 0.13 s; $p = 0.343$; ES = −0.29) and only-propulsive (faster: 1.21 ± 0.14 s; slower: 1.18 ± 0.13 s; $p = 0.556$; ES = 0.22) trials. Significant differences ($p < 0.05$) between faster and slower performers emerged for kinetic variables and are presented in Table 2. For braking/propulsive trials, faster performers exhibited: (a) greater braking VGRF, HGRF, HImp, and resultant GRF in the PFC; (b) greater braking and propulsive HGRF, braking HImp, propulsive resultant GRF, lower propulsive and total CT, and propulsive and total VImp in the FFC; (c) greater propulsive HGRF, propulsive and total HImp, propulsive resultant GRF, lower propulsive CT, and propulsive and total VImp in the AFC, compared with slower performers. For only-propulsive trials, faster performers exhibited: (a) greater braking HGRF in the PFC; (b) greater braking and propulsive HGRF, braking and total HImp, and lower propulsive VImp in the FFC; (c) greater propulsive HGRF and HImp in the AFC, compared with slower performers.

**Table 2.** Comparison of kinetic variables during the turning phase between faster and slower performers for braking/propulsive and only-propulsive trials (mean ± SD).

| | Variables | Braking/Propulsive Trials | | | Only-Propulsive Trials | | |
|---|---|---|---|---|---|---|---|
| | | Faster | Slower | *p* (ES) | Faster | Slower | *p* (ES) |
| Penultimate Foot Contact | Total CT (s) | 0.392 ± 0.068 | 0.355 ± 0.084 | 0.119 (0.48) | 0.403 ± 0.084 | 0.352 ± 0.091 | 0.116 (0.58) |
| | Braking VGRF (N/kg) | 29.2 ± 8.8 | 24.1 ± 7.1 | 0.046 (0.62) | 29.4 ± 7.6 | 25.7 ± 6.3 | 0.163 (0.52) |
| | Braking HGRF (N/kg) | 16.2 ± 4 | 12.4 ± 4.2 | 0.005 (0.91) | 16.7 ± 3.6 | 12.9 ± 3.6 | 0.005 (1.06) |
| | Braking VImp (N·s/kg) | 2.3 ± 0.3 | 2.1 ± 0.5 | 0.066 (0.57) | 2.2 ± 0.4 | 2.4 ± 0.5 | 0.201 (−0.47) |
| | Braking HImp (N·s/kg) | 1.5 ± 0.2 | 1.2 ± 0.3 | <0.001 (1.3) | 1.4 ± 0.2 | 1.3 ± 0.2 | 0.145 (0.53) |
| | Braking resultant GRF (N/kg) | 32.4 ± 8.9 | 26.7 ± 7.7 | 0.03 (0.68) | 33.1 ± 8 | 28.5 ± 6.8 | 0.099 (0.62) |
| Final Foot Contact | Braking CT (s) | 0.227 ± 0.04 | 0.223 ± 0.036 | 0.724 (0.11) | 0.231 ± 0.056 | 0.233 ± 0.047 | 0.915 (−0.04) |
| | Propulsive CT (s) | 0.277 ± 0.044 | 0.330 ± 0.055 | 0.001 (−1.1) | 0.275 ± 0.049 | 0.317 ± 0.069 | 0.055 (−0.72) |
| | Total CT (s) | 0.504 ± 0.059 | 0.552 ± 0.074 | 0.02 (−0.73) | 0.506 ± 0.069 | 0.556 ± 0.094 | 0.091 (−0.63) |
| | Braking VGRF (N/kg) | 20.8 ± 3.9 | 20.5 ± 3.3 | 0.789 (0.08) | 21.3 ± 3.5 | 21.4 ± 5.2 | 0.927 (−0.03) |
| | Propulsive VGRF (N/kg) | 14.4 ± 1 | 13.9 ± 0.9 | 0.088 (0.53) | 14.7 ± 1.2 | 15.2 ± 0.9 | 0.204 (−0.47) |
| | Braking HGRF (N/kg) | 17.1 ± 2.7 | 15.0 ± 2.5 | 0.012 (0.82) | 17.4 ± 2.5 | 14.5 ± 1.9 | 0.001 (1.29) |
| | Propulsive HGRF (N/kg) | 11.9 ± 1.6 | 10.0 ± 0.9 | <0.001 (1.45) | 11.7 ± 1.5 | 10.6 ± 0.9 | 0.031 (0.79) |
| | Braking VImp (N·s/kg) | 2.7 ± 0.4 | 2.6 ± 0.4 | 0.316 (0.31) | 2.9 ± 0.6 | 2.7 ± 0.6 | 0.567 (0.21) |
| | Propulsive VImp (N·s/kg) | 2.8 ± 0.4 | 3.3 ± 0.5 | <0.001 (−1.17) | 2.9 ± 0.4 | 3.4 ± 0.7 | 0.025 (−0.86) |
| | Total VImp (N·s/kg) | 5.5 ± 0.5 | 5.9 ± 0.7 | 0.043 (−0.63) | 5.8 ± 0.5 | 6.1 ± 0.9 | 0.19 (−0.48) |
| | Braking HImp (N·s/kg) | 2.3 ± 0.4 | 1.9 ± 0.4 | 0.001 (1.08) | 2.4 ± 0.4 | 1.9 ± 0.4 | 0.004 (1.11) |
| | Propulsive HImp (N·s/kg) | 2.2 ± 0.3 | 2.3 ± 0.3 | 0.231 (−0.38) | 2.3 ± 0.3 | 2.3 ± 0.4 | 0.918 (−0.04) |
| | Total HImp (N·s/kg) | 4.5 ± 0.4 | 4.3 ± 0.5 | 0.054 (0.61) | 4.7 ± 0.3 | 4.2 ± 0.6 | 0.006 (1.03) |
| | Braking resultant GRF (N/kg) | 26.7 ± 4.6 | 25.2 ± 3.8 | 0.248 (0.35) | 27.4 ± 4.3 | 25.7 ± 5.1 | 0.333 (0.36) |
| | Propulsive resultant GRF (N/kg) | 18.6 ± 1.7 | 17.1 ± 1.2 | 0.002 (1) | 18.7 ± 1.8 | 18.6 ± 1.1 | 0.869 (0.06) |
| First Accelerating Foot contact | Braking CT (s) | 0.089 ± 0.035 | 0.088 ± 0.027 | 0.913 (0.03) | N/A | N/A | N/A |
| | Propulsive CT (s) | 0.203 ± 0.03 | 0.230 ± 0.038 | 0.012 (−0.8) | N/A | N/A | N/A |
| | Total CT (s) | 0.293 ± 0.052 | 0.316 ± 0.047 | 0.133 (−0.46) | 0.299 ± 0.058 | 0.270 ± 0.048 | 0.143 (0.54) |
| | Braking VGRF (N/kg) | 8.8 ± 2.9 | 9.3 ± 2.9 | 0.579 (−0.17) | N/A | N/A | N/A |
| | Propulsive VGRF (N/kg) | 16.0 ± 2 | 15.2 ± 1.6 | 0.162 (0.43) | 17.0 ± 2.1 | 17.0 ± 1.5 | 0.996 (0) |
| | Braking HGRF (N/kg) | 4.8 ± 1.5 | 4.4 ± 1.8 | 0.418 (0.25) | N/A | N/A | N/A |
| | Propulsive HGRF (N/kg) | 9.6 ± 1.1 | 7.6 ± 1 | <0.001 (1.82) | 10.0 ± 1 | 8.7 ± 1.2 | 0.003 (1.12) |
| | Braking VImp (N·s/kg) | 0.4 ± 0.2 | 0.5 ± 0.2 | 0.133 (−0.46) | N/A | N/A | N/A |
| | Propulsive VImp (N·s/kg) | 2.1 ± 0.3 | 2.3 ± 0.4 | 0.022 (−0.72) | 2.5 ± 0.3 | 2.5 ± 0.2 | 0.705 (−0.14) |
| | Total VImp (N·s/kg) | 2.5 ± 0.3 | 2.8 ± 0.4 | 0.003 (−0.96) | N/A | N/A | N/A |
| | Braking HImp (N·s/kg) | 0.2 ± 0.1 | 0.2 ± 0.1 | 0.53 (−0.2) | N/A | N/A | N/A |
| | Propulsive HImp (N·s/kg) | 1.2 ± 0.1 | 1.1 ± 0.2 | 0.014 (0.79) | 1.4 ± 0.2 | 1.3 ± 0.1 | 0.004 (1.09) |
| | Total HImp (N·s/kg) | 1.5 ± 0.1 | 1.3 ± 0.3 | 0.045 (0.64) | N/A | N/A | N/A |
| | Braking resultant GRF (N/kg) | 9.9 ± 3 | 9.5 ± 3.7 | 0.637 (0.14) | N/A | N/A | N/A |
| | Propulsive resultant GRF (N/kg) | 18.6 ± 2.4 | 16.9 ± 1.7 | 0.013 (0.78) | 19.6 ± 2.2 | 18.9 ± 1.7 | 0.362 (0.33) |

Note: AU = arbitrary unit; CT = contact time; ES = effect size; HGRF = horizontal ground reaction force; HImp = horizontal impulse; N/A = not available; VGRF = vertical ground reaction force; VImp = vertical impulse.

### 3.4. Analysis of Playing Level

A significant difference emerged for height (high playing level: 181.4 ± 6 cm; low playing level: 172.1 ± 10 cm; $p = 0.001$; ES = 1.13), but not for body mass (high playing level: 76.4 ± 9 kg; low playing level: 69.5 ± 12 kg; $p = 0.59$; ES = 0.65).

The high-playing-level group demonstrated a shorter completion time (high playing level: 2.69 ± 0.14 s; low playing level: 2.82 ± 0.11 s; $p < 0.001$, ES = −1.05), a higher approach velocity (high playing level: 5.68 ± 0.44 m/s; low playing level: 5.19 ± 0.38 m/s;

$p < 0.001$, ES = −1.21), and a longer step length for PFC (high playing level: 129.4 ± 29.5 cm; low playing level: 103.4 ± 31.6 cm; $p < 0.001$, ES = 0.85) and FFC (high playing level: 97.2 ± 7.4 cm; low playing level: 86.6 ± 10.8 cm; $p < 0.001$, ES = 1.12). A similar time for turning phase emerged for both braking/propulsive (high playing level: 1.20 ± 0.12 s; low playing level: 1.24 ± 0.17 s; $p = 0.369$, ES = −0.22) and only-propulsive (high playing level: 1.21 ± 0.16 s; low playing level: 1.23 ± 0.21 s; $p = 0.672$, ES = −0.12) trials. Significant differences ($p < 0.05$) between the high-playing-level and low-playing-level groups emerged for kinetic variables and are presented in Table 3. For braking/propulsive trials, the high-playing-level group exhibited: (a) greater braking VGRF, HGRF, VImp, HImp, and resultant GRF in the PFC; (b) greater braking and propulsive VGRF, propulsive HGRF, braking VImp, HImp, total HImp, and propulsive resultant GRF in the FFC; (c) greater propulsive VGRF and HGRF, braking HGRF, total HImp, propulsive and braking resultant GRF, and lower propulsive and total CT in the AFC, compared with the low-playing-level group. For only-propulsive trials, the high-playing-level group exhibited: (a) greater braking VGRF, HGRF, and resultant GRF in the PFC; (b) greater braking VGRF, VImp and HImp, total HImp, and braking resultant GRF in the FFC; (c) greater propulsive HGRF and HImp in the AFC, compared with the low-playing-level group.

**Table 3.** Comparison of kinetic variables during the turning phase between the high- and low-playing-level groups for braking/propulsive and only-propulsive trials (mean ± SD).

| | Variables | Braking/Propulsive Trials | | | Only-Propulsive Trials | | |
|---|---|---|---|---|---|---|---|
| | | High Playing Level | Low Playing Level | *p* (ES) | High Playing Level | Low Playing Level | *p* (ES) |
| Penultimate Foot Contact | Total CT (s) | 0.381 ± 0.081 | 0.383 ± 0.1 | 0.902 (−0.03) | 0.378 ± 0.098 | 0.405 ± 0.141 | 0.454 (−0.22) |
| | Braking VGRF (N/kg) | 31.2 ± 7.3 | 23.5 ± 7.1 | <0.001 (1.08) | 31.4 ± 5.5 | 24.2 ± 7.1 | <0.001 (1.14) |
| | Braking HGRF (N/kg) | 16.6 ± 3.3 | 13.2 ± 4.3 | 0.001 (0.86) | 16.9 ± 3 | 13.5 ± 4.4 | 0.002 (0.91) |
| | Braking VImp (N·s/kg) | 2.5 ± 0.3 | 2.2 ± 0.5 | 0.007 (0.68) | 2.4 ± 0.4 | 2.2 ± 0.5 | 0.144 (0.43) |
| | Braking HImp (N·s/kg) | 1.5 ± 0.2 | 1.3 ± 0.3 | 0.001 (0.85) | 1.4 ± 0.2 | 1.3 ± 0.3 | 0.076 (0.51) |
| | Braking resultant GRF (N/kg) | 34.4 ± 7.4 | 26.4 ± 7.8 | <0.001 (1.05) | 34.9 ± 5.9 | 27.6 ± 8.1 | 0.001 (1.05) |
| Final Foot Contact | Braking CT (s) | 0.233 ± 0.031 | 0.216 ± 0.043 | 0.081 (0.43) | 0.239 ± 0.05 | 0.215 ± 0.035 | 0.062 (0.56) |
| | Propulsive CT (s) | 0.298 ± 0.037 | 0.313 ± 0.059 | 0.225 (−0.30) | 0.295 ± 0.058 | 0.308 ± 0.076 | 0.531 (−0.18) |
| | Total CT (s) | 0.531 ± 0.047 | 0.528 ± 0.071 | 0.858 (0.04) | 0.535 ± 0.072 | 0.527 ± 0.093 | 0.745 (0.10) |
| | Braking VGRF (N/kg) | 22.3 ± 5.2 | 20.2 ± 3 | 0.037 (0.52) | 23.4 ± 5.3 | 20.3 ± 2.7 | 0.017 (0.72) |
| | Propulsive VGRF (N/kg) | 14.7 ± 1 | 13.8 ± 1.2 | 0.001 (0.81) | 14.9 ± 1.2 | 14.3 ± 1.3 | 0.088 (0.51) |
| | Braking HGRF (N/kg) | 16.5 ± 2.5 | 15.8 ± 2.7 | 0.246 (0.29) | 17.0 ± 2.5 | 16.0 ± 2.5 | 0.190 (0.38) |
| | Propulsive HGRF (N/kg) | 11.5 ± 1.3 | 10.4 ± 1.4 | 0.001 (0.87) | 11.2 ± 1.3 | 10.7 ± 1.3 | 0.151 (0.41) |
| | Braking VImp (N·s/kg) | 2.8 ± 0.3 | 2.6 ± 0.5 | 0.013 (0.62) | 3.0 ± 0.5 | 2.6 ± 0.4 | 0.008 (0.81) |
| | Propulsive VImp (N·s/kg) | 3 ± 0.4 | 3.1 ± 0.6 | 0.386 (−0.213) | 3.1 ± 0.6 | 3.2 ± 0.7 | 0.546 (−0.18) |
| | Total VImp (N·s/kg) | 5.8 ± 0.5 | 5.7 ± 0.6 | 0.258 (0.28) | 6.0 ± 0.6 | 5.8 ± 0.8 | 0.212 (0.37) |
| | Braking HImp (N·s/kg) | 2.3 ± 0.3 | 2.0 ± 0.4 | 0.001 (0.83) | 2.4 ± 0.4 | 2.0 ± 0.4 | 0.004 (0.86) |
| | Propulsive HImp (N·s/kg) | 2.3 ± 0.3 | 2.2 ± 0.3 | 0.579 (0.14) | 2.3 ± 0.4 | 2.2 ± 0.4 | 0.661 (0.12) |
| | Total HImp (N·s/kg) | 4.6 ± 0.4 | 4.3 ± 0.5 | 0.002 (0.81) | 4.7 ± 0.4 | 4.3 ± 0.5 | 0.002 (0.93) |
| | Braking resultant GRF (N/kg) | 27.7 ± 5.4 | 25.5 ± 3.7 | 0.05 (0.49) | 28.8 ± 5.5 | 25.5 ± 3.3 | 0.016 (0.73) |
| | Propulsive resultant GRF (N/kg) | 18.7 ± 1.3 | 17.1 ± 1.7 | <0.001 (1.01) | 19.6 ± 4.5 | 17.8 ± 1.7 | 0.076 (0.53) |
| First Accelerating Foot Contact | Braking CT (s) | 0.090 ± 0.037 | 0.087 ± 0.029 | 0.745 (0.08) | N/A | N/A | N/A |
| | Propulsive CT (s) | 0.202 ± 0.03 | 0.237 ± 0.053 | 0.003 (−0.77) | N/A | N/A | N/A |
| | Total CT (s) | 0.290 ± 0.055 | 0.324 ± 0.06 | 0.021 (−0.58) | 0.297 ± 0.066 | 0.302 ± 0.053 | 0.780 (−0.08) |
| | Braking VGRF (N/kg) | 9.6 ± 2.4 | 8.4 ± 3 | 0.07 (0.45) | N/A | N/A | N/A |
| | Propulsive VGRF (N/kg) | 16.3 ± 2 | 15.3 ± 1.6 | 0.025 (0.56) | 16.6 ± 2.1 | 16.6 ± 1.4 | 0.952 (−0.02) |
| | Braking HGRF (N/kg) | 5.2 ± 1.3 | 4.2 ± 1.6 | 0.009 (0.67) | N/A | N/A | N/A |
| | Propulsive HGRF (N/kg) | 9.6 ± 1.2 | 8.1 ± 1.3 | <0.001 (1.19) | 9.6 ± 1.2 | 8.7 ± 1.1 | 0.008 (0.78) |
| | Braking VImp (N·s/kg) | 0.5 ± 0.2 | 0.4 ± 0.2 | 0.537 (0.15) | N/A | N/A | N/A |
| | Propulsive VImp (N·s/kg) | 2.2 ± 0.3 | 2.3 ± 0.4 | 0.056 (−0.47) | 2.5 ± 0.3 | 2.6 ± 0.3 | 0.513 (−0.19) |
| | Total VImp (N·s/kg) | 2.6 ± 0.3 | 2.8 ± 0.4 | 0.07 (0.45) | N/A | N/A | N/A |
| | Braking HImp (N·s/kg) | 0.2 ± 0.1 | 0.2 ± 0.1 | 0.282 (0.27) | N/A | N/A | N/A |
| | Propulsive HImp (N·s/kg) | 1.2 ± 0.1 | 1.2 ± 0.2 | 0.099 (0.42) | 1.4 ± 0.2 | 1.3 ± 0.1 | 0.04 (0.6) |
| | Total HImp (N·s/kg) | 1.5 ± 0.1 | 1.4 ± 0.2 | 0.015 (0.62) | N/A | N/A | N/A |
| | Braking resultant GRF (N/kg) | 10.8 ± 2.5 | 8.8 ± 3.3 | 0.007 (0.67) | N/A | N/A | N/A |
| | Propulsive resultant GRF (N/kg) | 18.8 ± 2.2 | 17.2 ± 1.9 | 0.001 (0.83) | 19 ± 2.2 | 18.8 ± 1.6 | 0.623 (0.14) |

Note: AU = arbitrary unit; CT = contact time; ES = effect size; HGRF = horizontal ground reaction force; HImp = horizontal impulse; N/A = not available; VGRF = vertical ground reaction force; VImp = vertical impulse.

### 3.5. Stepwise Multiple Regression Analysis

Table 4 shows the steps necessary to create the model for both braking/propulsive and only-propulsive trials. For braking/propulsive trials, model five has been identified to better predict the completion time, including the five predictors (i.e., FFC propulsive HGRF, AFC propulsive HGRF, FFC propulsive VGRF, AFC Total VImp, and AFC step length) that explain 75% of the common variance (Table 5). For the only-propulsive trials, model six has been identified to better predict the completion time, including the six predictors (i.e., approach velocity, FFC braking HGRF, FFC braking VGRF, AFC propulsive HGRF, FFC total CT, and AFC propulsive VGRF) that explain 76.2% of the common variance (Table 5). Data for correlations (partial and part) and collinearity analysis have been reported for the predictors included in both models for braking/propulsive and only-propulsive trials (Table 5). In particular, the lack of multicollinearity is demonstrated from the values higher than 0.20 for tolerance and lower than 10 for VIF for all the predictors included in the models.

**Table 4.** Models derived from the stepwise multiple regression analysis.

| | Model | R | $R^2$ | Adjusted $R^2$ | SEE | F | *p* |
|---|---|---|---|---|---|---|---|
| Braking/Propulsive Trials | 1 | 0.708 | 0.501 | 0.493 | 0.100 | 65.3 | <0.001 |
| | 2 | 0.763 | 0.582 | 0.569 | 0.092 | 44.5 | <0.001 |
| | 3 | 0.843 | 0.711 | 0.697 | 0.077 | 51.6 | <0.001 |
| | 4 | 0.856 | 0.733 | 0.716 | 0.075 | 42.6 | <0.001 |
| | 5 | 0.866 | 0.750 | 0.730 | 0.073 | 36.7 | <0.001 |
| Only-Propulsive Trials | 1 | 0.536 | 0.287 | 0.271 | 0.123 | 17.3 | <0.001 |
| | 2 | 0.726 | 0.527 | 0.504 | 0.101 | 23.4 | <0.001 |
| | 3 | 0.813 | 0.661 | 0.636 | 0.087 | 26.6 | <0.001 |
| | 4 | 0.834 | 0.695 | 0.665 | 0.083 | 22.8 | <0.001 |
| | 5 | 0.857 | 0.734 | 0.700 | 0.079 | 21.5 | <0.001 |
| | 6 | 0.873 | 0.762 | 0.725 | 0.075 | 20.3 | <0.001 |

Note: For braking/propulsive trials: 1. FFC propulsive HGRF; 2. FFC propulsive HGRF, AFC propulsive HGRF; 3. FFC propulsive HGRF, AFC propulsive HGRF, FFC propulsive VGRF; 4. FFC propulsive HGRF, AFC propulsive HGRF, FFC propulsive VGRF, AFC Total VImp; 5. FFC propulsive HGRF, AFC propulsive HGRF, FFC propulsive VGRF, AFC Total VImp, AFC step length. For only-propulsive trials: 1. Approach velocity; 2. Approach velocity, FFC braking HGRF; 3. Approach velocity, FFC braking HGRF, FFC braking VGRF; 4. Approach velocity, FFC braking HGRF, FFC braking VGRF, AFC propulsive HGRF; 5. Approach velocity, FFC braking HGRF, FFC braking VGRF, AFC propulsive HGRF, FFC total CT; 6. Approach velocity, FFC braking HGRF, FFC braking VGRF, AFC propulsive HGRF, FFC total CT, AFC propulsive VGRF. AFC = first accelerating foot contact; CT = contact time; FFC = final foot contact; HGRF = horizontal ground reaction force; SEE = standard error of estimate; VGRF = vertical ground reaction force; VImp = vertical impulse.

**Table 5.** Predictive variables of completion time.

| | Model | Unstandardized Coefficients B | Unstandardized Coefficients Std. Error | Standardized Coefficients Beta | t (*p*) | 95% CI for B Lower Bound | 95% CI for B Upper Bound | Correlations Partial * | Correlations Part # | Collinearity Statistics Tolerance | Collinearity Statistics VIF |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Braking/Propulsive Trials | (Constant) | 3.087 | 0.174 | | 17.721 (<0.001) | 2.738 | 3.435 | | | | |
| | FFC propulsive HGRF | −0.076 | 0.009 | −0.771 | −8.520 (<0.001) | −0.093 | −0.058 | −0.737 | −0.545 | 0.500 | 2.001 |
| | AFC propulsive HGRF | −0.049 | 0.008 | −0.500 | −6.147 (<0.001) | −0.065 | −0.033 | −0.618 | −0.393 | 0.619 | 1.616 |
| | FFC propulsive VGRF | 0.061 | 0.011 | 0.522 | 5.409 (<0.001) | 0.038 | 0.083 | 0.569 | 0.346 | 0.440 | 2.274 |
| | AFC total VImp | 0.081 | 0.029 | 0.199 | 2.771 (0.007) | 0.023 | 0.139 | 0.334 | 0.177 | 0.796 | 1.257 |
| | AFC step length | −0.002 | 0.001 | −0.144 | −2.051 (0.045) | −0.004 | <−0.0001 | −0.254 | −0.131 | 0.831 | 1.203 |
| Only-Propulsive Trials | (Constant) | 3.522 | 0.208 | | 16.904 (<0.001) | 3.100 | 3.944 | | | | |
| | Approach velocity | −0.095 | 0.026 | −0.321 | −3.684 (0.001) | −0.147 | −0.043 | −0.051 | −0.291 | 0.821 | 1.217 |
| | FFC braking HGRF | −0.030 | 0.007 | −0.551 | −4.569 (<0.001) | −0.044 | −0.017 | −0.595 | −0.361 | 0420 | 2.326 |
| | FFC braking VGRF | 0.009 | 0.004 | 0.274 | 2.180 (0.035) | 0.001 | 0.016 | 0.333 | 0.172 | 0.397 | 2.516 |
| | AFC propulsive HGRF | −0.048 | 0.014 | −0.403 | −3.543 (0.001) | −0.075 | −0.021 | −0.498 | −0.280 | 0.484 | 2.064 |
| | FFC total CT | 0.402 | 0.178 | 0.217 | 2.253 (0.03) | 0.041 | 0.762 | 0.343 | 0.178 | 0.675 | 1.482 |
| | AFC propulsive VGRF | 0.018 | 0.008 | 0.226 | 2.122 (0.04) | 0.001 | 0.035 | 0.325 | 0.168 | 0.553 | 1.807 |

Note: AFC = first accelerating foot contact; CI = confidence interval; CT = contact time; FFC = final foot contact; HGRF = horizontal ground reaction force; VGRF = vertical ground reaction force; VImp = vertical impulse. * Shared contributions of the predictors. # Unique contributions of the predictors.

## 4. Discussion

This study intended to examine the effects of leg preference, COD performance, and playing level and to explore the prediction of the completion time from spatial–temporal and kinetic variables. The main finding of this study is a superior performance of faster performers and the high-playing-level group (Tables 2 and 3). Moreover, this study demonstrated for the first time the predictive variables of completion time (Table 5). The novelty of this study is the inclusion of the first accelerating foot contact in the analysis together with the penultimate and final foot contacts, revealing different executions. The lack of leg preference in making directional changes supports the controversy regarding the influence of interlimb asymmetries on sports performance. However, the inconsistency in evidence for interlimb asymmetries also depends on a lack of consensus regarding the definition and determination of leg preference and/or dominance [34,35].

A descriptive analysis shows that the AFC is characterized by lower values for contact time, braking GRF and impulse in both vertical and horizontal components, and resultant GRF compared with the PFC and FFC. Moreover, the AFC also revealed a shorter step length compared with the PFC and FFC. In particular, shorter contact times and step lengths might be expected to be necessary for the reacceleration in a new direction, given that AFC is the first foot contact after turning when the horizontal velocity of the center of mass is zero.

The finding of the different executions of the AFC was unexpected, with a higher proportion of the trials indicating braking before the propulsive phase, even though a full explanation has not been reached with this investigation. In fact, when braking/propulsive and only-propulsive trials were compared with spatial–temporal and kinetic variables (Table 1), marginal differences were found in the PFC and FFC, whereas in the AFC, higher values for propulsive vertical, horizontal, and resultant GRFs were found for the only-propulsive trials. However, the total vertical impulse was higher for the braking/propulsive trials, which can be explained by the further contribution of the impulse during the braking phase. Moreover, a difference in step length emerged between trials, with the braking/propulsive trials showing a longer AFC step length compared with the only-propulsive ones. Therefore, the presence of the braking phase could be attributed to the longer step length of the AFC. In fact, this longer step length may require a supporting base at the initial contact resulting in the application of the braking force. This action will also require the application of the SSC with the braking phase (i.e., eccentric action) acting to store elastic strain energy, which is subsequently recovered during the propulsive phase (i.e., concentric action) [36]. It is well-documented that the enhancement of sports performance can be achieved through the amplification of the force and power produced during the shortening cycle as a consequence of the previous elastic strain energy stored during the lengthening cycle [5,36]. In contrast, in the only-propulsive trials, the shorter step length allowed for the immediate exertion of the propulsive phase without the need to accumulate elastic energy in a braking phase. This may also reflect the existence of a different foot strike pattern between the two executions. It can be speculated that in the braking/propulsive trials, the foot contact comprised the rearfoot strike pattern, whilst a forefoot strike pattern was used in the only-propulsive trials [37]. Considering this first attempt to characterize the AFC and the observation of different executions, further research to confirm the first findings obtained by this study is highly recommended.

In line with previous research on COD performance [15–18], the current study demonstrated differences between faster and slower performers. The higher approach velocities for faster performers are in accordance with previous research on 505 tests [17] and athletes with higher eccentric strength [30]. Recently, approach velocity has been recognized as an important factor influencing COD performance, together with the angle of the COD (e.g., from 45° to 180°) [13]. Therefore, this study can contribute new evidence to the existing knowledge about approach velocity, using a photoelectric system for its determination. Further evidence is also provided for the step length, showing that a faster performance required longer steps length in the PFC and FFC, whilst no differences emerged for the AFC.

Regarding kinetic variables, several profiles and characteristics can be highlighted. For the PFC, the results demonstrate greater values for braking vertical and horizontal GRFs, horizontal impulse, and resultant GRF for faster performers, even though the contact times were similar. Therefore, for the same ground contact time, a higher force was exerted. Considering the higher approach velocities, these results might indicate that higher force production is necessary for the deceleration of the body [17]. Moreover, a higher force production has been associated with superior movement mechanisms and strength capacity, hence increasing the exit velocity during COD movements [16,38]. In particular, eccentric strength has been determined as the sole predictor of a 505 test in a sample of female basketball players [38]. Therefore, the single braking phase characterizing the PFC may explain the need for higher eccentric action to decelerate the body. For the FFC, higher values of horizontal GRF in both braking and propulsive phases, coupled with shorter total contact times, vertical propulsive, and total impulses, may confirm an efficient application of the SSC [17]. Considering that the FFC consisted of both braking and propulsive phases, faster performers might display superior ability in maximizing the application of the SSC, compared with their slower counterparts [17], based on the shorter ground contact times and impulses in the vertical component. Similarly, considering the braking/propulsive trials of the AFC, faster performers demonstrated lower values for contact time and vertical propulsive and total impulses, which can be required to accelerate the body. Therefore, the comparisons of kinetic variables between faster and slower performers may explain the action of foot contacts, with the PFC and FFC remaining critical foot contacts for reducing the momentum of the center of mass [15,19], whilst the AFC is important for the acceleration of the body in the new direction.

Higher- and lower-skilled athletes have been commonly investigated for completion time, revealing COD speed tests are not able to discriminate playing level [23–27]. Conversely, in this study, the high-playing-level group had a lower completion time and a higher approach velocity. These results may have also determined the longer step lengths and the higher values for force-related variables in both the PFC and FFC compared with the low-playing-level group, even though similarities existed for the contact times. Greater force production during the braking phase in the PFC is required to start reducing the momentum of the center of mass due to the higher approach velocity [17]. However, contradictory results emerged in the FFC, with higher values for GRFs in both braking and propulsive phases, but also for impulses, which prevent the confirmation of a superior application of the SSC. Regarding the AFC, the high-playing-level group exhibited shorter contact times, as a result of the shorter propulsive phase, and higher values for GRFs during the propulsive phase, but only a difference for the total horizontal impulse. A superior reacceleration capacity in the new direction for the AFC is still speculated. However, the effect of playing level on spatial–temporal and kinetic variables may require further investigation to confirm the presented findings.

The regression analysis was proposed to explore the prediction of the completion time from spatial–temporal and kinetic variables. Different models emerged for braking/propulsive and only-propulsive trials, comprising variables of the FFC and AFC, with $\geq$75% of the variance of completion time being explained. The propulsive horizontal GRF of the AFC was the only variable in common between the two trials. This result, combined with the higher propulsive horizontal GRF values found for faster performers and the high-playing-level group in both braking/propulsive and only-propulsive trials, might highlight the role of this variable as an important determinant of COD performance. The total vertical impulse and step length of the AFC were also included in the model for the braking/propulsive trials, together with propulsive horizontal and vertical GRF of the FFC. Therefore, the predictive analysis showed the importance of including the AFC in the assessment of a 180° COD test for a complete characterization of the turning phase. Conversely, none of the variables of the PFC were included in both models, even though the PFC has always been considered a critical determinant of the COD performance [14]. Moreover, recent research suggests that the antepenultimate foot contact might play a superior role in deceleration compared with the PFC [18]. Unfortunately, the antepenultimate foot contact was not included in the current investigation. However, we suggest that the turning phase should be investigated for all foot contacts composition. In summary, for braking/propulsive trials, an AFC characterized by a higher propulsive horizontal GRF and step length and a lower total vertical impulse, and an FFC characterized by a higher propulsive horizontal GRF and a lower propulsive vertical GRF, can predict shorter completion time. Conversely, for only-propulsive trials, an AFC characterized by a higher propulsive horizontal GRF and lower vertical GRF, and an FFC characterized by a higher braking horizontal GRF, a lower braking vertical GRF and total contact time, and a higher approach velocity, can predict shorter completion time. It might be speculated that approach velocity may play a role in discriminating between the two different executions and could determine the other kinetic variables since it entered the predictive model only for only-propulsive trials. Therefore, due to the differences in models and predictive variables, further research is necessary to fully explain the different executions identified in this study.

The present study has some limitations that need to be addressed and can serve as guidance for future research. The present findings cannot be extended to COD tests with a different degree of angle, since the COD performance is angle- and velocity-dependent [12]. Therefore, the turning phase can be investigated with different COD tests. Approach velocity was determined with a photoelectric system which, though reliable, is not as accurate as other methods. Future research can consider the measurement of approach velocity with trunk and lower limbs' center of mass computation as proposed in previous investigations [17,30]. Moreover, 3D motion analysis has not been applied in the current study, limiting the investigation of kinematic determinants of the turning phase. It is strongly advised to replicate the current study design while adding 3D motion analysis. Although differences did not emerge between female and male participants, the different sample sizes between the two groups did not allow us to make definitive conclusions. It is advised to explore the gender differences using the same sample sizes. Similarly, all participants were basketball players, hence these findings cannot be generalized to other team sports players. Another limitation of this study, due to the laboratory setting, is the impossibility of really detecting different strategies used by participants and the potential interaction between dominance/preference and strategy. This is considered a critical issue when investigating preplanned action in a laboratory setting and the implication for training and agility actions (i.e., unplanned COD in response to a stimulus), which occur in open-skill conditions, such as team sports [18]. However, this study implemented an experimental approach to the investigation of the turning phase in several team sports players. The present investigation suggests that the penultimate, final, and first accelerating foot contacts should be assessed for a comprehensive understanding of the turning phase. Together with previous research [15–19,21], we have evidence from four foot contacts characterizing the 180° COD performance. However, further research can be encouraged to extend the analysis of other foot contacts and their contribution to completion time.

## 5. Conclusions

The present study provided a characterization of the turning phase during the modified 505 test, demonstrating that each of the three foot contacts can play an important role in COD performance. In particular, the PFC and FFC are considered critical foot contacts for the deceleration of the body and the preparation for reacceleration in the new direction. Conversely, the AFC is the first foot contact after turning when the horizontal velocity of the center of mass is zero and the reacceleration in the new direction has to be executed. Among several spatial–temporal and kinetic variables, the propulsive horizontal GRF of the AFC can be emphasized, as it is able to indicate faster performers and the high-playing-level group and predict faster completion times in both braking/propulsive and only-propulsive trials. The findings of this study can be translated to practical implications for training. An important component of COD speed is the deceleration phase, meaning that athletes should have a high braking ability. Furthermore, an efficient COD performance can be achieved with a fast transition from the deceleration phase to the acceleration phase, meaning a fast coupling of eccentric and concentric muscle action, which is an expression of the SSC. Therefore, to achieve these goals, it is confirmed that training programs should be implemented with strength training [39]. Due to the contribution of eccentric, concentric, dynamic, and isometric strength to COD performance [38], a variety of exercises may be proposed in order to enhance the ability to change momentum and coordinate body movement within the constraints of the activity [39]. Among the several forms of strength training, the application of eccentric training for the improvement of the braking ability of athletes has been recently emphasized. Eccentric exercises can be executed under several conditions and modalities, as summarized in recent reviews, and are strongly recommended for the wide spectrum of training adaptations [40–42]. Moreover, exercises for the application of the SSC should be implemented. Change-of-direction speed can surely benefit from a variety of exercises considering machine-based, elastic band, and plyometric exercises, particularly when executed in a unilateral, multiplanar, and multidirectional fashion, to replicate the demands of team sports performance. Therefore, to be faster in performing directional changes, athletes should follow these recommendations.

**Supplementary Materials:** The following are available online at https://www.mdpi.com/article/10.3390/ijerph18115519/s1. Graphical representation of the laboratory setting is available as supplementary material with Figure S1. Intraclass correlation coefficients with the 95% confidence intervals of the variables investigated are reported in Table S1. The analysis of the effect of leg preference on variables investigated is provided in Table S2.

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# Musculoskeletal Pain in Gymnasts: A Retrospective Analysis on a Cohort of Professional Athletes

**Giacomo Farì [1,*], Francesco Fischetti [1], Alessandra Zonno [1], Francesco Marra [1], Alessia Maglie [2], Francesco Paolo Bianchi [3], Giuseppe Messina [4], Maurizio Ranieri [1] and Marisa Megna [1]**

1 Department of Basic Medical Sciences, Aldo Moro University, Piazza Umberto I, 70121 Bari, Italy; francesco.fischetti@uniba.it (F.F.); alessandrazonno2014@gmail.com (A.Z.); dr.francescomarra@gmail.com (F.M.); maurizio.ranieri@uniba.it (M.R.); marisa.megna@uniba.it (M.M.)
2 Department of Biological and Environmental Science and Technologies (Di.S.Te.B.A.), University of Salento, Piazza Tancredi 7, 73100 Lecce, Italy; alessia.maglie@studenti.unisalento.it
3 Department of Biomedical Science and Human Oncology, Aldo Moro University, Piazza Umberto I, 70121 Bari, Italy; frapabi@gmail.com
4 Department of Psychology, University of Palermo, Via delle Scienze, Ed 15, 90128 Palermo, Italy; giuseppe.messina17@unipa.it
* Correspondence: dr.giacomofari@gmail.com; Tel.: +39-080-559-5416

**Abstract:** Gymnastics athletes are exposed to a high risk of injury, but also of developing musculoskeletal pain. These data are still little investigated in the available scientific literature. An online survey was distributed to 79 professional athletes who practiced artistic and rhythmic gymnastics. The survey collected demographic and anthropometric data, information about the sport practice, the training sessions, the prevalence of musculoskeletal pain gymnastics-related, and lifestyle habits. Musculoskeletal pain had a high prevalence, involving 65 of 79 athletes (82.3%). A significant correlation was found between musculoskeletal pain and the duration of sports practice, both for general pain ($p = 0.041$) and for specific districts: right wrist pain ($p = 0.031$), left wrist pain ($p = 0.028$), right shoulder ($p = 0.039$), left hip ($p = 0.031$), right thigh ($p = 0.031$), and left knee ($p = 0.005$). Another statistical association was found between right wrist pain and BMI ($p = 0.001$), and hip pain and BMI ($p = 0.030$). Hours spent in a sitting position were also correlated with the incidence of pain ($p = 0.045$). Wrist pain and right shoulder pain had a statistically significant association with the age of the athletes (right wrist pain: $p = 0.038$; left wrist pain: $p = 0.004$; right shoulder pain: $p = 0.035$). The more the gymnasts practice this sport, the more likely they are to develop musculoskeletal pain. Increased age and a higher BMI, as well as daily prolonged sitting position, seem to be potential risk factors for the onset of musculoskeletal pain. Future studies could plan training strategies aimed at preventing musculoskeletal pain associated with gymnastics, in order to promote its further spread.

**Keywords:** overload training; wrist pain; injury prevention; overuse; sitting position

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## 1. Introduction

Gymnastics is a grueling sport that requires considerable physical and mental effort for a continuous search for harmony between biomechanics and aesthetics efforts. Current International Gymnastic Federation (IGF) disciplines include rhythmic gymnastics and artistic gymnastics, which is further divided in men's artistic gymnastics (MAG) and women's artistic gymnastics (WAG) [1].

Gymnastic elements that must be assimilated and acquired by gymnasts necessarily require the development of coordination, joint mobility, postural adaptation, strength, speed, rhythm, agility, and dynamism. In rhythmic gymnastics, a refined quality of motor control, excellent expression skills, and elegance of the technical gesture are quite important [2–5].

In order to achieve the proper skills required for a correct execution of sports gestures from an early age, high-performance training is required. The athletes usually train for, on average, 25–30 h per week and, in some cases, 40 h per week. This is due to the high technical demands of this sports discipline [6]. Therefore, it is reasonable to hypothesize that rhythmic and artistic gymnastics are sports that put athletes at risk of musculoskeletal disorders such as wrist pain [5], low-back pain [2,7–11], shoulder pain [12,13], postural disorders [14,15], and many injuries [16,17], all mainly caused by overuse and repeating the same gestures several times for every type of training.

In addition, this sports practice, that usually begins at an early age, lasts throughout the growth period, including the phases of rapid growth [18]; consequently, gymnasts are exposed to injuries and to the onset of musculoskeletal pain (MP) [10] related to sports practice.

Gymnastics is affected by a high incidence of sport-related pain and lesions [7]. Since the number of those who practice these sports has increased over the years [19], there is a risk of an increase in the costs of medical care, so it is crucial to design strategies for the prevention of MP and injuries.

Moreover, it is also interesting for gymnasts to try to understand if and how lifestyles, especially in professional athletes, affect the onset of musculoskeletal pain. This is all the more interesting in a historical period such as the present one, in which the restrictions on the usual sporting activity imposed by the COVID-19 pandemic have led to inevitable postural and musculoskeletal dysfunctions [20,21].

The aim of this study is to determine the prevalence of musculoskeletal pain, differentiated by anatomical districts, in a cohort of artistic and rhythmic professional gymnasts and to investigate the main risk factors involved.

## 2. Materials and Methods

### *2.1. Study Design and Participants*

The study model is that of an observational retrospective study.

All gymnasts were professional athletes. An online survey was set up using Google Forms. The survey was distributed by email on 12 June 2020 and was requested to be completed and submitted by 27 June 2020.

Informed consent was obtained from all participants involved in this study; in the case of underage athletes, consent forms were filled by parents (or by holder of the responsibility on the minor).

All the procedures were conducted in accordance with the principles set forth in the Helsinki Declaration.

### *2.2. Procedures*

The survey consisted of multiple choice and open-ended questions divided in three different sections:

The first section provided information about the study and contained the informed consent; this section also includes demographic and anthropometric data.

The second section concerned the athletes' practice and the characteristics of the training sessions.

The third section focused on musculoskeletal pain related to specific sports activities. To define this pain, we gave gymnasts the following definition: "Any pain involving muscles, tendons, and joints that occurs in a manner closely related to the specific sports practice, and that recurs in a cyclical way following the usual gymnastic sessions, in the absence of specific traumas that can justify it". In order to delve into the origin of MP, we collected data about lifestyle habits that could also affect the onset of MP (daily hours spent in a sitting position, for usual daily activities such as working or studying).

### *2.3. Statistical Analysis*

Continuous variables are expressed as mean $\pm$ standard deviation and range; categorical variables are expressed as proportions, with an indication of the 95% confidence interval (95% CI), where deemed appropriate. The $\times$ 100 person-months incidence rate was calculated using the sports activity time (months) as the denominator and the number of events as the numerator; 95% CI was subsequently indicated.

Univariate logistic regression was used to evaluate the association between dichotomic outcomes and determinants; the odds ratio (OR) was calculated with the indication of 95% CI.

A $p$-value < 0.05 was considered significant for all tests.

All the statistical analyses were conducted using the Excel Real Statistics Resource Pack (Microsoft Corporation, Redmond, WA, USA).

## 3. Results

The cohort consisted of 79 athletes: 54 rhythmic gymnasts, 24 WAG athletes, and 1 MAG athlete, whose demographic characteristics are described in Table 1.

**Table 1.** Sample demographic characteristics.

| Variable | Value |
|---|---|
| Females, *n* (%) | 78 (98.7%) |
| Age, mean ± DS (range) | 13.7 ± 3.0 (6–21) |
| Height (mt); mean ± DS (range) | 1.55 ± 0.13 (1.20–1.83) |
| Weight (kg); mean ± DS (range) | 44.6 ± 10.0 (24–77) |
| BMI; mean ± DS (range) | 18.4 ± 2.1 (14.1–23.7) |
| Discipline; *n* (%)<br>Rhythmic gymnastics<br>Artistic gymnastics | <br>54 (68.4)<br>25 (31.6) |
| Practice period (months); mean ± DS (range) | 80.5 ± 37.0 (0–180) |
| Number of training sessions per week; mean ± DS (range) | 4.1 ± 1.3 (2–8) |
| Hours spent in a sitting position per day; *n* (%)<br>Less than 2 hours<br>Between 2 and 4 hours<br>Between 4 and 6 hours<br>Between 6 and 8 hours<br>More than 8 hours | <br>19 (24.1)<br>26 (32.9)<br>18 (22.8)<br>15 (19.0)<br>1 (1.2) |

As described in Table 2. A total of 65 out of 79 athletes (82.3%) experienced recurrent MP related to gymnastics practice.

The period of sports practice is strongly correlated with the incidence of pain (OR = 1.01; 95% CI = 1.01–1.04; $p$ = 0.041). In particular, the athletes who have practiced for many years are more affected by painful wrist syndromes: wrist pain has a statistically significant association with the period of sports practice (right wrist pain: OR = 1.02, 95% CI = 1.01–1.03, $p$ = 0.031; left wrist pain: OR = 1.02, 95%, CI = 1.01–1.04, $p$ = 0.028), but also with the age of the athletes (right wrist pain: 1.23; 95%, CI = 1.01–1.50, $p$ = 0.038; left wrist pain: 1.46, 95% CI = 1.13–1.90, $p$ = 0.004). Another statistical association is between right wrist pain and BMI (OR = 1.72, 95% CI = 1.24–2.39, $p$ = 0.001).

The same evidence was found for right shoulder pain. Gymnasts more prone to musculoskeletal pain in this anatomical region are the older athletes (OR = 1.30, 95% CI = 1.02–1.66, $p$ = 0.035) and the ones who have practiced sports for a longer time (OR = 1.02, 95% CI = 1.01–1.04, $p$ = 0.039); at the same time, the hip pain is associated with the period of sports practice (OR = 1.02, 95% CI = 1.01–1.03, $p$ = 0.031) and with BMI (OR = 1.47, 95% CI = 1.04–2.07, $p$ = 0.030).

**Table 2.** Prevalence of pain and incidence × 100 months-person, by anatomical district.

| District | Prevalence | | | Incidence × 100 Months-Person | |
|---|---|---|---|---|---|
| | *n* | % | 95% CI | Inc. | 95% CI |
| Musculoskeletal pain | 65 | 82.9 | 72.1–90.0 | 10.2 | 8.0–13.0 |
| Right hand | 0 | 0.0 | 0.0–4.6 | 0.0 | - |
| Left hand | 0 | 0.0 | 0.0–4.6 | 0.0 | - |
| Right wrist | 15 | 19.0 | 11.0–29.4 | 2.4 | 1.4–3.9 |
| Left wrist | 10 | 12.7 | 6.2–22.0 | 1.6 | 0.8–2.9 |
| Right elbow | 1 | 1.3 | 0.3–6.9 | 0.02 | 0.01–0.11 |
| Left elbow | 0 | 0.0 | 0.0–4.6 | 0.0 | - |
| Right shoulder | 9 | 11.4 | 5.3–20.5 | 1.4 | 0.1–2.7 |
| Left shoulder | 9 | 11.4 | 5.3–20.5 | 1.4 | 0.1–2.7 |
| Cervical spine | 0 | 0.0 | 0.0–4.6 | 0.0 | - |
| Dorsal spine | 10 | 12.7 | 6.2–22.0 | 1.6 | 0.8–2.9 |
| Lumbar spine | 19 | 24.1 | 15.1–35.0 | 3.0 | 1.9–4.7 |
| Sacrococcygeal spine | 8 | 10.1 | 4.5–19.0 | 1.3 | 0.1–2.5 |
| Right hip | 13 | 16.5 | 9.1–26.5 | 2.0 | 1.2–3.5 |
| Left hip | 9 | 11.4 | 5.3–20.5 | 1.4 | 0.1–2.7 |
| Right thigh | 13 | 16.5 | 9.1–26.5 | 2.0 | 1.2–3.5 |
| Left thigh | 12 | 15.2 | 8.1–25.0 | 1.9 | 1.1–3.3 |
| Right knee | 21 | 26.6 | 17.3–37.7 | 3.3 | 2.2–5.1 |
| Left knee | 21 | 26.6 | 17.3–37.7 | 3.3 | 2.2–5.1 |
| Right ankle | 20 | 17.7 | 16.2–36.4 | 3.1 | 2.0–4.9 |
| Left ankle | 14 | 17.7 | 10.0–27.9 | 2.2 | 1.3–3.7 |
| Right foot | 3 | 3.8 | 0.8–10.7 | 0.05 | 0.02–0.15 |
| Left foot | 2 | 2.5 | 0.3–8.8 | 0.03 | 0.00–0.13 |

There is also a significant association between right thigh pain and the period of sports practice (OR = 1.02, 95% CI = 1.01–1.03, $p = 0.031$), and also between left knee pain and the period of sports practice (OR = 1.02, 95% CI = 1.01–1.04, $p = 0.005$).

A total of 43.6% of the sample spent more than 4 hours in a seated position; it emerged that the athletes who spent more daily hours in a sitting position were more exposed to MP (OR = 1.91, 95% CI = 1.01–3.59, $p = 0.045$).

## 4. Discussion

We found a significant correlation between musculoskeletal pain and the duration of sports practice, both for general pain (OR = 1,01, 95% CI = 1.01–1.04, $p = 0.041$) and for specific districts: right wrist pain (OR = 1.02, 95% CI = 1.01–1.03, $p = 0.031$), left wrist pain (OR = 1.02, 95% CI = 1.01–1.04, $p = 0.028$), right shoulder (OR = 1.02, 95% CI = 1.01–1.04, $p = 0.039$), left hip (OR = 1.02, 95% CI = 1.01–1.03, $p = 0.031$), right thigh (OR = 1.02, 95% CI = 1.01–1.03, $p = 0.031$), and left knee (OR = 1.02, 95% CI = 1.01–1.04, $p = 0.005$). This evidence is in line with the current scientific literature. In fact, MP is more frequent in high frequency and intensity sports [17,18] and in long sports practice [17]. In 2016, Kamada et al. [19] carried out research into the dose-response relationship between sports activity and MP in adolescents and found that each additional 1 h/wk of sports activity was associated with a 3% higher probability of having pain. Moreover, this evidence is found in relation to the duration of sports practice, regardless of age;

therefore, it also concerns younger athletes, such as those belonging to our sample [19]. The longer is the time dedicated to the sports practice, the greater is the biomechanical overload on the musculoskeletal system. Many studies stated the correlation between sports overuse and MP [22,23]. In gymnastics, if subjected to excessive stress, such as excessive load, inadequate preparation, and insufficient rest-recovery phase, the musculoskeletal system can undergo various types of overuse injuries and pain that can affect different musculoskeletal anatomical districts [22]. This is mainly detected in artistic and rhythmic gymnastics athletes. These activities particularly overload certain joints, less interested in most other sports, such as wrists, whose pain incidence increases as participation and level of competition increase [2,24–26]. Hence, the definition of "gymnast's wrist" [27]. DiFiori et al. suggest that a threshold of training intensity may be important in the development of wrist pain: they found that gymnasts with wrist pain trained more hours per week and trained at a higher skill level [5].

As the duration of sports practice increases, MP increases in another district of the upper limb as well, such as the right shoulder (probably more affected due to the prevalence of right-handed gymnasts), and in three districts of the lower limb, which are left hip, right thigh, and right knee. These findings are confirmed in the updated scientific literature [19,27,28].

Our statistical analysis points out that hours spent in a sitting position seem to be correlated with the incidence of pain (OR = 1.91, 95% CI = 1.01–3.59, $p$ = 0.045) as well. These are the most important data relating to lifestyles that seem to affect the appearance of pain net of the causes directly attributable to sporting activity. Prolonged sitting is typical among the habits of contemporary society [29]. Referring to our specific sample, made up predominantly of young adolescents, the circumstances related to prolonged sitting are likely the hours spent at school or studying, the time spent at home, for example watching TV, or using a computer and a mobile phone. Often, the sitting position is incorrect, and this could have important implications for the onset of MP; in fact, pain due to prolonged incorrect postures is quite frequent in many districts of the musculoskeletal system, such as the cervical spine, with referred pain to the head, upper limbs [29], and lumbar spine [29–31], so education in appropriate sitting postures should be promoted from a young age [29]. It is desirable that future epidemiological studies on larger samples can investigate to what extent this lifestyle factor influences the onset of musculoskeletal pain in those who practice gymnastics in a professional manner, and especially if—and to what extent—sports practice can mutually influence this lifestyle factor.

Wrist pain has a statistically significant association with the age of the athletes (right wrist pain: OR = 1,23, 95% CI = 1.01–1.50, $p$ = 0.038; left wrist pain: OR = 1.46; 95% CI = 1.13–1.90, $p$ = 0.004). The same evidence was also found for right shoulder pain: gymnasts more prone to musculoskeletal pain in this anatomical region are the older ones (OR = 1.30; 95% CI = 1.02–1.66, $p$ = 0.035). Another interesting statistical association is that between right wrist pain and BMI (OR = 1.72, 95% CI = 1.24–2.39, $p$ = 0.001); at the same time, hip pain is associated with BMI (OR = 1.47, 95% CI = 1.04–2.07, $p$ = 0.030). Gymnastics, unlike many other sports, requires athletes to use their upper extremities to bear large loads, exposing musculoskeletal system to repetitive biomechanical stresses, where it is not usually expected. The lower extremity is also subjected to considerable physical loading, through repetitive impacts on the ground resulting from vault takeoffs and dismounts from different heights, and during tumbling activities [19]. Our evidence is supported by Chawla et al., who noticed that wrist pain and injury are more common among athletes who are older, taller and with a larger BMI [24]. As the age increases, there occurs an increase in difficulty of the skills practiced, as well as an increase in hours and intensity of gymnastics training. This often contributes to the overuse of certain anatomical structures, causing long-term effects. In addition, as the age increases, usually the body weight of young athletes increases too, due to the physiological individual growth, resulting in higher loads on joints, already stressed by overuse [3,27,31,32]. Lastly, older gymnasts are more susceptible to MP or injury than younger ones, because of a prolonged time of exposure to risk [33].

The findings of this research also suggest the need for gymnastics to rethink training programs [34,35], making them more suitable in terms of athletic loads so as to prevent the development of musculoskeletal pain syndromes, in particular those of chronic nature [36,37]. To achieve this, it is desirable to integrate traditional training programs with new technologies, which are increasingly widespread in kinesiology and sports rehabilitation, with therapeutic and preventive purposes [38–45]. These are already used in other areas of rehabilitation, such as neurological rehabilitation [46], in which the new frontiers of telemedicine even provide the possibility of using serious games based on virtual reality for rehabilitative purposes and in order to follow and treat patients remotely [47].

It would be desirable to periodically schedule health screenings and physical examinations for professional gymnasts, both at the beginning of their career and at high levels of competition, with the aim of creating special and tailor-made training programs. These screening measures assume a certain importance in a context where the involvement of athletes at an early age is observed, so it is necessary to identify any individual risk to develop MP or injury as soon as possible [8]. Moreover, physicians and therapists who treat gymnasts' MP need to be adequately educated about the biomechanical requirements of this sports activity, where overuse pain and injuries involve specific anatomical districts. Benjamin et al. suggest some strategies aimed at the prevention and treatment of wrist pain, according to which physical therapy should include core stabilization exercises, mobility, and stabilization exercises of shoulder and elbow, in order to better redistribute loads during activities involving the upper limbs [2]. In addition, gymnastics coaches should be strongly competent in proper training volume and adequate rest, which are critical to pain and symptom management and recovery. A medical evaluation is advisable at the first manifestation of painful symptoms, which should be considered a warning and therefore promptly investigated for an early detection of developing stress injuries [10,24,27]. Coaches are required to supervise and protect athletes' practice from early on, and in a gradual progression of technique to more complex executions [27,48,49].

These precautions, combined with greater care of one's lifestyle, could certainly allow to maintain high levels of sports performance by limiting the risk of developing painful disorders affecting the musculoskeletal system. This way, the general quality of life of gymnasts could also improve, since even the normal activities of daily life would be free from limitations that are due to algo-dysfunctional syndromes. A set of prevention strategies should minimize the risk of MP and injuries due to the competitive nature of the sport, characterized by the ever-increasing physical demands [33,50].

*Limitations*

The main limitation of this study is the retrospective and self-reporting nature of the survey questions. The data were therefore provided without any clinical monitoring, and, sometimes, this may have led to an inaccurate definition of the MP by participants. Moreover, the sample is small, even if it refers to a sport whose diffusion is limited compared to other sports.

On the contrary, we consider a strength of this study to be the fact that, to our knowledge, it was the first research to delve into the possible association between MP in all the possible exposed anatomical districts and gymnastics at a professional level.

## 5. Conclusions

Gymnastics is one of the most popular competitive sports in the world, but it also exposes athletes to develop MP and injuries. As observed in this research, many anatomical districts are subjected to MP due to sports overuse, and this is particularly evident for wrists, lumbar spine, and lower limbs.

The more gymnasts practice this sport, especially in terms of long sports practice, the more likely they are to develop pain in many musculoskeletal districts. Increased age and BMI seem to be potential risk factors for arising MP as well. Finally, it is important to understand how, and if, lifestyle habits could affect the MP prevalence among professional gymnasts.

It is desirable that further research delves into gymnastics-related MP and designs new training strategies to prevent it, in order to limit the risk of abandonment and to improve the diffusion of these sports activities, which traditionally allow to develop psychophysical benefits when practiced from a very young age.

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# Hypovitaminosis D in Young Basketball Players: Association with Jumping and Hopping Performance Considering Gender

**Borja Ricart [1,2,*], Pablo Monteagudo [1,3,*] and Cristina Blasco-Lafarga [1]**

[1] Sport Performance and Physical Fitness Research Group (UIRFIDE), Physical Education and Sports Department, University of Valencia, 46010 Valencia, Spain; M.Cristina.Blasco@uv.es
[2] Alqueria LAB, Valencia Basket, 46013 Valencia, Spain
[3] Education and Specific Didactics Department, Jaume I University, 12071 Castellón, Spain
* Correspondence: borjaricart@hotmail.com (B.R.); pmonteag@uji.es (P.M.)

**Abstract:** This study aimed to verify whether a group of young well-trained basketball players presented deficiencies in vitamin D concentration, and to analyze whether there was an association between vitamin D concentration and jumping and hopping performance. Gender differences were considered. Twenty-seven players from an international high-level basketball club (14 female, 16.00 ± 0.55 years; 13 male, 15.54 ± 0.52 years) participated in this cross-sectional study. Rate of force development was evaluated by means of the Abalakov test (bilateral: AbB; right leg: AbR; left leg: AbL); and the triple hop test (right leg: THR; left leg: THL). Blood samples were collected for the determination of serum 25-hydroxyvitamin D and nutritional status. Vitamin D insufficiency was found in both women (29.14 ± 6.08 ng/mL) and men (28.92 ± 6.40 ng/mL), with no gender differences regarding nutritional scores. Jumping and hopping performance was confirmed to be significantly larger in males (AbL, THR, and THL $p < 0.005$), whose CV% were always smaller. A positive correlation was found between AbB and vitamin D ($r = 0.703$) in males, whereas this correlation was negative (−0.611) for females, who also presented a negative correlation ($r = -0.666$) between THR and vitamin D. A prevalence of hypovitaminosis D was confirmed in young elite athletes training indoors. Nutritional (i.e., calciferol) controls should be conducted throughout the season. Furthermore, whilst performance seems to be affected by low levels of this vitamin in men, these deficiencies appear to have a different association with jumping and hopping in women, pointing to different performance mechanisms. Further studies accounting for differences in training and other factors might delve into these gender differences.

**Keywords:** vitamin D; explosive strength; performance; nutrition; training

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## 1. Introduction

Nutrition plays an important role in the health and performance of athletes. In particular, vitamins are essential in various processes, including hemoglobin synthesis, maintenance of bone health, immune function, protection against oxidative damage, neuronal functions, and the synthesis and repair of muscle tissue during recovery from injury [1,2]. Over the last decade, the monitoring of vitamin D, or calciferol, a fat-soluble vitamin with the structure of a steroid hormone that is functionally different from all others, has been of particular interest [3]. We refer to vitamin D3, a vital isomer synthesized in the cell membrane of the epidermis and dermis as a response to solar radiation, as its other common form, D2, is derived from plants and is impossible for the human body to synthesize [4,5].

Vitamin D3 regulates the expression of more than 900 gene variants, which in turn significantly [6] impacts numerous functions related to sporting performance. Among other things, it is involved in the regulation of exercise-induced inflammation, neurological function, cardiovascular health, glucose metabolism, bone health, and skeletal muscle performance [7]. More specifically, it is attributed with an ergogenic effect on neuromuscular efficiency and the muscle-contraction mechanism [8,9], as well as optimizing acute adaptive response to physical exercise [10], so that performance in athletes may be affected by deficient levels of this vitamin [11,12].

However, recent research suggests that high-performance athletes are at constant risk of vitamin D deficiency, increasing the risk of stress fractures, acute illness, and sub-optimal muscle function [3]. In addition to a possible nutritional deficit due to insufficient calorie intake in athletes with high energy needs [13], or poor diet [14], vitamin D deficiency has been linked to a lack of or drastic reduction in vitamin D production in the winter months due to a lower incidence of sun on the skin [15]. For example, Bescos and Rodriguez [16] found that more than half of one professional basketball team had hypovitaminosis D after the winter. More recently, Fishman et al. [17] found a high prevalence of vitamin D insufficiency in National Basketball Association (NBA) players.

Therefore, it seems that vitamin D deficiency is accentuated in athletes who train and compete indoors throughout the year, as is the case of basketball. Taking also into account the relationship between vitamin D and the aforementioned optimization of muscle contraction [8,9] and/or prevention of bone health issues [7], it seems that this deficiency is particularly important in a sport that involves continuous accelerations and braking, jumps and receptions [18]. The rate of force development in the lower extremity is of the utmost importance [19,20], and the risk of musculoskeletal injuries is high [21]. Moreover, jumping, which may be affected by calciferol deficit, is one of the most common actions performed in this sport [22,23], with between 40 and 60 jumps being made per athlete during a single game [24]. Jumping is also one of the most common ways of assessing player performance [25], condition-maturity level [26,27], level of functional health over the course of the season [28,29], and sporting life success [30,31].

Knowing whether basketball players are calciferol deficient from their early formative stages, and the possible relationship between their vitamin concentrations and muscle function as assessed by jumping, is therefore of interest to the medical and technical staff who care for these athletes. Although there is no evidence to suggest gender differences in vitamin D intake [32] and/or deficit [33,34], differences between male and female basketball players tend to be significant in jumping ability [35], so it is equally important to analyze these associations while taking gender into account. The aims of this study are, therefore, to test whether a group of young high-performance basketball players are vitamin D deficient (1); and to analyze whether there is any relationship between vitamin D levels and muscle strength performance as measured by two types of jumps (2), taking into account gender differences. To our knowledge, no studies have previously investigated this potential relationship.

## 2. Materials and Methods

### 2.1. Participants

This quantitative, descriptive, and correlational study involved 27 young basketball players belonging to a top-level competitive club in the ACB (Asociación de Clubes de Baloncesto) league, of whom 14 were girls (16.00 ± 0.55 years, all of them had attained menarche), and 13 were boys (15.54 ± 0.52 years). Before data collection began, both the subjects and their legal guardians were informed of the purpose of the study. Each participant signed an informed consent form, agreeing to participate in the study, which had been approved by the ethics committee of the local university (H1553774899546).

### 2.2. Protocol

The data collection was carried out during the regular season in the month of December, and on three alternate days of the same week. The week prior to the first assessment, the participants were informed that they should consume no stimulant drinks (caffeine or energy drinks); they could not eat two hours prior to the tests; and they should maintain their normal nutritional habits. The first evaluation session involved blood tests. In the second session, the anthropometric measurements of the players were taken and the Abalakov vertical jump test was performed first bilaterally (both legs at a time), and then unilaterally (one leg at a time). In the final evaluation session, data on the triple hop test were collected. Prior to the jumping tests, a standardized 10-min warm-up was performed on both days, consisting of jogging, dynamic stretching, lower and upper limb strength exercises, plyometric exercises, and high-intensity running with changes of direction. No familiarization phase was carried out for the evaluation tests, as all of the athletes had already taken these at some point during the season.

### 2.3. Assessment Tools

#### 2.3.1. Blood Test

The method for determining the body's vitamin D status consisted of measuring the serum 25-hydroxyvitamin D concentrations [36]. For many years, there has been a consensus that blood concentrations of this metabolite reflect total body vitamin D, including endogenous synthesis by exposure to sunlight, dietary intake in supplemented or unsupplemented meals, and drug treatments [37]. The blood samples were taken by a medical professional from a hospital in the same city. The players were summoned to the medical center, along with their fathers, mothers, or legal guardians, with an overnight fast required before attending.

For the blood tests, 5 mL of venous blood were extracted from the antecubital vein of each participant. Once obtained, the blood samples were allowed to clot and then centrifuged at 3000 rpm for 10 min at room temperature to isolate the serum. The serum was aliquoted into an Eppendorf tube and conserved at −80 °C until biochemical analysis. Serum vitamin D concentrations were determined using the LIAISON 25(OH) Vitamin D TOTAL Assay (CLIA) (Eurofins Megalab S.A., Valencia, Spain), which is a direct competitive chemiluminescence immunoassay for human serum intended for use on the DiaSorin LIAISON automated analyzer (DiaSorin S.P.A., Saluggia, Italy). Once the laboratory tests had been performed, the reports containing the analytical data were submitted to the researchers for further analysis.

#### 2.3.2. Anthropometric Measurements

Mass (kg) and height (cm) measurements were recorded using a scale (SECA 769, CE 0123, Hamburg, Germany) and a stadiometer (SECA 220, CE 0123, Hamburg, Germany). The body mass index (BMI) of the participants was calculated using the formula mass/height$^2$ (kg/cm$^2$).

#### 2.3.3. Abalakov Test

In order to evaluate the rate of force development of the lower extremity, the Abalakov test [38] was performed both bilaterally (Ab) and unilaterally (Abalakov right or AbR; and Abalakov left or AbL), with the height of the jump being recorded. All players performed three jumps in each modality, with a recovery period of two minutes between the jumps [39], although only the best jump in each modality was included in the statistical analysis. The jumps were recorded using a Din-A2 contact platform (420 × 594 mm) and Chronojump software (Boscosystem®, Barcelona, Spain).

#### 2.3.4. Triple Hop Test

To evaluate the power and neuromuscular control of a horizontal jump, the participants took the triple hop test [40,41]. This test consists of three consecutive jumps on one leg, with the distance reached after the last jump being recorded [40]. Each player performed the test twice with each leg alternatively (triple hop left or THL; and triple hop right or THR), and the best jump with each leg was used in the subsequent analysis. A standard 12-metre tape measure was used to measure each jump.

### 2.4. Statistical Analysis

The data were analyzed using the statistics package SPSS v23 for Windows (SPSS Inc. Chicago, IL, USA). Once the normality of the sample had been analyzed (Shapiro–Wilk test), the descriptive variables were then calculated and expressed as the mean and standard deviation (mean ± *SD*). *T*-tests for independent samples or Mann Whitney U-tests were performed to analyze whether there were sex-related differences between the main study variables. *T*-tests for related samples and the Wilcoxon test were also performed to compare whether there were sex-related asymmetries between the legs. To check whether there was a relationship between vitamin D levels and performances in the jumping tests, we performed a correlation analysis (Pearson's *R* or Spearman's Rho according to the normality), both with and without controlling for the covariate BMI. Statistical significance was set at $p < 0.05$, with the absolute correlation coefficients considered being: $r < 0.1$, trivial; 0.1–0.3, low; 0.3–0.5, moderate; 0.5–0.7, strong; 0.7–0.9, very strong; >0.9, almost perfect; and 1, perfect [42].

## 3. Results

The final sample comprised 14 girls (16.00 ± 0.55 years, 174.20 ± 6.35 cm, 67.98 ± 6.73 kg) and 13 boys (15.54 ± 0.52 years, 190.73 ± 6.45 cm, 78.17 ± 8.87 kg). No significant differences were found between boys and girls in terms of age, but significant differences were found for weight and height ($p < 0.05$), with higher values recorded in the boys. Table 1 presents the results of the main blood composition parameters. No significant differences between boys and girls were found for any of the items, and the coefficients of variation were generally high in both cases.

**Table 1.** Blood composition variables.

| Parameters | Girls (*N* = 14) | | Boys (*N* = 13) | | *p* |
|---|---|---|---|---|---|
| | Mean ± *SD* | CV (%) | Mean ± *SD* | CV (%) | |
| Vitamin D (ng/mL) | 29.14 ± 6.08 | 20.86 | 28.92 ± 6.40 | 22.13 | 0.905 |
| Folic acid (ng/mL) | 6.53 ± 3.38 | 51.76 | 7.24 ± 2.79 | 38.54 | 0.302 |
| Cortisol (µg/dL) | 15.37 ± 3.41 | 22.19 | 15.04 ± 1.86 | 12.37 | 0.616 |
| Magnesium (mg/dL) | 1.99 ± 0.60 | 30.15 | 2.08 ± 0.11 | 5.29 | 0.088 |
| Iron (µg/dL) | 87.35 ± 31.68 | 36.26 | 96.84 ± 38.72 | 39.98 | 0.491 |
| Vitamin B12 (pg/mL) | 559.78 ± 190.02 | 33.94 | 593.00 ± 177.33 | 29.90 | 0.643 |
| TSH (µUI/mL) | 2.74 ± 1.34 | 48.90 | 2.43 ± 0.87 | 35.80 | 0.491 |
| Calcium (mg/dL) | 9.59 ± 0.23 | 2.40 | 9.73 ± 0.21 | 2.16 | 0.105 |

CV: coefficient of variation in %; *SD*: standard deviation; TSH: serum thyroid stimulating hormone.

Table 2 shows the values obtained in the neuromuscular performance tests, with lower coefficients of variation with respect to the analytical assessment, and even greater homogeneity among the boys. When analyzing the differences by sex, significant differences ($p < 0.01$) were observed in the Abalakov test for the left leg. Significant differences were also found in the triple hop test, both for the left leg ($p < 0.001$) and right leg ($p < 0.001$). Finally, significant differences were found in boys ($p < 0.010$) between the results for the right and left legs in the Abalakov test.

Table 3 shows the correlation analyses between vitamin D concentration and the results of the neuromuscular performance tests. While in boys, a high positive correlation was found between the Abalakov test (performed in a bipedal manner) and serum vitamin D concentration, in girls this relationship was also high, but negative. When BMI was considered as a covariate, the correlation coefficient increased slightly in boys, while it decreased in girls. There was also a high negative correlation between the triple hop test performed with the right leg and vitamin D in girls, which in this case increased slightly when considering BMI.

**Table 2.** Performance variables.

| Tests | Girls (*N* = 14) | | Boys (*N* = 13) | | *p* |
|---|---|---|---|---|---|
| | Mean ± *SD* | CV (%) | Mean ± *SD* | CV (%) | |
| AbB (cm) | 33.37 ± 4.83 | 14.47 | 35.71 ± 3.92 | 10.98 | 0.182 |
| AbL (cm) | 19.14 ± 4.32 | 22.57 | 24.14 ± 2.24 [a,b] | 9.28 | 0.005 |
| AbR (cm) | 20.31 ± 3.42 | 16.84 | 21.29 ± 2.99 | 14.04 | 0.436 |
| THL (cm) | 5.10 ± 0.70 | 13.72 | 6.10 ± 0.37 | 6.07 | <0.001 |
| THR (cm) | 5.23 ± 0.69 | 13.19 | 6.13 ± 0.61 | 9.95 | 0.001 |

CV: coefficient of variation in %; *SD*: standard deviation; AbB: Abalakov bilateral; AbL: Abalakov left; AbR: Abalakov right; THL: triple hop left; THR: triple hop right. [a]: Difference with the AbR of boys ($p = 0.002$); [b]: Difference with the AbR of girls ($p = 0.002$).

**Table 3.** Correlations between jumping and hopping and vitamin D, considering both the whole sample, and male and female athletes separately, with and without the covariate body mass index (BMI).

| Tests | Girls (*N* = 14) | Boys (*N* = 13) | All (*N* = 27) | Girls [a] (*N* = 14) | Boys [a] (*N* = 13) | All [a] (*N* = 27) |
|---|---|---|---|---|---|---|
| AbB (cm) | −0.611 * | 0.703 ** | 0.047 | −0.597 * | 0.796 ** | 0.081 |
| AbL (cm) | −0.219 | 0.218 | −0.036 | −0.183 | 0.248 | −0.025 |
| AbR (cm) | −0.465 | −0.067 | −0.227 | −0.439 | −0.040 | −0.192 |
| THL (cm) | −0.415 | 0.050 | −0.106 | −0.413 | 0.162 | −0.098 |
| THR (cm) | −0.666 ** | 0.128 | −0.216 | −0.685 ** | 0.210 | −0.248 |

AbB: Abalakov bilateral; AbL: Abalakov left; AbR: Abalakov right; THL: triple hop left; THR: triple hop right; *: $p < 0.05$; **: $p < 0.01$; [a]: BMI as a covariate.

## 4. Discussion

For the first objective of this study (to check whether young basketball players of a formative age suffer from vitamin D deficiency), our results confirm that both girls and boys show this deficiency at the age of 14–16, while the other components analyzed were found to be within the normal range. As for whether this deficit could influence explosive strength as assessed by jumping, the second objective of this study, the data reveals that at these ages there is no association between these variables when considering the sample as a whole. However, when taking sex into account, the data points to differences regarding the correlations in young players of the two sexes, while at the same time the expected differences are observed in the rate of force development in some of the jumps that are determining factors for basketball performance (AbL, THR, and THL).

According to the levels previously established by some authors [43], young players of both sexes already suffer vitamin D insufficiency (20–30 ng/mL), while they present normal values for the other blood components [44–48]. Our results are, therefore, consistent with other studies that have shown low concentrations of vitamin D in elite athletes [49,50], with up to 56% of one sample of athletes being below the levels considered adequate [51]. In agreement with other studies [33,34] there were no differences between sexes in the vitamin D deficiencies.

As previously noted, indoor sports involve a vitamin D deficiency rate almost twice that of outdoor sports [52]. Seasonal variation in the levels of this vitamin has also been observed [15,53]. This seasonal variation should be taken into account, as it has been observed that athletes who are vitamin D deficient during the winter are at a higher risk of having lower levels in the spring [54]. This latter period is one of the most important phases of the season since the final rankings are decided and, moreover, there are more matches, therefore leading to a greater risk of fatigue and injury [55]. Both indoor training and seasonal variation are associated with low sun and ultraviolet (UVB) exposure, the main source from which the body synthesizes this vitamin [56]. It seems important, therefore, to monitor 25(OH)D concentrations throughout the basketball season in order to mitigate any potential effects that this insufficiency may cause for the players, despite the fact that these are initial stages in which they are still training and competing quite below the level of professional athletes [57,58].

Based on this, the second objective of this study was to find out whether lower vitamin D concentrations could influence basketball performance (by assessing the rate of force development of the players through two different types of jumps). Although we did not find sex differences regarding vitamin D, all the analyses were also performed considering the sex of the participants because individual differences in jumping ability in male and female basketball players tend to be significant [35]. Our data reinforces the importance of always considering these sex differences when analyzing performance, because although there is no association between these variables when considering the entire sample in general, the data does reveal different results for men and women.

On the one hand, there is a very strong positive correlation seen in the boys between vitamin D and the bilateral Abalakov test, with a correlation coefficient that increases even more when BMI is considered as a covariate. Some authors have argued that this vitamin increases the size and number of type II muscle fibers [54,59], which could influence an athlete's jumping ability. However, this association is negative in the case of the girls, and decreases when BMI is taken into account. These results differ from those obtained by Ward et al. [60], who concluded that vitamin D was significantly associated with muscle strength in adolescent girls, although the participants in that study were not athletes.

In this sense, it is important to emphasize that at this age, boys may be less mature than their female peers [61]. Even close to full maturity, less vitamin D does not imply less jumping ability in these young female players, but rather the opposite, suggesting that there may be other mechanisms (for example, those related to good intermuscular coordination) that help these girls to jump more. Not surprisingly, the jumps where sex-related differences were found (AbL, THL, and THR), presented the lowest coefficient of variation in the boys, with these being clearly lower for the boys than their female counterparts for these same jumps. Further studies involving larger sample sizes and a more heterogeneous performance profile for girls should confirm whether, as it appears, only their male counterparts are likely to rely more heavily on explosive force production rates, with vitamin D concentration exerting a positive influence on this variable.

Considering the previous reasoning, the game and specific training would not have highlighted differences between the right and left leg in girls when performing the Abalakov test in a unilateral manner, again contrary to that seen in boys (with a significantly better AbL than AbR, and, indeed, higher AbR and AbL than those of the more mature girls in this study). As pointed out by Jones and Bampouras [62], the dominant leg of male athletes tends to present higher strength values than the non-dominant leg, which could explain the difference recorded for our male athletes. The reason behind why we found no association between vitamin D and the unilateral tests in men could be related to a lack of stability during these movements due to coordination problems [63]; to perform well in unilateral tests, an individual must have adequate balance, coordination, muscle strength, and neuromuscular control [64], and not just rate of force development. This would account for why we only found the correlation in the bilateral test, where it is easier to coordinate movements and thereby apply a greater amount of force.

The fact that the girls did not show significant asymmetries between legs suggests that women do not tend to have a more dominant leg [65]. This information, together with the fact that the strength values (performance in cm) produced by the trainee players in our study are already similar to those obtained by professional athletes [66], could indicate that the potential for further improving this ability in women may be limited, and that jumping and hopping ability may not be the most determining factor in terms of becoming a professional player. This suggests that adequate levels of vitamin D are more important for performance in men than in women, although we should not forget the significance that this vitamin may also have for women in other aspects, such as injury prevention [67].

In the triple hop test, once again there were no differences in performance between the sexes, and only the girls showed a negative correlation with vitamin D when the test was performed with the right leg, a result that was reinforced when BMI was also factored in. New gender differences in the association between vitamin D and performance seem to indicate a different use of strength in women and men in terms of the jumping actions involved in basketball performance. Notably, the lack of control of the menstrual cycle could have influenced our results. The majority of female subjects do not menstruate on a regular basis [68], and this factor was not considered at the time of blood sampling; however, despite the high coefficient of variation, our data did not show differences in iron concentration between male and female participants.

This study has several limitations. Firstly, the cross-sectional design of this study does not allow us to determine a direct cause and effect relationship. Comprehensive nutritional monitoring would have improved our knowledge of the origin of the vitamin D deficiencies found. Similarly, it is necessary to test whether vitamin D levels vary throughout the season and whether this is associated with a change in jump values in different periods. New and less invasive assessment systems based on tear biosensing or salivary samples [69,70] could streamline the process to obtain biomarkers during the competitive season, and therefore would allow relationships between strength and vitamin D to be analyzed from a more holistic (and rapid) view. Multidisciplinary teams—included nutritionists—regardless of the level of the sport club (elite and amateur), would facilitate the interpretation of these assessments, periodizated and tailored on a regular basis, therefore promoting health and young athletic success. Secondly, a larger sample size would allow more robust correlation coefficients to be obtained, for which reason our results cannot be extrapolated to other contexts and further studies are required. Finally, the differences found between men and women suggest that future studies should analyze whether the menstrual cycle somehow affects vitamin D, and thus sports performance in female basketball players, given their high incidence of injuries [71]. Some studies have demonstrated relationships between low levels of this vitamin and the frequency of menstrual disorders [72], confirming that this is a variable to control in these stages of development.

## 5. Conclusions

Our results suggest that, despite their youth, trainee basketball players have insufficient vitamin D levels. Since this deficiency appears to be common in elite athletes, especially those competing indoors, various means of controlling vitamin D levels throughout the season (diet, supplementation, and sun exposure) should be considered. Furthermore, these deficiencies appear to be differentially associated with jumping performance in men and women. Thus, while performance in men does seem to be compromised by low levels of this vitamin, it would be interesting to further investigate the different role it might play in women, as vitamin D deficiency is not only related to rate of force development.

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# Predicting the Unknown and the Unknowable. Are Anthropometric Measures and Fitness Profile Associated with the Outcome of a Simulated CrossFit® Competition?

**Javier Peña [1,2,3,†], Daniel Moreno-Doutres [3,*,†], Iván Peña [3], Iván Chulvi-Medrano [4], Alberto Ortegón [5], Joan Aguilera-Castells [5] and Bernat Buscà [5]**

1 Sport and Physical Activity Studies Centre (CEEAF), University of Vic—Central University of Catalonia, 08500 Vic, Spain; javier.pena@uvic.cat
2 Sport Performance Analysis Research Group (SPARG), University of Vic—Central University of Catalonia, 08500 Vic, Spain
3 ICON Training S.L., 08912 Barcelona, Spain; ivanpenalopez4@gmail.com
4 Sport Performance and Physical Fitness Research Group (UIRFIDE), Department of Physical and Sports Education, Faculty of Physical Activity and Sports Sciences, University of Valencia, 46010 Valencia, Spain; ivan.chulvi@uv.es
5 Department of Sports Sciences, Ramon Llull University, FPCEE Blanquerna, 08022 Barcelona, Spain; a.ortegon@outlook.es (A.O.); joanac1@blanquerna.url.edu (J.A.-C.); BernatBS@blanquerna.url.edu (B.B.)
* Correspondence: dani.moreno@dmtrainingpro.com
† Co-first author, these authors contributed equally to this work.

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**Abstract:** The main objective of this research was to find associations between the outcome of a simulated CrossFit® competition, anthropometric measures, and standardized fitness tests. Ten experienced male CrossFit® athletes (age 28.8 ± 3.5 years; height 175 ± 10.0 cm; weight 80.3 ± 12.5 kg) participated in a simulated CrossFit® competition with three benchmark workouts ("Fran", "Isabel", and "Kelly") and underwent fitness tests. Participants were tested for anthropometric measures, sit and reach, squat jump (SJ), countermovement jump (CMJ), and Reactive Strength Index (RSI), and the load (LOAD) corresponding to the highest mean power value (POWER) in the snatch, bench press, and back squat exercises was determined using incremental tests. A bivariate correlation test and k-means cluster analysis to group individuals as either high-performance (HI) or low performance (LO) via Principal Component Analysis (PCA) were carried out. Pearson's correlation coefficient two-tailed test showed that the only variable correlated with the final score was the snatch LOAD ($p < 0.05$). Six performance variables (SJ, CMJ, RSI, snatch LOAD, bench press LOAD, and back squat LOAD) explained 74.72% of the variance in a k = 2 means cluster model. When CrossFit® performance groups HI and LO were compared to each other, *t*-test revealed no difference at a $p \leq 0.05$ level. Snatch maximum power LOAD and the combination of six physical fitness tests partially explained the outcome of a simulated CrossFit competition. Coaches and practitioners can use these findings to achieve a better fit of the practices and workouts designed for their athletes.

**Keywords:** performance; athlete; high-intensity functional training; cross-training; functional fitness

## 1. Introduction

CrossFit® is a training method property of CrossFit® Inc. (Washington, DC, USA), a company established in 2000 by Greg Glassman and Laura Jenai. This form of physical exercise incorporates elements from other disciplines, such as weightlifting, powerlifting, gymnastics, calisthenics, and strength athletics, while following high-intensity exercise principles and using constant variability as one of its core elements. According to data from the company, the number of official CrossFit® affiliated gyms in the world is close to 15,000 [1], a figure that shows the worldwide interest in this exercise regime. Apart from the CrossFit® activity aimed at the general population, CrossFit® Inc. has developed a competitive trend that also enjoys considerable international popularity. In 2019, 144,276 people completed all the workouts of the day (WODs) of the CrossFit Open® as prescribed or "RX" [2] (meaning that the athletes used the prescriptive weight or height, completed the prescribed number of repetitions, and followed the full standards for each movement). Alongside 15 sanctioned events, the CrossFit Open® is the only way to qualify for the CrossFit Games®, where the elite of this sport has convened every year since 2007.

Adult CrossFit® participation seems to entail similar physical demands (in terms of $VO_2$ max, muscle size, strength and endurance gains) to other high-intensity physical activities [3]. Several cohort studies have reported improvements in $VO_2$ max [4,5], body composition [6,7], and specific work capacity [8] in men and women in interventions ranging from 6 to 10 weeks. Thus, CrossFit® WODs are a demanding form of exercise, and physiologically, both aerobic and anaerobic metabolisms influence the athlete's performance [9].

General strength improvements associated with CrossFit® participation are also described in the literature with conflicting results. Significant increases in several muscular strength and endurance tests after participation in CrossFit® workouts have been reported in some studies [5], while in some others, no significant differences were noted post-intervention [8].

However, all the studies mentioned above have two critical limitations highlighted in systematic reviews: a reduced number of scientific studies because the discipline is still incipient, and a lack of a high level of evidence at low risk of bias [10].

To date, several studies have highlighted that the physical stress caused by CrossFit® WODs is comparable to a 20 min high-intensity treadmill run at 90% of maximal heart rate [11] and superior to an ACSM-based training session in terms of fatigue, muscle soreness, and muscle swelling [12]. Rating of perceived exertion (RPE) seems consistently high after CrossFit® routines [12,13], and increased lactate [13–15] and pro/anti-inflammatory cytokine production [14] is also present in several scientific reports assessing these activities.

Although CrossFit® athletic competitions generate significant revenues, not many previous studies have dealt with competitive performance factors. Numerous scientific contributions have investigated the epidemiology of CrossFit® [3,16–18], with several cases of spinal injuries [19] and rhabdomyolysis [20] reported, but not many pieces of research have provided insight about the relevant elements of fitness to succeed in competitions. For instance, a study comparing the outcomes in three benchmark WODs—"Grace" (30 clean and jerks for time), "Fran" (three rounds of thrusters and pull-ups for 21, 15, and 9 repetitions), and "Cindy" (20 min of rounds of 5 pull-ups, 10 push-ups, and 15 bodyweight squats)—found that whole-body strength and anaerobic threshold exhibited association with specific CrossFit® performance [21]. In a similar analysis with 32 healthy adult males, age, group (experienced vs. inexperienced), $VO_2$ max, and anaerobic power were predictors of a 12 min as many repetitions as possible WOD with 12 throws of a 9.07 kg medicine ball at a 3.05 m target, 12 swings of a 16.38 kg kettlebell, and 12 burpee pull-ups [22]. In the same article, only CrossFit® experience was a significant predictor in a WOD with sumo deadlift high pull, a 0.5 m box jump, and a 40 m farmer's walk with 40 kg following a three-round with 21, 15, and 9 repetitions per exercise structure. Recent research has also found that absolute $VO_2$ peak values and CrossFit® Total (one repetition maximum tests for the back squat, deadlift, and overhead press) were predictors of the 19.1 CrossFit Open® workout and the benchmark "Fran" performances, respectively [23]. Body composition was revealed as the most significant success predictor in the 2018 CrossFit Open® [24].

Despite an increased number of scientific studies due to the growth in popularity of CrossFit®, there is still an important space for further research about CrossFit® athletic competitions. The main objective of this cross-sectional study was to find associations between the outcome of a simulated CrossFit® competition, anthropometric measures, and standardized fitness tests, providing insight to coaches and athletes to achieve better competitive performance.

## 2. Materials and Methods

### 2.1. Participants

A purposive sample of ten experienced male CrossFit® athletes (age 28.8 ± 3.5 years; height 175 ± 10.0 cm; weight 80.3 ± 12.5 kg; one-hand reach 223 ± 15 cm) without relevant injuries at the moment of the study and recruited from official CrossFit® affiliates volunteered to participate in the study. The inclusion criteria were set based on weekly training volume (≥5 sessions/week), competitive CrossFit® background (≥2 years), regular participation in regional (*n* = 1), national (*n* = 5), or international (*n* = 4) competitions, and their ability to perform the RX versions of the workouts (respecting the metabolic purpose of the WOD and being able to lift the weights without fatal technical flaws in the presence of fatigue). Before starting the study, we informed the participants about the experimental procedures and they signed informed consent and provided additional data by filling out a modified Physical Activity Readiness Questionnaire (PAR-Q) [25]. Procedures followed the Declaration of Helsinki and its later amendments [26] and were approved by the Research Ethics Committee of the University of Vic - Central University of Catalonia in Barcelona, Spain (ref. no. 46/2018).

### 2.2. Experimental Procedures

Testing was conducted over two separate sessions. In the first session, before starting a simulated CrossFit® competition, we tested the participants for anthropometric measures and a sit-and-reach flexibility test. Weight was assessed on an electronic scale (PS160, Beurer, Germany) with an accuracy of ±0.1 kg. Height was measured using a roll-up measuring tape with wall attachment (206, Seca®, Hamburg, Germany) with an accuracy of ±0.01 m. One-hand reach was assessed using a measuring tape (TM-CO2, Tacklife, New York, NY, USA). Body fat percentages were calculated using the equation of Jackson and Pollock [27] measuring the skinfold thickness at three sites (chest, abdomen, and thigh) using a caliper (Holtain Ltd. Tanner/Whitehouse Skinfold Caliper, Holtain, Dyfed, UK). One experienced anthropometrist carried out all the tests following the protocols established by the International Society for the Advancement of Kinanthropometry (ISAK). The sit-and-reach test was performed twice using a sit-and-reach box (Sit and Reach testing box, Eveque, Northwich, UK) and considering the best score as the final result in the test. Later, all of the participants completed three benchmark WODs in random order with a 30 min rest in between them, simulating a CrossFit® Competition. The three selected WODs were "Fran", "Isabel", and "Kelly", and they were performed in that same order (Table 1). These WODs were selected because they are popular benchmark WODs in the CrossFit® community and because they incorporate very diverse skills and fitness elements (Olympic lifting movements, calisthenics, pure conditioning movements, and exercises with high $VO_2$ max demands).

**Table 1.** Workouts performed in the simulated CrossFit® competition.

| WOD 1 "FRAN" | WOD 2 "ISABEL" | WOD 3 "KELLY" |
|---|---|---|
| 21-15-9 Repetitions of thrusters (42.5 kg) and pull-ups as fast as possible. | 30 Repetitions of snatch (60 kg) as fast as possible. | Five rounds as fast as possible of 400 m run, 30 box jumps (0.5 meters), and 30 wall balls (9.07 kg medicine ball at a 3.05 m target). |

Every participant was assigned a certified CrossFit® judge to control their performance, and the WODs were completed in two series or "heats". Participants for the two heats in the first WOD were selected at random, while for the second and third WODs, the athletes with better accumulated scores were assigned to the second heat reproducing the usual CrossFit® competition procedures. During the second session, a week later, we carried out the rest of the measurements (Table 2). Squat jump (SJ), countermovement jump (CMJ), and a 0.7 m drop jump (DJ) were measured using a contact mat (Ergojump-Plus, Ergotest

Innovation, Norway) consisting of a switch mat connected to a digital timer (with an accuracy of ±0.001 s). Contact time and resulting height in the DJ were used to calculate Reactive Strength Index (RSI) by using the formula: RSI = Jump Height (cm)/Ground Contact Time (ms). All of the jumps were performed three times, and the best score was the final result in the tests. The loads (LOAD) corresponding to the highest mean power value (POWER) in the snatch, bench press, and back squat exercises were determined using incremental tests [28,29] and were measured with a linear encoder (MuscleLabTM, Ergotest Innovation, Stathelle, Norway) attached to the barbell. To assess the ability of the athletes to perform intermittent efforts, a Yo-Yo intermittent recovery test 2 (IR-2) was administered, and the distance covered was used to calculate $VO_2$ max (mL/min/kg) using the formula: IR-2 distance (m) × 0.0136 + 45.3 [30]. All the mentioned tests were chosen because they show ecological and construct validity, the movements used are very similar to those of CrossFit®, and the tests enabling calculations have been validated by previous scientific literature.

**Table 2.** Protocols followed in the incremental tests.

| SNATCH | BENCH PRESS | BACK SQUAT |
|---|---|---|
| First load was set at the 65% of the one-repetition maximum (1RM) in the movement with 5% increments until failure. | Concentric execution of the exercise with 4 different loads ranging between 30 and 80% of the one-repetition maximum (1RM) in the movement. | Concentric execution of the exercise with 4 different loads ranging between 30 and 80% of the one-repetition maximum (1RM) in the movement. |
| Participants performed 2 repetitions at any given load with 10 s of rest between attempts and a 3 min rest between loads. | Participants performed 2 repetitions at any given load with 10 s of rest between attempts and a 3 min rest between loads. | Participants performed 2 repetitions at any given load with 10 s of rest between attempts and a 3 min rest between loads. |

### *2.3. Statistical Analysis*

Using a statistical package (SPSS 21 for macOS, SPSS Inc, Chicago, IL, USA), a Shapiro–Wilk test was used to determine if the sample data was normally distributed prior to conducting a bivariate correlation test between the final competition score—assigning 10 points to the best-ranked competitor in each WOD, 9 to the next one, and consecutively so until the last competitor—and the different physical condition tests conducted in the study. Significance level was established at $p < 0.05$ ($\alpha = 5\%$) with a 95% confidence interval. In the second term, R, a language and environment for statistical computing (R 3.5.1 GUI 1.70 for macOS, R Foundation for Statistical Computing, Vienna, Austria), was used to normalize physical tests, centering them at 0 to avoid between-variable scale differences, carrying out a k-means cluster (k = 2) analysis considering the outcome of the physical tests to group individuals as either high (HI) or low (LO) performance. Later, a *t*-test was used to compare composite WOD scores between HI and LO groups. Finally, a Principal Component Analysis (PCA) was carried out to determine the influence of each physical test on the simulated CrossFit® competition final composite score.

## 3. Results

The Shapiro–Wilk test showed that the variables included in the analysis were normally distributed ($p > 0.05$). A bivariate Pearson's correlation coefficient two-tailed test of significance showed that the only variable showing a very large correlation [31] with the final score of the competition was the snatch LOAD ($p < 0.05$); none of the other variables showed association with the competition outcome (Table 3). Although weekly volume of training was not significantly correlated with the final competition score ($p = 0.142$), the r-value showed a promising correlation (0.50) with this factor.

**Table 3.** Correlation coefficients, interpretation, and significance levels in the variables included in the study.

| Variables | Correlation (r and Interpretation) | Significance (*p*-Value) |
|---|---|---|
| Age (y) | −0.36, moderate | 0.300 |
| Weight (kg) | 0.12, small | 0.736 |
| Height (cm) | 0.25, small | 0.490 |
| Reach (cm) | 0.21, small | 0.566 |
| Hours of training per week (h) | 0.50, large | 0.142 |
| Body fat % | 0.06, trivial | 0.874 |
| Sit and reach (cm) | 0.05, trivial | 0.896 |
| Squat jumpJ (cm) | 0.27, small | 0.452 |
| Countermovement jump (cm) | 0.31, medium | 0.390 |
| Reactive strength index | 0.14, small | 0.695 |
| Snatch LOAD (kg) | 0.74, very large | 0.014 * |
| Snatch POWER (W) | −0.13, small | 0.721 |
| Bench press LOAD (kg) | 0.32, moderate | 0.368 |
| Bench press POWER (W) | 0.34, moderate | 0.337 |
| Back squat LOAD (kg) | 0.30, moderate | 0.392 |
| Back squat POWER (W) | 0.2, trivial | 0.548 |
| Yo-Yo test IR-2 (m) | 0.40, moderate | 0.253 |

* Denotes significant correlation ($p < 0.05$).

A k-means model established two centroids that determined the two groups, HI ($n = 6$) and LO ($n = 4$) (Figure 1). The unpaired *t*-test comparison revealed no differences between HI and LO groups in WOD scores.

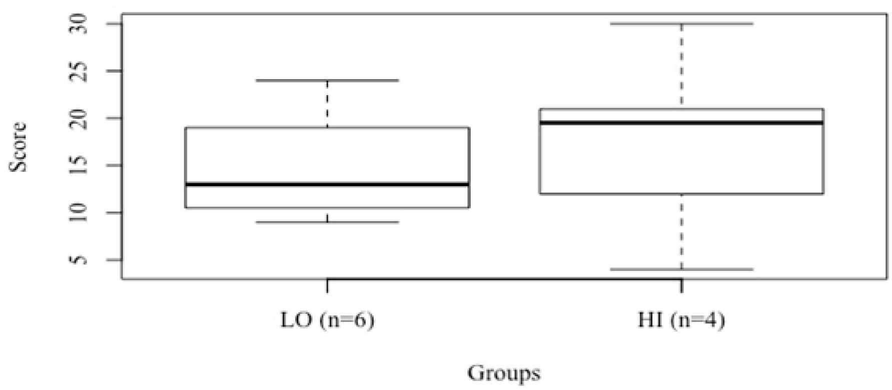


**Figure 1.** Boxplot visualization of the k-means cluster analysis grouping individuals as either high-performance (HI) or low performance (LO) and showing the minimum score, first quartile, median, third quartile, and maximum score achieved in the simulated competition by every group.

PCA cluster explains 74.72% of the variance using six performance variables measured in the study (SJ, CMJ, RSI, snatch LOAD, bench press LOAD, and back squat LOAD) (Figure 2). When CrossFit® performance groups HI and LO were compared, the *t*-test revealed no difference at $p \leq 0.05$ level.

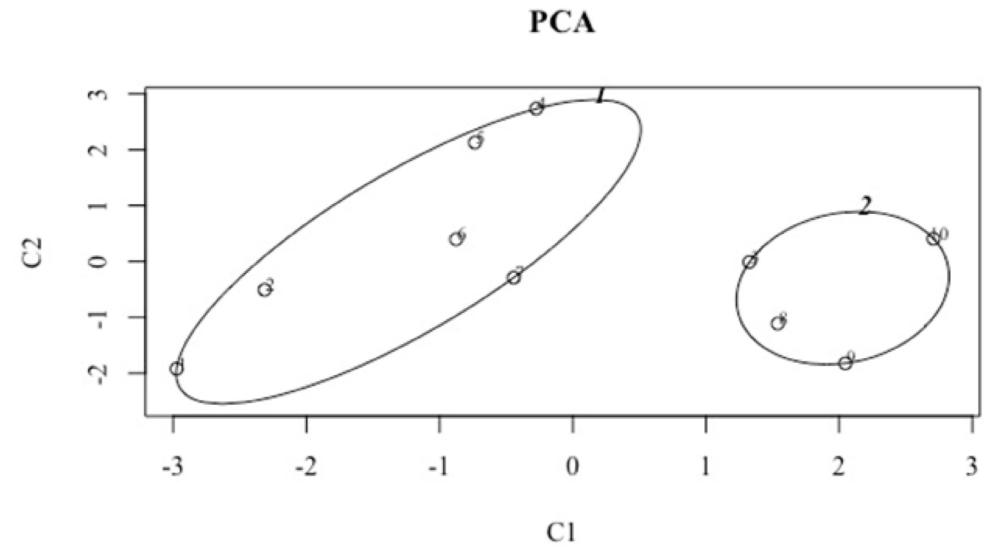


**Figure 2.** Principal Component Analysis with concentration and confidence ellipses around each group, including the six performance measures. Each main component is obtained by linear combination of the original six variables, and every dot inside the ellipses represents one individual in the HI ($n$ = 6) and LO ($n$ = 4) groups. These two components explain 74.72% of the point variability.

The average values obtained in the tests included in the PCA are presented to describe the performances obtained by the athletes who participated in our study (Table 4).

**Table 4.** Average values obtained in the tests included in the PCA.

| Descriptive Statistics | SJ (cm) | CMJ (cm) | RSI | Snatch LOAD (kg) | Bench Press LOAD (kg) | Squat LOAD (kg) |
|---|---|---|---|---|---|---|
| Mean | 33.1 | 38.1 | 0.114 | 59.6 | 53.8 | 65.7 |
| Standard deviation | 8.7 | 7.2 | 0.033 | 9.7 | 14.8 | 21.6 |

## 4. Discussion

The purpose of this study was to determine if a battery of standardized physical fitness tests can predict the outcome of a simulated CrossFit® competition. Competitive CrossFit® is a complex discipline, where many different skills and elements of physical fitness (endurance, stamina, strength, flexibility, power, speed, coordination, agility, balance, and accuracy) come into play to achieve success. Due to this complexity, the CrossFit® community has always accepted that the best way to assess performance (and therefore fitness levels) is to perform CrossFit® benchmark WODs and participate in CrossFit® competitions. This approach has significant limitations; specific CrossFit® workouts test more than one capacity, making it difficult to attribute the progress in a workout to all of them equally. If we improve our time or repetitions in one particular CrossFit® benchmark WOD, it is unfeasible to know if strength, skill, or conditioning was the main explanatory factor of this enhancement in performance. Additionally, CrossFit® competitive performance requires psychological and physiological settings. Thus, understanding the attributes related with CrossFit® performance can be relevant for two main reasons: it can be helpful to predict individual competitive outcomes and to work on the athletes' weaknesses, improving their performances.

Previous research has suggested a relationship between a combination of power measurements [22], whole-body strength [21], and power in the full-squat test [32], and CrossFit® performance. However, this approach has limitations. On the one hand, it is undeniable that benchmarks and competitions are specific; they reproduce the "unknown and unknowable" axiom of the sport. Nevertheless, using them to test fitness can be time-consuming, and for some recreational athletes, the RX standards can be unachievable. In some WODs, this changes the "testing" conditions dramatically, because it is evident that it is not the same to perform the benchmark "Fran" with a 30 kg barbell and jumping pull-ups or to use the prescribed weight and movements in the RX version. Standardized tests are valid, reliable, accurate, and sensitive to detect changes in fitness, being useful in different populations and age groups. Their main disadvantage is the need for equipment that can be expensive and, in some cases, requires training to be used. However, their application is fast, and they equalize the execution conditions for everyone.

The data reported in the present study partially support the initial hypothesis. Only the result of one incremental test, the snatch, showed a strong (but not perfect) correlation with the outcome of the competition, and this was more than likely conditioned by the fact that one of the benchmark WODs in the event ("Isabel") depended exclusively on the ability to perform this movement repeatedly with a high requirement of power. Despite this, the battery used in our study could discriminate between high (HI) and (low) LO performance athletes in the sample, explaining 74.72% of the variance with six performance variables measured. This result is consistent with that of other researchers arguing that CrossFit® experience and training level is a critical component of performance in CrossFit® workouts [22]. Weekly volume of training was not significantly correlated with the final competition score in our data, but a large correlation value (0.50) indicates that this factor can be considered as relevant in future research.

The lack of association between the individual outcome of the different fitness tests proposed and the simulated competition can be solved using a battery of tests. In one of the few investigations that we know regarding this matter, it was found that it is unfeasible to pretend that a single test of any nature can predict the result of a benchmark WOD in CrossFit® [21].

Although the benchmark WODs in this study were selected because they present very different physical condition elements (aerobic and anaerobic demands, weightlifting, gymnastics, and conditioning movements), the variables that could explain the variance were all of a similar nature; the only test assessing $VO_2$ max in our design showed no predictive power. "Fran" and "Isabel" are WODs that elite and sub-elite athletes can finish in less than five minutes, and "Kelly" lasts no longer than 20 min in these populations. This data agrees with previous research, where $VO_2$ max did not predict CrossFit® performance [21]. However, $VO_2$ max has explained 68% of the variance in the outcome of the workout "Nancy" [33], with five rounds of 400 m run. In our case, the chosen workouts had an anaerobic predominance, and the rest periods between WODs were enough to emphasize the importance of muscular power in the competitive outcome, showing an enhanced specific work capacity in the athletes [8]. In this direction, a test using four consecutive Wingate anaerobic tests has predicted CrossFit® specific performance in previous investigations [34].

We did not find any relationship between anthropometric measures and CrossFit® specific performance. This may be attributed to the participants' characteristics as expert athletes with suitable body composition (body fat 8.2 ± 2.83%) for their competitive development. The intrinsic characteristics of advanced CrossFit® athletes and the purposive sampling used in this research piece may have been a limiting factor in finding an association between body composition and competition outcome. All the athletes in our sample clearly showed a physical condition above the average among CrossFit® enthusiasts.

Flexibility levels were also shown not to be correlated with CrossFit® performance in our study. To the best of our knowledge, no previous research has included flexibility as a possible predictor of CrossFit® performance.

The present results should be interpreted with caution. The competition level of the athletes volunteering in our study (sub-elite) and the sample size are limitations to use our results to make inferences about other populations like elite athletes (CrossFit Games® caliber) or inexperienced CrossFit® recreational athletes. The selection of tests and benchmark WODs could also be a limitation. We should also understand that although all participants were instructed to perform all the WODs at the maximum intensity, the context (a simulated competition) could be less motivating than real competition settings.

Future work on the current topic is therefore recommended to apply these findings to different cohorts, using other benchmark WODs or workouts from a real competitive event. Incorporating different standardized tests that can lead to more robust results, and a higher percentage of the variance of the outcome explained by the selected performance factors, could also be desirable.

This study set out to know in greater depth what the critical elements of physical fitness are that allow one to achieve a good result in a simulated CrossFit® competition. The load at which the maximum snatch power was achieved and the combination of six physical fitness tests (SJ, CMJ, RSI, snatch LOAD, bench press LOAD, and back squat LOAD) partially explained the outcome of a simulated CrossFit® competition with the benchmarks "Fran", "Isabel", and "Kelly". Coaches and practitioners can use these findings to improve their decision-making processes and to use these tests as an element that can allow a better fit of the practices and workouts designed for their athletes.

## 5. Conclusions

Results coming from this article show that isolated physical condition tests can be misleading to explain the outcome of a CrossFit® WOD. These individual tests can only be useful in cases where the benchmark WODs performed in the CrossFit® context and its results are strongly related to the execution of one particular movement. Batteries of tests can help to discriminate athletes of different levels, showing that a better physical condition expressed in the battery is partially associated with a better overall performance in the specific CrossFit® activity. These batteries should implement tests that are valid, reliable, accurate, and sensitive to detect changes in fitness, but at the same time show some level of specificity with competitive CrossFit® requirements and CrossFit® athletes' specific needs.

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# Subjective versus Objective Measure of Physical Activity: A Systematic Review and Meta-Analysis of the Convergent Validity of the Physical Activity Questionnaire for Children (PAQ-C)

**Danilo Marasso [1], Corrado Lupo [2,*], Simone Collura [1], Alberto Rainoldi [2] and Paolo Riccardo Brustio [2]**

[1] School of Exercise and Sport Sciences (SUISM), University of Torino, 10124 Turin, Italy; danilo.marasso@unito.it (D.M.); simone.collura@edu.unito.it (S.C.)

[2] NeuroMuscularFunction Research Group, School of Exercise and Sport Sciences (SUISM), Department of Medical Sciences, University of Torino, 10143 Turin, Italy; alberto.rainoldi@unito.it (A.R.); paoloriccardo.brustio@unito.it (P.R.B.)

* Correspondence: corrado.lupo@unito.it; Tel.: +39-0116708083

**Abstract:** This study aimed to highlight the relationship between moderate-to-vigorous physical activity (MVPA) as assessed by accelerometer devices and the Physical Activity Questionnaire for Children (PAQ-C) to estimate the convergent validity of the questionnaire. A systematic review and a meta-analysis were applied by collecting pertinent studies (PubMed, Web of Science, PsycINFO, and SCOPUS) from 1997 until November 2020. The relationship between PAQ-C and MVPA scores was estimated considering correlation coefficients such as the effect size. Fisher's transformation was used to convert each correlation coefficient into an approximately normal distribution. The pooled correlations between PAQ-C and MVPA scores were measured by r values after converting the Fisher's z values back into correlation coefficients for presentation. A total of 13 studies were included in the meta-analysis, and a random effects model was adopted. The pooled correlation between PAQ-C and MVPA scores was significant but with a moderate effect size (r = 0.34 [0.29, 0.39], Z = 15.00, $p < 0.001$). No heterogeneity among the studies was observed ($I^2 < 25\%$). In conclusion, the results highlighted a moderate relationship (around 0.30–0.40) between PAQ-C and accelerometer measurements. These results suggested to concurrently administer both tools to reach a more comprehensive description of children's PA, in terms of quality and quantity.

**Keywords:** PA; MVPA; accelerometer; questionnaire; children

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## 1. Introduction

International guidelines recommend that children should accumulate at least 60 min of daily moderate-to-vigorous physical activity (MVPA) including sports and leisure activities [1]. Reaching these recommendations is associated with positive health outcomes, such as the reduction of overweight and obesity [1,2] and risk for chronic diseases and cancer in adulthood [3–5], and improvement of psychological well-being (e.g., reduction of depression and stress) [6], cognitive function and academic outcomes [1], and quality of life in general [7]. On the contrary, a low level of physical activity (PA) and the increase of sedentary behavior (e.g., screen time) are associated with both short- and long-term negative health consequences [1,8,9]. Despite the benefits of PA, two-thirds of children do not meet the international recommendations [10] and spend a large part of their waking time in sedentary activities [11–13]. Public health actions are necessary to counter this trend [1,11,12]. For this purpose, one of the global targets of the World Health Organization for the next years to prevent non-communicable diseases is to reduce the prevalence of insufficient PA by 15% [12,14]. Thus, an accurate assessment of childhood PA behavior is fundamental to accurately identify the effectiveness and the progression of healthcare interventions [15,16].

Data collection to assess and measure PA behavior can involve subjective and self-report (e.g., diaries/logs, questionnaires, or interviews) procedures, as well as objective and direct instruments including motion sensors (e.g., accelerometers, pedometers, and heart rate monitors), physiological marker (e.g., biomarkers), and calorimetry (e.g., direct and indirect) [15,17]. Among self-report instruments, PA questionnaires (PAQ) are practical to administer, relatively inexpensive, acceptable, and allow an insight into the PA of a large-scale population [18]. Nevertheless, PAQ can present some limitations. Socioeconomic and sociodemographic factors and measurement bias including misinterpretation or deliberate changes (e.g., social desirability) and difficulty to recall activities may affect the final score [18,19]. In particular, it is common that children have difficulties in understanding questions and accurately recalling activities [20], leading to an overestimate or underestimate of the overall PA level [15,21]. An alternative approach to a self-reported measure is the objective monitoring of PA using wearable devices, such as accelerometers. Accelerometer technology allows the measurement of accelerations produced by movement and may be considered an effective and feasible instrument to measure PA levels. Nevertheless, even though accelerometer technology objectively estimates the frequency, duration, and intensity of PA, it is time and cost intensive and difficult to administer to a large-scale population [15,17]. Moreover, due to physical constraints, some specific activities (e.g., swimming or bicycle activities) may be difficult to assess [22].

Among the numerous PAQs for children (see [22] for a complete review), none emerges as the best in terms of psychometric characteristics, but the Physical Activity Questionnaire for Older Children (PAQ-C) is one of the most promising [18]. The PAQ-C has been widely used in research and field settings (e.g., school context) to discern general levels of PA over the last seven days in children aged 8–14 years [23], even if it should not be used to assess PA in the summer or holiday periods [24]. The PAQ-C assesses activities related to common sports, leisure activities, games, and physical education classes [18,23]. It consists of ten items, nine of which are used to calculate summary activity scores with a score ranging from 1 to 5 for each item, where a higher score indicates higher levels of activity [23]. Interestingly, the first item is an activity checklist of common activities aimed to aid children to recall with memory cues. The PAQ-C demonstrated acceptable psychometric properties [18,23] with an acceptable-to-good internal consistency, test–retest reliability, and sensitivity to detect gender differences [23,25–28]. The PAQ-C demonstrated convergence with athletic competence, enjoyment perception, body mass index, cardiorespiratory, and cardiovascular fitness [16,25–27,29]. Nevertheless, while some studies showed a moderate correlation with accelerometer scores, and in particular with MVPA [16,20,26–28,30–32], others reported a low or no correlation [23,33–36].

The PAQ-C is used in different countries and cultural contexts for research purposes (e.g., Italy [16], Greece [28], Netherlands [29], China [30]). Thus, it is necessary to better understand the convergent validity (e.g., the extent to which different measurement tools measure the same construct) [37] of the questionnaire and synthesize the concurrent evidence in children's populations. Although previous systematic reviews discussed evidences about the convergent validity of PAQ versus accelerometers data reporting low-to-moderate correlation in children [18,22,38], no study specifically focused on the PAQ-C. Therefore, the purpose of this study was to systematically summarize the evidence on the relationship between MVPA measured with an accelerometer device and PAQ-C data. Specifically, we focus our research on MVPA because it is the reference value recommended by the general PA guidelines [1,11]. A systematic review in this field will help to provide a better understanding of the validity of PAQ-C to investigate PA patterns and behaviors in children. In addition, this study will be able to provide evidence-based recommendations for guiding population health programs aiming to promote active living and healthy lifestyles among children.

## 2. Materials and Methods

Four electronic databases including PubMed, Web of Science (WOS), PsycINFO (APAPsycNET), and SCOPUS were considered to search pertinent papers by using search strategies, which were similar and adaptable to each database. Search was performed using the strings ("acceleromet*" OR "motion senso*") AND ("physical activity questionnair*" OR "PAQ-C") AND ("child*" OR "young"). The research included the published articles from January 1997 to November 2020. We started from January 1997 because PAQ-C was developed in that period. In addition, references of included articles were screened to identify potential eligible studies.

### *2.1. Eligibility Criteria*

The following inclusion criteria were adopted: (1) all participants in the studies were children with an age range 8–14 years; (2) all participants did not present any mental, psychological, physical, or motor disorders; (3) PA was measured objectively using accelerometers and subjectively using the PAQ-C; (4) articles written in English language. No restriction in relation to uniaxial and triaxial devices was performed. Authors were contacted if a study failed to report data about the correlation between accelerometry (i.e., MVPA data) and PAQ-C. Only original, peer-reviewed studies that used the PAQ-C and an accelerometer score were included. If a study presented longitudinal assessment (e.g., physical exercise intervention), we considered only baseline measurements. Other sources (e.g., reviews, meta-analyses, abstracts, opinion articles, books, statements, letters, editorials, comment, and non-peer-reviewed journal articles) were excluded.

### *2.2. Article Selection*

All potential studies were imported into Zotero (www.zotero.org, accessed on 21 February 2021), and duplicates were removed. A summary of the study screening protocol and selection has been provided in Figure 1. The selection process was conducted by two authors (D.M. and S.C.), who independently screened the title and/or the abstract of the selected studies to identify studies that potentially met the inclusion criteria. Then, the full texts of the potentially suitable studies were examined by the same authors for eligibility. Disagreements were resolved through discussion with a third author (P.R.B.), who finally decided in case of conflicting results. If any information useful for the data collection was missed, the corresponding author of the manuscript was contacted. If no response was provided or data were not available, the study was excluded from the analysis.

### *2.3. Study Quality Assessment*

An adapted version of the Strengthening the Reporting of Observational Studies in Epidemiology checklist (STROBE) [39] was used to assess the quality of the study reporting. The checklist included 20 items grouped into five categories: Abstract (#1 items), Introduction (#2–#3 items), Methods (#4–#11 items), Results (#12–#15 items), and Discussion (#16–#19 items). The assessment of the quality of each item was scored as 1 (i.e., present) or 0 (i.e., not present). The total resultant score (i.e., sum of each item) was considered according to the following level: "low quality" (0–9 points), "medium quality" (10–15 points), and "high quality" (16–19 points). Two independent authors (D.M. and S.C.) completed the study quality assessment. Disagreements were resolved by discussion between assessors.

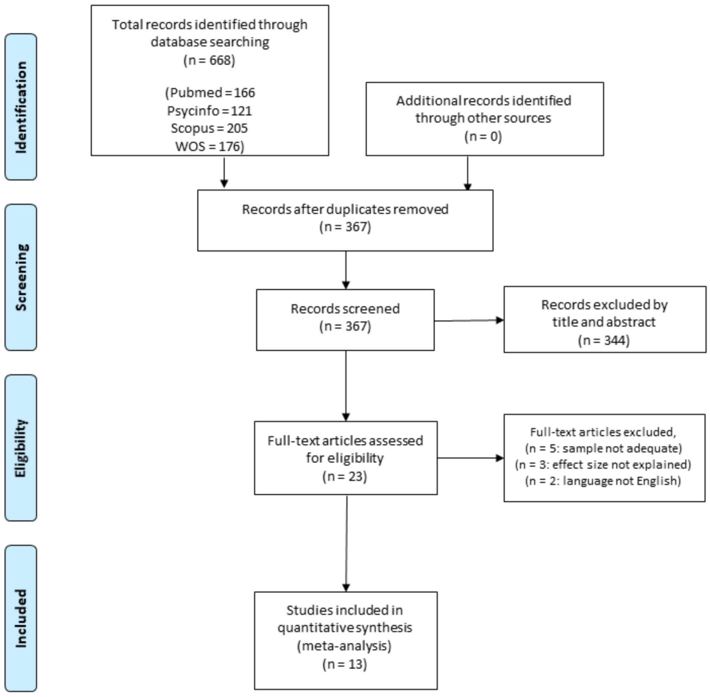


**Figure 1.** Flow diagram for screening and selection of studies.

### *2.4. Meta-Analyses*

A Microsoft Excel® (Microsoft Corp., Redmond, WA, USA) spreadsheet was compiled with the following information: study information (i.e., lead author, location, and year of publication); study population characteristics (i.e., sample size, age, and gender); accelerometer information (i.e., placement position, number of days per week and weekend, epoch length, algorithm used to investigate PA intensity, and outcome); principal outcomes (i.e., PAQ-C and MVPA scores) and correlation analysis (i.e., Pearson correlation coefficient or Spearman's rho). The data were extracted from any section of the manuscript.

The relationship between PAQ-C and MVPA scores was estimated considering the effect size based on the correlation coefficients. Data reported as Spearman's rho were converted into Pearson correlation coefficient using the formula $r = 2sin(r_s \frac{\pi}{6})$, where $r$ is the Pearson's correlation coefficient and $r_s$ the Spearman's rho [40]. Fisher's transformation was used to convert each correlation coefficient into an approximately normal distribution. The pooled correlations between PAQ-C and MVPA scores were measured by $r$ values after converting the Fisher's z values back into correlation coefficients for presentation. Heterogeneity (i.e., the percentage of the total variability in an effect size between studies) was evaluated using the $I^2$ index. The level of heterogeneity represented by the $I^2$ index was interpreted as low (25% to ≤50%), moderate (50% to ≤75%), and large (>75%) [41]. A random-effects model was adopted. Publication bias was assessed by visual inspection of the funnel plot and Begg's and Egger's tests. All statistical analyses were conducted using the packages "meta" and "metacor" [42] of R (version 4.0.0; R Core Team, Foundation for Statistical Computing, Vienna, Austria). The inverse variance weighting approach was used for pooling [43]. According to Cohen's guidelines, pooled correlations were interpreted as low (<0.30), moderate (0.31–0.49), and large (≥0.50) [44]. A $p$-value <0.05 was considered statistically significant.

## 3. Results

### *3.1. Studies Systematically Identified*

Figure 1 summarizes the systematic search and study selection process.

The initial database search yielded 668 articles. After the removal of the duplicates (N = 301), articles were screened for titles and abstracts, and 23 full-text articles were selected. Five studies were removed because they also included children older than the reference population of the questionnaire, two studies were removed because they were not written in English, and three as they did not report correlation data and the authors did not respond to our request. Overall, 13 studies met the inclusion and reporting criteria.

### 3.2. Study Description

Table 1 summarizes the characteristics of the identified studies according to the following items: general information, sample characteristics, accelerometer information, principal outcomes, and correlation scores between PAQ-C and MVPA scores.

Ten studies were published in the last eight years [16,28,30,31,33–36,45,46], whereas three studies were published between 1997 and 2011 [27,32,47]. The studies were conducted in Europe [16,28,32–34,45], Asia [30,31,35], North America [27,46], North Africa [36], and Oceania [47]. Twelve studies included both male and female participants, whereas one examined girls only [45]. One study [27] did not report data about gender. Sample sizes across studies ranged from 20 to 365; eight studies had sample size ≥100 [28,30–32,34,35,45,46]. To objectively investigate PA, 11 studies used ActiGraph [16,28,30–36,46,47], one the Caltrac [27], and one the Cosmed Liferecorder device [45]. In particular, eight studies adopted triaxial accelerometers [16,28,30,31,33–36], and five uniaxial accelerometers [27,32,45–47].

In all 13 studies included in the meta-analysis, accelerometer devices were worn on the waist. Nevertheless, seven of them placed accelerometers on the right side through an elastic belt [16,31–34,36,47], whereas the other six studies did not specify on which side the accelerometers were worn [27,28,30,35,45,46]. The accelerometers were worn for seven consecutive days in nine studies [16,27,28,30,31,33–35,46], and for five days [32] and four days [47] in one study, respectively. One study [36] did not specify the total days but only four days as the minimum unit of time, whereas another one [45] did not report the days of wearing. The majority of the studies (N = 10) reported an epoch of 15 s or less [16,28,30–36,45], one of 30 s [46], and the other two did not report the data [27,47].

### 3.3. Study Quality

According to selected criteria, seven studies out of thirteen (54%) were considered "high quality" and six (46%) were considered "medium quality", while none was considered "low quality". Criteria commonly absent in reporting were related to defining potential confounders, using adequate power calculations to ensure the study size, and reporting statistical estimate(s) and precision (e.g., 95% CI). Additional information about quality scores is presented in Table 2.

**Table 1.** Summary of the studies included in the meta-analysis (alphabetical order).

| Study Information | | | Study Population | | | Accelerometer Information | | | | | | | Outcomes | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Authors** | **Location** | **Years** | **Sample Size** | **Mean Age (Range)** | **Gender (% Girls)** | **Model (Axis)** | **Placement** | **N Days (Week-end)** | **Epoch Length (s)** | **Outcomes** | **Cut-Point PA Intensity Level (Non-Wearing Definition)** | **h/Day** | **PAQ-C (Points)** | **MVPA (min/Day)** | ***r*** |
| Ben Jemaa et al. [36] | Tunisia | 2018 | 40 | 9.34 ± 0.94 (8–11) | 47.5% | ActiGraph GT3X + (triaxial) | hip | 4 (1) | 15 | ST, LPA, MPA VPA, MVPA | Evenson et al. (≥60 min) | ≥6 | 2.55 ± 0.67 | 59.77 ± 22.01 | 0.119 |
| Benitez-Porres et al. [34] | Spain | 2016 | 146 | 10.8 ± 1.3 (9–12) | 43.1% | ActiGraph GT3X (triaxial) | hip | 7 (1) | 1 | MVPA step/day | Evenson et al. (≥60 min) | ≥10 (week) ≥8 (WE) | 3.09 ± 0.64 | 62.80 ± 13.90 | 0.170 ¥ |
| Benitez-Porres et al. [33] | Spain | 2016 | 78 | 10.98 ± 1.17 (9–12) | 46.1% | ActiGraph GT3X (triaxial) | hip | 7 (1) | 1 | MVPA | Evenson et al. (≥60 min) | ≥10 (week) ≥8 (WE) | 3.24 ± 0.64 | 63.22 ± 14.40 | 0.248 ¥ |
| Chan et al. [35] | China | 2018 | 191 | 9.9 ± 1.0 (8–11) | 59,7% | ActiGraph GT3X + (triaxial) | hip | 7 (1) | 15 | MVPA | Evenson et al. (≥20 min) | ≥6 | 2.67 ± 0.70 | 40.86 ± 14.07 | 0.190 |
| Fairclough et al. [32] | England | 2011 | 175 | 10.6 ± 0.3 (10–11) | 55.4% | ActiGraph GT1M (uniaxial) | hip | 5 (1) | 5 | MPA, VPA, MVPA, counts/min | Ekelund et al. (≥20 min) | ≥6 (week) ≥6 (WE) | 3.39 ± 0.13 (M) 3.00 ± 0.11 (F) | 66.30 ± 3.70 (M) 54.10 ± 3.20 (F) | 0.338 |
| Gobbi et al. [16] | Italy | 2016 | 55 | 9.5 ± 0.4 (9–10) | 50.9% | ActiGraph GT3X + (triaxial) | hip | 7 (n.r.) | 15 | MVPA | Evenson et al. (≥60 min) | ≥9 | 2.79 ± 0.52 | n.r. | 0.300 * |
| Kowalski et al. [27] | Canada | 1997 | 70 | 11.30 ± 1.39 (9–13) | n.r. | Caltrac (uniaxial) | hip | 7 (1) | n.r. | MVPAMVPA > 10min | n.r.(n.r.) | n.r. | 3.32 ± 0.68 | n.r. | 0.390 |
| Labbrozzi et al. [45] | Italy | 2012 | 118 | n.r. (11–13) | 100% | COSMED Lifecorder (uniaxial) | hip | n.r. | 4 | LPA, MPA, VPA | Kumahara et al. (n.r.) | n.r. | n.r. | n.r. | 0.456 |
| Ni Mhurchu et al. [47] | New Zealand | 2008 | 20 | 12 ± 1.5 (10–14) | 40% | ActiGraph 7164 (uniaxial) | hip | 4 (2) | n.r. | PA counts, LPA, MPA, VPA | Freedson et al. (≥20 min) | ≥8 | 1.8 ± 0.6 | n.r. | 0.440 * |
| Saint-Maurice et al. [46] | USA | 2014 | 103 | 10.8 ± 2.0 (8–13) | 52.4% | ActiGraph GT1M (uniaxial) | hip | 7 (1) | 30 | MVPA | Freedson et al. (≥90 min) | ≥9 | 3.1 ± 0.7 | n.r. | 0.350 ¥ |
| Venetsanou et al. [28] | Greece | 2020 | 218 | 10.99 ± 1.52 (9–13) | 56.9% | ActiGraph GT3X + (triaxial) | hip | 7 (1) | 5 | MVPA, steps/day | Evenson et al. (n.r) | n.r. | 2.70 ± 0.55 (M) 2.51 ± 0.53 (F) | 42.46 ± 12.46 (M) 31.70 ± 9.21 (F) | 0.354 ¥ |
| | | | | | | | | | | | | | 2.78 ± 0.37 (M) 2.35 ± 0.47 (F) | 40.33 ± 11.95 (M) 33.31 ± 8.41 (F) | |

**Table 1.** *Cont.*

| Study Information | | | Study Population | | | Accelerometer Information | | | | | | | Outcomes | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Authors** | **Location** | **Years** | **Sample Size** | **Mean Age (Range)** | **Gender (% Girls)** | **Model (Axis)** | **Placement** | **N Days (Weekend)** | **Epoch Length (s)** | **Outcomes** | **Cut-Point PA Intensity Level (Non-Wearing Definition)** | **h/Day** | **PAQ-C (Points)** | **MVPA (min/Day)** | ***r*** |
| Wang et al. [30] | China | 2016 | 365 | 10.2 ± 1.1 (8–13) | 45.2% | ActiGraph GT3X (triaxial) | hip | 7 (1) | 5 | MVPA | Evenson et al. (≥20 min) | ≥8 | 2.70 ± 0.70 | 43.10 ± 12.74 | 0.390 |
| Wang et al. [31] | China | 2016 | 358 | 10.5 ± 1.1 (9–12) | 45.8% | ActiGraph GT3X (triaxial) | hip | 7 (1) | 5 | MPA, VPA, MVPA | Evenson et al. (≥20 min) | ≥8 | 2.60 ± 0.68 | 43.00 ± 13.72 | 0.330 ¥ |

Notes: n.r., data not reported in the paper; M, male; F, female; SB, Sedentary Behavior; LPA Light Physical Activity; MPA, Moderate Physical Activity; VPA, Vigorous Physical Activity; MVPA, Moderate to Vigorous Physical Activity; WE, weekend; ¥, data are reported as Spearman's rho; *, data directly provided by the authors. Cut-point PA intensity level: Evenson's PA cutoff: SB (0–100 counts/min), LPA (101–2295 counts/min), MPA (2296–4011 counts/min), VPA (≥4012 counts/min); Ekelund's PA cutoff: SB (<500 counts/min), LPA (501–2000 counts/min), MPA (2001–3999 counts/min), VPA (≥4000 counts/min); Freedson's PA cutoff: LPA (1.5–2.9 MET), MPA (3.0–5.9 MET), VPA (≥ MET); Kumahara's PA cutoff: LPA (<3 MET), MPA (3–6 MET), VPA (≥6 MET). PAQ-C, Physical Activity Questionnaire for Children.

**Table 2.** The Strengthening the Reporting of Observational Studies in Epidemiology checklist (STROBE) scores and summary of studies' quality.

| | 1# | 2# | 3# | 4# | 5# | 6# | 7# | 8# | 9# | 10# | 11# | 12# | 13# | 14# | 15# | 16# | 17# | 18# | 19# | Score/19 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ben Jemaa et al. [36] | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 14 |
| Benitez-Porres et al. [34] | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 15 |
| Benitez-Porres et al. [33] | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 17 |
| Chan et al. [35] | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 16 |
| Fairclough et al. [32] | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 16 |
| Gobbi et al. [16] | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 15 |
| Kowalski et al. [27] | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 12 |
| Labbrozzi et al. [45] | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 16 |
| Ni Mhurchu et al. [47] | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 14 |
| Saint-Maurice et al. [46] | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 14 |
| Venetsanou et al. [28] | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 16 |
| Wang et al. [30] | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 16 |
| Wang et al. [31] | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 16 |

Notes: 0 = Item criterion is absent or insufficient information is provided; 1 = item criterion is present and explicitly described. #1. In the abstract, an informative and balanced summary of what was done and what was found is provided. #2. Explains the scientific background and rationale for the investigation being reported. #3. States clear, specific objectives and/or any prespecified hypotheses. #4. Describes the setting (e.g., school context), locations (e.g., nation), and relevant dates for data collection. #5. Give characteristics of study participants (must include age and gender) and eligibility criteria. #6. Clearly defines all outcomes, potential confounders, and effect modifiers. #7. For each variable of interest, gives sources of data and details of methods of assessment (e.g., information about accelerometer time of wearing, epoch length, wearing position). #8. Describes any efforts to address potential sources of bias (e.g., minimum of daily wearing, statistical treatment of outliers). #9. Checks whether the study used power calculations to ensure the study size was adequately powered to detect hypothesized relationships? #10. Explains how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen, and why. #11. Describes all statistical methods, including those used to control for confounding and any methods used to examine subgroups and interactions (if applicable). #12. Indicates the number of participants with missing data for each variable of interest. #13. Cohort study—Report numbers of outcome events or summary measures over time. #13. Cross-sectional study—Reports numbers of outcome events or summary measures. #14. A measure of effect size is provided (e.g., Cohen's effect size, Pearson's r, Spearman's rho). #15 Provides statistical estimate(s) and precision (e.g., 95% CI) for each sample or subgroup group examined. #16. A summary of key results with reference to study objectives is provided. #17. Discusses limitations of the study, considering sources of potential bias, confounding factors, or imprecision. #18. A cautious overall interpretation of results considering objectives and relevant evidence. #19. Discusses the generalizability of the study results to similar or other contexts. TOTAL/19.

### 3.4. Meta-Analyses

A total of 13 studies were included in the meta-analysis. A random-effects model was adopted. The pooled correlation between PAQ-C and MVPA scores was significant but moderate (r = 0.34, 95% CI [0.29, 0.39], Z = 12.16, $p < 0.001$) and was homogeneous ($I^2 = 24.7\%$; $\tau^2 = 0.0024$, $p = 0.194$). Forest plot results are presented in Figure 2.

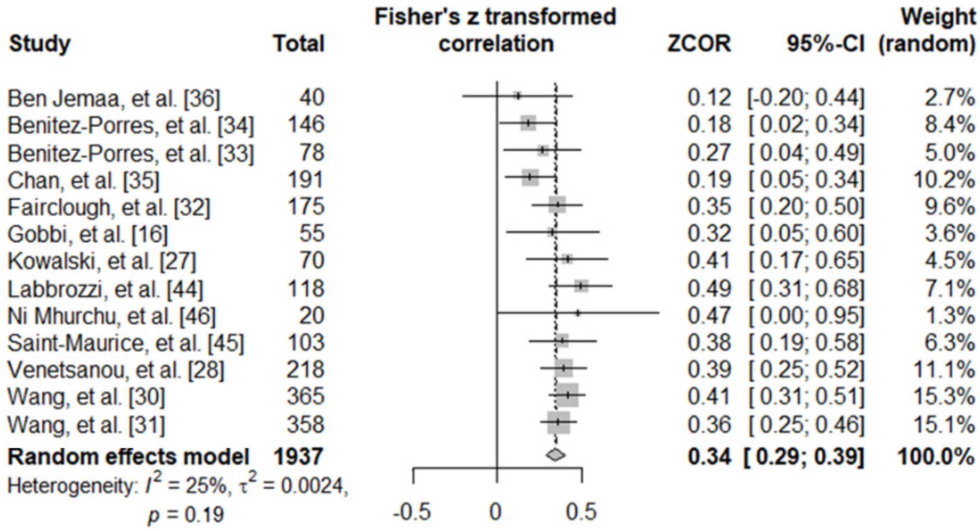


**Figure 2.** Forest plot showing the relative and pooled correlations between PAQ-C and MVPA scores of the included studies.

## 4. Discussion

This systematic review aimed to summarize existing evidence on the convergent validity of the PAQ-C to investigate absolute PA pattern and behavior in children aged 8–14 years. For this purpose, we investigated the aggregated effect size between PAQ-C and accelerometer scores considering 13 publications. The present work is novel because there are only few reviews discussing self-reported questionaries versus objective PA in children [18,22,38], and it focused on a specific questionnaire (i.e., PAQ-C). The PAQ-C is growing in popularity in different sociocultural contexts. Thus, it is necessary to understand whether the PAQ-C may correctly monitor absolute PA in children and accurately assess the effectiveness and changes of interventions designed to increase activity levels, examine relationships between PA and health, and inform public health policy [38]. This aspect is particularly challenging because it may influence healthy lifestyles during adulthood and older age.

A review on the qualitative attributes and measurement properties of PAQ suggested that a correlation coefficient of 0.5 or higher should be acceptable for the validity of PA [48]. The present study disclosed significant moderate pooled correlations of 0.34 [0.29, 0.39] (see Figure 2) with a low degree of heterogeneity among the considered studies ($I^2 = 24.7\%$, $\tau^2 = 0.002$, $p = 0.194$). Additionally, our results were quite consistent: none of the selected studies reached the standard of 0.5 in correlation result (range: 0.119–0.456). These data indicate a moderate convergent validity of PAQ-C, although lower than the acceptable standard [48], when compared with the accelerometer. This result suggests a difference in the ability of PAQ-C and accelerometers to measure the same construct (i.e., PA). Thus, it is possible to argue that when investigating absolute PA with PAQ-C, the risk of bias may be large, corroborating the idea of substantial discrepancies between indirect and direct methods to assess PA in pediatric populations [38]. In other words, the wide correlation variability reported in the considered studies indicates that no clear picture can be drawn regarding the PA levels when using PAQ-C.

Our results are in line with previous reviews on children and youth [18,22,38], adult [15,17,37,49], and older population [17] that reported a large variability in correlation results between direct and indirect methods. In an extensive systematic review on the topic in adult population (age $\geq$ 18 years), Prince at al. [15] found a low-to-moderate correlation ($-0.71$ to 0.96) between PAQs and accelerometer measures pointing out that the agreement between the two methods was remarkably low. Similarly, Lee et al. [49] reported a greater variability in correlations (from $-0.18$ to 0.76) between vigorous or moderate activities assessed by means of the International Physical Activity Questionnaire-Short Form and accelerometer measures, as well as an overestimation in PA by 36% to 173% using self-report questionnaires. Again, with a meta-analytic approach similar to that herein presented, Kim et al. [37] examined the convergent validity of the International Physical Activity Questionnaire with an accelerometer and reported an average effect size of 0.21 [0.17, 0.26] with moderate PA. Similar comparisons were conducted in children and youth (5–17 years old). Chinapaw et al. [18] reviewed 61 PAQs for children and adolescents and reported heterogeneity in the results, with correlations between PAQ and accelerometers ranging from very low to high. These data were confirmed in a recent update study that reported lower acceptable validity, partly due to the low methodological quality of the studies [22].

In our analysis, we did not find heterogeneity among the studies (see $I^2$ and $\tau^2$ values), despite the methodological differences of studies included in the meta-analysis. Different types of accelerometers (i.e., uniaxial and triaxial), settings of recorded data (e.g., epoch length or number of days recorded), and data analysis algorithms, such as non-wear-time definition and cutoff point to identify PA intensities (e.g., light, moderate, and vigorous PA), were identified in the selected studies. About two thirds of the studies (i.e., 61.5%) used triaxial rather than uniaxial accelerometers, which are considered more accurate than the latter. Nevertheless, it should be pointed out that all the studies using triaxial accelerometers calculated cutoff PA intensity level through Everson criteria [50], which are based only on the acceleration in the vertical plane. Additionally, we observed a wide variability in epoch lengths setting (ranging from 1 to 30 s). It is well known that the epoch length may affect the estimation of the PA bouts under free-living conditions especially in children [51], and this estimation decreases as epoch length increases [52]. Even if shorter epochs (e.g., 5 s or less) are potentially more sensitive to detect MVPA than longer ones, it seems not to weaken the correlation between PAQ-C and accelerometers. Similarly, while eight studies [16,28,30,31,33–36] used the international recommend cut-point for children [50,53] to determine the time spent on different PA intensity levels (i.e., range 0–100 counts/min for sedentary behavior, range 101–2295 counts/min for light, range 2296–4011 counts/min for moderate, and $\geq$4012 counts/min for vigorous PA) five studies [27,32,45–47] chose different cut-points. Moreover, while the PAQ-C recalls the PA behavior in the last seven days, 3 out of 13 studies [32,36,45,47] failed to collect the same timeframe due to limiting the accelerometer wearing or considering less than seven days sufficient in the data analysis. Again, not all the studies reported that the self-report and directly assessed PA levels were measured concurrently [30,31,35] leading to an increase of bias. Most of the studies (9 out of 13) [16,27,28,30,31,33–35,46] reported requiring that subjects wear the device at least for seven days, but higher variability range in correlation score was reported among these studies (range 0.170–0.390).

All these methodological differences among studies seems not to weaken the correlation between PAQ-C and accelerometers. On the contrary, we were not able to investigate the effect of wearing placement because all included studies placed the accelerometer on the waist. As previously discussed, accelerometers could not measure certain kinds of activities, and the wearing position could amplify this lack. For example, Troiano et al. [54] argued that wearing accelerometers on the wrist could improve wear compliance and allow the measurement of movement during sleep, while Rosemberger et al. [55] claimed that the hip is better for estimating activity energy expenditure and identify activity intensity thresholds. Probably, the appropriate wear location is dependent on specific objectives and will be outlined in the study protocol. For this reason, the effect of wearing placement on correlation between PAQ-C and accelerometers should be taken into account in future studies on the topic.

As a reasonable gold standard for measuring PA does not exist [18], in our study we focused on accelerometers as an objective criterion for measuring PA. Nevertheless, caution is needed when interpreting the findings herein. Indeed, we believe that the results from our study may not be generalized as the overall convergent validity of PAQ-C. Commonly, accelerometer devices are the most used tools to objectively evaluate levels of physical behavior. It allows to directly evaluate the frequency, duration, and intensity of movement and is considered a useful device for estimating energy expenditure [56] in different real contexts. Nevertheless, accelerometer technology did not allow the quantification of some types of activities, such as cycling- and water-based activities or upper body movements, when it is worn on the waist and is not able to discriminate between qualitatively different activities [45,57,58]. On the contrary, the PAQ-C investigates a broad range of leisure and sport activities, which can lead to a larger description of the weekly PA in terms of activity types, time frame during daily and weekly routine, and self-perception of physical activity involvement. Furthermore, differences between PAQ-C score and accelerometers MVPA could be interpreted as the children's difficulty in judging and feeling their own physical engagement. According to the above findings, our results suggested that PAQ-C and accelerometers may be considered two different tools to investigate PA. In other words, it is possible to suggest that the PAQ-C may be used to investigate children's PA behaviors (i.e., type and schedule of PA) rather than absolute PA. Concurrently using the two instruments might provide both a qualitative and quantitative evaluation of PA that could permit better exploration of the relation between self-perceived and actual PA in children, to make, for example, corrections to planned activities or to dedicate time to the improvement of self-perception ability. Thus, with the aim of an accurate and effective assessment of PA, it is possible to suggest the use of both instruments to have a deeper overview of PA behavior and level, especially in the first step of the assessment and design of PA interventions [33]. In light of our results, it could be possible to propose the use of the PAQ-C to take information about the type and weekly distribution of physical activities and, thus, provide a global measure of children's PA, while accelerometers could provide more information about the quantification of the PA.

Some limitations should be finally pointed out. In this systematic review, we focused on the convergent validity of the PAQ-C, but we did not consider measurement properties such as reliability, validity, criterion validity, and measurement error. We considered only correlation coefficients that are not able to detect the agreement and the absolute difference between objective and self-report measures. We focused only on MVPA and not on total PA. It is possible that the correlation between objective and subjective measures of total PA may be larger, due to the lower specificity of the total PA to the use of different cutoffs. Moreover, comparing the PAQ-C score with total PA could overcome difficulties in the perception of physical intensity of children. Additionally, we are not able to investigate gender-related differences in convergent validity. This might be interesting considering the difference in self-perception of PA between males and females [59], even if differences in the considered samples seem not to modify our conclusion, as low heterogeneity shows. Finally, we only focused on English articles disregarding relevant studies published in other languages.

## 5. Conclusions

To our knowledge, the present study is the first comprehensive attempt to synthesize the scientific evidence on the convergent validity of PAQ-C using meta-analysis. Together the results of this study heightened the moderate convergent validity of PAQ-C with accelerometer measurements. Currently, the drawing of any definitive conclusion concerning the convergent validity of PAQ-C in comparison with the accelerometers is not possible. This suggests that the PAQ-C may be valid for identifying children' PA behavior rather than for absolute PA. Both subjective and objective assessments of PA have limits and advantages. Considering the different nature of both measurements, it is suggested that, for a more comprehensible and deeper PA overview, a combination of PAQ-C and accelerometer devices appears the most promising. Finally, caution should be exerted when comparing studies using PAQ-C and accelerometers.

As practical applications, caution is needed in the choice of instruments to investigate PA in children. PAQ-C and accelerometers seem to measure different aspects of the same construct. While the first one may provide a qualification of PA (e.g., time frame, weekly routine, and self-perception) the second one may provide information about movement quantification (e.g., intensity, frequency, and duration). In addition, the use of both instruments may provide a deeper overview of PA behavior and level, especially in the first step of the assessment and planning of appropriate PA intervention in children. Finally, the use of both instruments allows for a better understanding of the association between actual and perceived physical activity in children.

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# The Impact of Fluid Loss and Carbohydrate Consumption during Exercise, on Young Cyclists' Fatigue Perception in Relation to Training Load Level

**Leonardo Cesanelli [1], Berta Ylaitė [2], Giuseppe Messina [1,*], Daniele Zangla [1], Stefania Cataldi [3], Antonio Palma [1] and Angelo Iovane [1]**

[1] Sport and Exercise Sciences Research Unit, Department of Psychological, Pedagogical and Educational Sciences, University of Palermo, I-90128 Palermo, Italy; cesanelli.leonardo@gmail.com (L.C.); daniele.zangla@unipa.it (D.Z.); antonio.palma@unipa.it (A.P.); angelo.iovane@unipa.it (A.I.)
[2] Institute of Sport Science and Innovations, Faculty of Sport Biomedicine, Lithuanian Sports University, 44221 Kaunas, Lithuania; berta.ylaite@gmail.com
[3] Department of Basic Medical Sciences, Neuroscience and Sense Organs, School of Medicine, University of Study of Bari, 70122 Bari, Italy; Stefania.cataldi@uniba.it
* Correspondence: giuseppe.messina17@unipa.it

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**Abstract:** High-level young athletes need to face a wide spectrum of stressors on their journey to élite categories. The aims of the present study are (i) to evaluate session rate of perceived exertion (sRPE) at different training impulse (TRIMP) categories and the correlations between these two variables and, (ii) evaluate the correlations between sRPE, fluid loss, and carbohydrate consumption during exercise. Data on Edward's TRIMP, sRPE, body mass loss pre- and post- exercise (Δ), and carbohydrate consumption (CHO/h) during exercise have been acquired from eight male junior cyclists during a competitive season. One-way ANOVA and correlation analysis with linear regression have been performed on acquired data. sRPE resulted in a significant difference in the three TRIMP categories ($p < 0.001$). sRPE resulted in being very largely positively associated with TRIMP values ($p < 0.001$; R = 0.71). Δ as well as CHO/h was largely negatively related with sRPE in all TRIMP categories ($p < 0.001$). The results confirmed the role of fluid balance and carbohydrate consumption on the perception of fatigue and fatigue accumulation dynamics independently from the training load. Young athletes' training load monitoring and nutritional-hydration support represent important aspects in athlete's exercise-induced fatigue management.

**Keywords:** fatigue; young athletes; cycling performance; sport nutrition; hydration

## 1. Introduction

High-level young athletes need to face a wide spectrum of stressors on their journey to élite categories [1,2]. Daily training and competitions represent the main physiological load expositions. However, school tasks, social interactions, and the additional physical activities to the training routine, determine a cumulative high-level physio-psychological workload and potentially, an increased fatigue perception [3].

Since the balance between stress and recovery has been widely recognized as a key aspect to ensure athlete health and to improve performance, different approaches have been investigated in order to analyze and modulate stressors and recovery factors [2,4]. Monitoring of training stress response represents a fundamental aspect to prevent disruption of this homeostatic balance. The importance of training load monitoring tools has been recently underlined by the observations of Hamlin and colleagues (2019), indicating how physio-psychological load markers may predict young athletes' injuries as well as a functional tool to manage athlete's overall stress [2]. Filipas et al., (2019) further reported how acute central fatigue may have a negative impact on endurance performance [5]. This seems to be explained by an increased perception of effort for internal and external loads and, suggesting the importance of fatigue perception monitoring [6,7]. Thus, monitoring of training load and fatigue perception seems to represent valid tools to preserve young athletes' health and to track and better manage performance fluctuations.

Nutritional support during exercise represents an additional fundamental aspect to preserve health and performance, with the main aims of covering energetic and plastic demands of physical activity and ensuring a successful recovery [8]. Carbohydrate ingestion during exercise has been associated with improved performance, preventing exercise-induced hypoglycemia, and maintaining high levels of carbohydrate oxidation [8–10]. Water has been also suggested as one of the most important ergogenic aids for athletes, with exercising performance described as being significantly impaired when 2% or more body weight is lost through sweat during exercise [9,10]. Further weight loss of more than 4% of body weight has been associated with heat illness, heat exhaustion, heat stroke and possibly death [9,10]. The increased and detailed requirements of young athletes, dictated by the growth process and by the previously described heterogeneity of daily tasks, made nutritional support a focal point in order to ameliorate athlete's performance and well-being [8]. Fluid intake and hydration status monitoring are also essential factors in young athletes' growth processes and performance development, as well as in preventing fatigue accumulation [8,11]. Taken together, evidence suggests how young athletes' training load monitoring and nutritional support are two main aspects to maintain the homeostatic balance between stress and recovery factors (Figure 1).

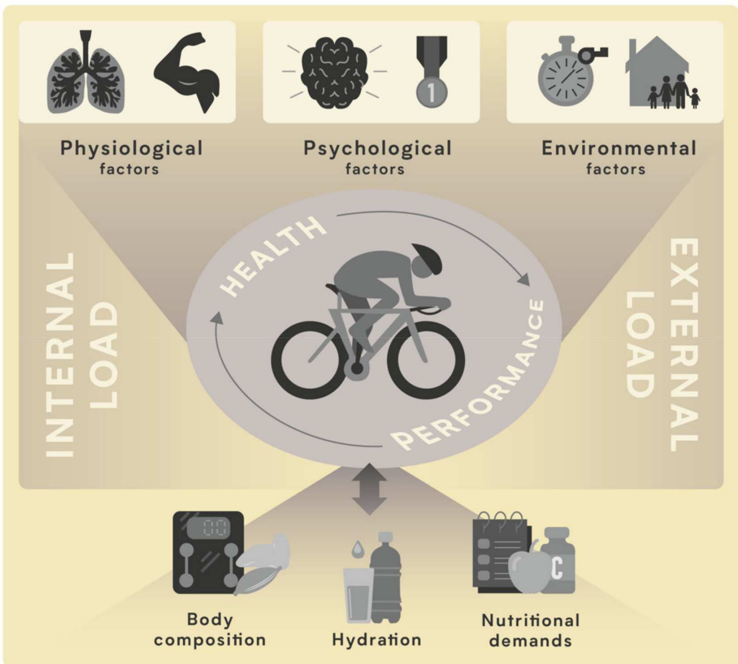


**Figure 1.** Graphical summary of the main performance and health determining factors of young competitive cyclists.

Thus, the aims of the present study are (i) to evaluate the fatigue perception (session-RPE scale) at different training impulse (TRIMP) categories (low, medium, and high load) and the correlations between these two variables and, (ii) evaluate the correlations fatigue perception (sRPE), fluid loss and carbohydrate consumption during exercise at different training impulse (TRIMP) categories (low, medium, and high load).

## 2. Materials and Methods

### *2.1. Study Participants*

Data from a team of 8 male competitive junior category cyclists (16.2 ± 0.7 years; 66.1 ± 4.5 kg; 174.6 ± 4.9 cm) have been acquired during the 2017–2018 season as part of a team health and performance monitoring program. All cyclists performed similar team-monitored training sessions for 2 to 5 days/week (depending on the period of the season and individual training periodization, planned, and prescribed by the team's staff). All the participants obtained health medical certificates for sport and physical activities as a mandatory procedure to participate in the competitive season. During the investigation period, dietary behaviors, body composition analysis, and training data have been acquired and analyzed by certified sports nutritionists and strength and conditioning coaches. All the participants and families of each participant were fully informed of all aspects of the study and signed a statement of informed consent. This research was designed in accordance with the Declaration of Helsinki (2008), with the Fortaleza update [12].

### 2.2. Measurements

Athletes' training data were acquired through their personal GPS and HR monitoring cyclocomputers and, successively, exported and analyzed. Based on pre-season testing parameters (i.e., incremental tests and rest HR data) and training data (i.e., HR and duration of training) the Edward's training impulse (TRIMP) has been calculated for each training as a non-invasive measurement of training load. TRIMP points have been thus obtained as the product of the accumulated training duration (minutes) of five different HR zones, by a coefficient related to each zone (50 to 59% of HRmax × 1; 60 to 69% of HRmax × 2; 70 to 79% of HRmax × 3; 80 to 89% of HRmax × 4, and 90–100% of HRmax × 5), and then summated to obtain the final training load value (i.e., duration in zone 1 × 1 + duration in zone 2 × 2 + duration in zone 3 × 3 + duration in zone 4 × 4 + duration in zone 5 × 5) [13]. The athletes further completed 30 min after each training, the session-RPE scale (BORG-CR10) with values ranging from 0 (no exertion at all) to 10 (maximal exertion) [14]. Body mass was measured using a mechanical balance scale (Seca 874) with a precision of 0.01 kg. Height was measured shoeless using a stadiometer (Seca 213) with a precision of 0.1 cm. The measurements were taken to check the correct position of the head in the standard position of the reference Frankfurt plane [15]. Body mass and height were measured at baseline. In addition, before and after each training session athletes were asked to measure their body mass through the same scale in order to measure the difference in body weight between pre- and post-training (Δ) as a non-invasive and easy-to-use fluid loss marker, allowing daily monitoring practices [16]. After each training, athletes reported through a food diary their liquid and/or solid food consumption during the activity [17]. Carbohydrate consumption during exercise (gCHO/h) was then quantified using the Winfood® analysis software. Data have been then categorized according to three training load levels according to TRIMP values: low (<100); medium (100–200); and high (>200). The training sessions has been divided into such categories considering the average characteristics of the training programs prescribed by the team's staff, respectively, as: recovery training (e.g., 60 min spent in 50–65% HRmax zone), specific training (e.g., 120 min with intervals of high and low intensity according to the target or long-distance low intensity trainings) and high intensity (e.g., competition simulations or real competitions).

### 2.3. Statistical Analysis

All data analyses were carried out using SPSS version 21.0 (IBM Corporation, Armond, NY, USA) and GraphPad Prism version 7.0 (GraphPad Software, San Diego, CA, USA). Descriptive statistics (mean ± SD) were calculated for each variable. Shapiro–Wilk test was used to assess the normality of the samples, revealing normally distributed values. Additionally, the Levene's test was adopted to assess the homogeneity of the variance for the studied variables indicating a $p > 0.05$. Therefore, One-Way ANOVA was performed to assess the difference in sRPE across the three different training load (TRIMP) categories (low, medium, high). In case of a statistically significant difference, a Tukey post-hoc analysis was applied. Mean difference across pairwise comparison with 95% confidence intervals (95% CI) were also calculated. Additionally, partial eta squared (np2) was used as One-Way ANOVA effect size and interpreted (<0.039—no effect; 0.040 to 0.249—minimum; 0.250 to

0.639—moderate; >0.640—strong [18]). Cohen's d effect size was established according to the following criteria: 0 to 0.19, trivial; 0.20 to 0.59, small; 0.60 to 1.19, moderate; 1.20 to 1.99, large; 2.00 to 3.99, very large; >4.0; nearly perfect [19]. Pearson correlation analysis and linear regression have been conducted on the data. The following criteria were adopted to interpret the magnitude of correlations between measurement variables: <0.09, trivial; 0.10 to 0.29, small; 0.30 to 0.49, moderate; 0.50 to 0.69, large; 0.70 to 0.89 very large; and >0.90, nearly perfect [19]. An alpha level of $p \leq 0.05$ was set to assess the statistical significance.

## 3. Results

### *3.1. Fatigue Perception in Different TRIMP Categories and Relationship between TRIMP and sRPE*

One-way ANOVA revealed a statistically significant difference ($p < 0.001$; n $p^2 = 0.721$—strong) between the three investigated training session groups (i.e., <100; 100–200; >200 TRIMP points). Post-hoc analysis indicated significantly lower sRPE (arbitrary unit, AU) in <100 TRIMP training sessions compared with 100–200 ($p < 0.001$; mean difference −1.34 AU) and >200 ($p < 0.001$; mean difference −2.58 AU) and significantly lower sRPE in 100–200 compared to >200 ($p < 0.001$; mean difference −1.24 AU) (Table 1).

**Table 1.** Summary of post-hoc analysis results.

| Pairwise Comparison | *p*-Value | sRPE (AU) Mean Difference (95% CI) | ES (95% CI) | Interpretation |
|---|---|---|---|---|
| <100 vs. 100–200 | <0.001 | −1.34 (−1.61; −1.06) | −1.53 (−1.96; −1.10) | Large |
| <100 vs. >200 | <0.001 | −2.58 (−2.97; −2.19) | −2.69 (−3.34; −2.04) | Very Large |
| 100–200 vs. >200 | <0.001 | −1.24 (−1.48; −1.01) | −1.80 (−2.19; −1.40) | Large |

The Pearson's r analysis with linear regression between TRIMP (AU) and sRPE (AU) showed a very large positive statistically significant correlation ($p < 0.001$; R = 0.71 (95% CI: 0.641; 0.768); R2 = 0.505) (Figure 2).

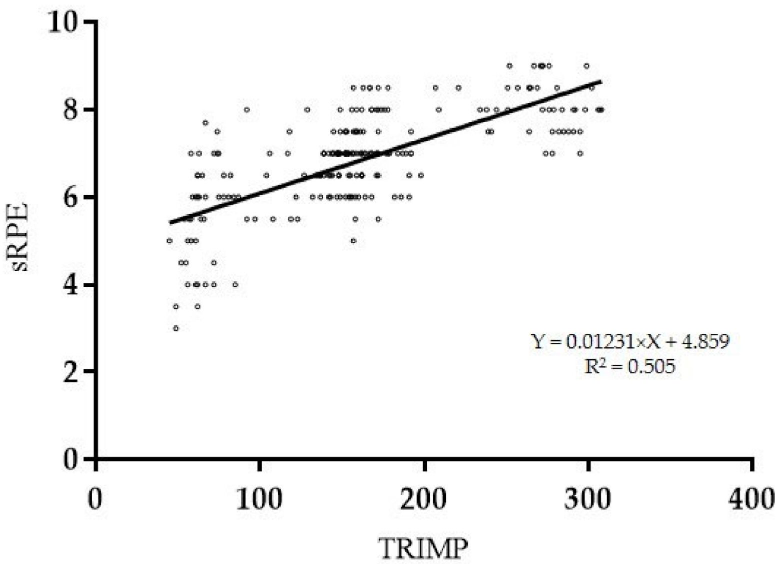


**Figure 2.** Linear regression between TRIMP (AU) and sRPE (AU).

### *3.2. Relationships between sRPE and Fluid Loss during Exercise*

Correlation analysis with linear regression of sRPE (AU) and pre- to post-training Δ (kg) variations revealed a very large negative statistically significant correlation for training sessions with <100 TRIMP points ($p < 0.001$; R = −0.79 (95% CI: −0.87; −0.67); R2 = 0.635) (Figure 3a); a very large negative statistically significant correlation for training sessions with 100–200 TRIMP points ($p < 0.001$; R = −0.86 (95% CI: −0.89; −0.81); R2 = 0.742) (Figure 3b) and a large negative statistically significant correlation for training sessions with >200 TRIMP points ($p < 0.001$; R = −0.67 (95% CI: −0.810; −0.474); R2 = 0.457) (Figure 3c).

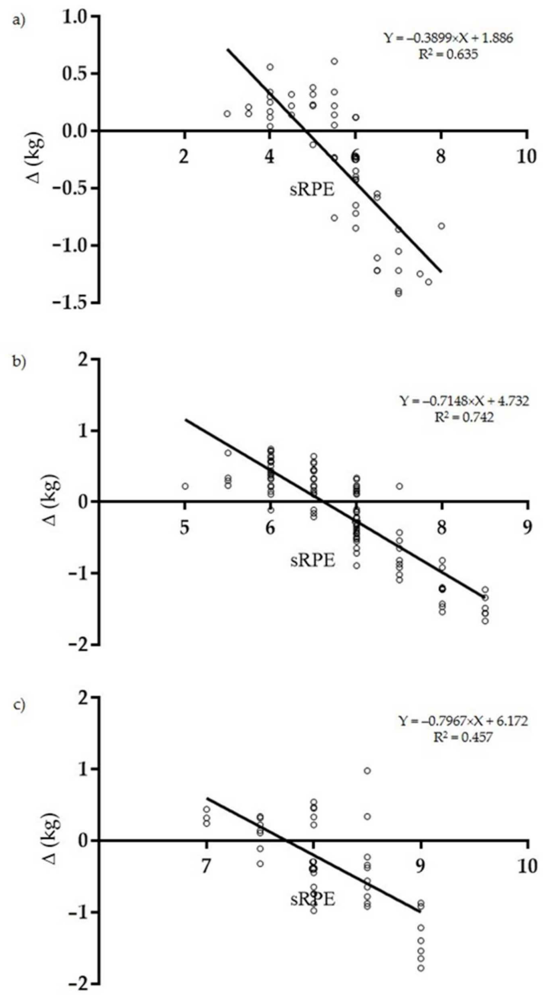


**Figure 3.** Linear regression between sRPE (AU) and pre- and post-training Δ (kg) variations of training sessions displaying <100 TRIMP points (**a**); 100–200 TRIMP points (**b**) and >200 TRIMP points (**c**).

*3.3. Relationships between sRPE and Carbohydrate Consumption During Exercise*

Correlation analysis with linear regression of sRPE (AU) and training session carbohydrates consumption (gCHO/h), revealed a large negative statistically significant correlation for training sessions with <100 TRIMP points ($p < 0.001$; R = −0.54 (95% CI: −0.70; −0.31); R2 = 0.294) (Figure 4a); a large negative statistically significant correlation for training sessions with 100–200 TRIMP points ($p < 0.001$; R = −0.54 (95% CI: −0.65; −0.41); R2 = 0.295) (Figure 4b) and a very large negative statistically significant correlation for training sessions with >200 TRIMP points ($p < 0.001$; R = −0.75 (95% CI: −0.85; −0.58); R2 = 0.561) (Figure 4c).

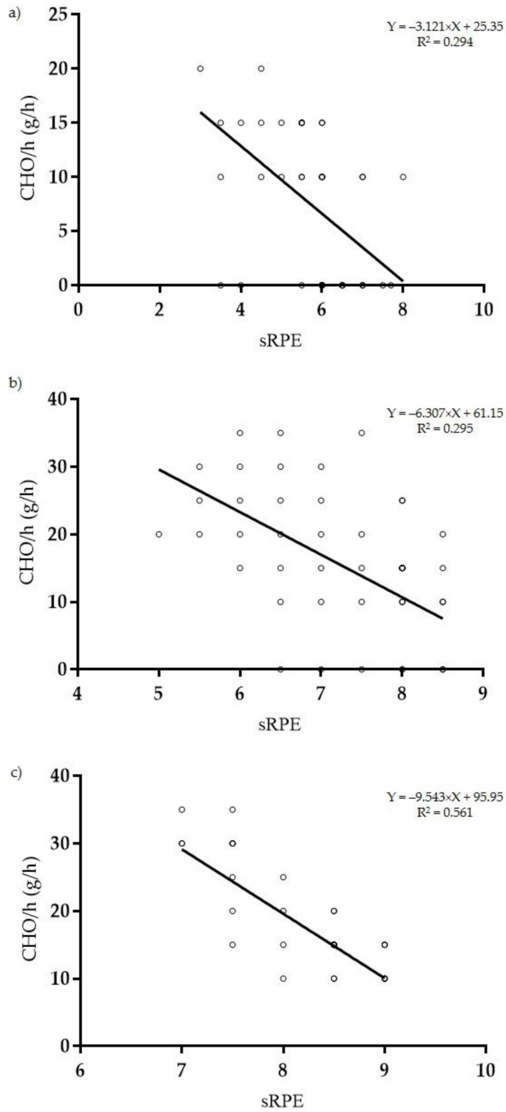


**Figure 4.** Linear regression between sRPE (AU) and training session carbohydrates consumption (gCHO/h) of training sessions displaying <100 TRIMP points (**a**); 100–200 TRIMP points (**b**) and >200 TRIMP points (**c**).

### *3.4. Relationships between TRIMP Categories, Fluid Loss and Carbohydrates Consumption During Exercise*

Correlation analysis of TRIMP (AU) within the three categories and pre- and post-training Δ (kg) revealed a small negative non-statistically significant correlation for training sessions with <100 TRIMP points ($p$ = 0.26; R = −0.15 (95% CI: −0.40; 0.12); R2 = 0.268), for training session with 100–200 TRIMP points ($p$ = 0.16; R = −0.12 (95% CI: −0.27; 0.04); R2 = 0.162), and for training session with >200 TRIMP points ($p$ = 0.27; R = −0.17 (95% CI: −0.44; 0.13); R2 = 0.273) (Table 2).

**Table 2.** Results of the correlation analysis between TRIMP within the three different categories, pre- and post-training Δ (kg) and CHO consumption (g/h).

| | TRIMP <100 cat. (AU) | | | TRIMP 100–200 cat. (AU) | | | TRIMP > 200 cat. (AU) | | |
|---|---|---|---|---|---|---|---|---|---|
| | r | *p* | | r | *p* | | r | *p* | |
| Δ (kg) | −0.15 | 0.26 | small | −0.12 | 0.16 | small | −0.17 | 0.27 | small |
| CHO (g/h) | −0.24 | 0.08 | small | 0.01 | 0.87 | trivial | 0.37 | 0.01 | moderate |

Correlation analysis of TRIMP (AU) within the three categories, and training session carbohydrates consumption (gCHO/h), revealed a small negative non-statistically significant correlation for training sessions with <100 TRIMP points ($p$ = 0.08; R = −0.24 (95% CI: −0.47; 0.03); R2 = 0.05), a trivial positive non-significant association for training session with 100–200 TRIMP points ($p$ = 0.87; R = 0.01 (95% CI: −0.15; 0.17); R2 = 0.877), and a moderate positive statistically significant association for training session with >200 TRIMP points ($p$ = 0.01; R = 0.37 (95% CI: 0.08; 0.60); R2 = 0.136) (Table 2).

## 4. Discussion

This study investigated the relationships between different TRIMP training load categories and sRPE and the role of fluid balance and carbohydrate supply during exercise on perceived fatigue, demonstrating the importance of training load monitoring and nutritional-hydration support for young cyclists' fatigue management. The investigation involved a team of junior's category cyclists, monitored as part of their team's performance and health optimization program that covered an entire season.

The significant differences between training load categories, delineating respectively, recovery, specific adaptations and high load training targets, and the very large correlation that emerged between sRPE and Edward's TRIMP suggested training and competitions as the main physiological and psychological fatigue perception factors for young athletes as previously described [20,21]. These results support previous observations on the reliability of sRPE as an internal load marker and as a useful non-invasive method to monitor young athletes' training load [2,4,22]. Thanks to the available non-invasive technologies such as GPS, HR monitoring devices, both Edward's TRIMP, and sRPE can be easily used as monitoring tools to assess fatigue perception dynamics in relation to training load during the competitive season of young athletes. This can potentially help athletes coaches and team staff to better manage the balance between stress and recovery, that has been linked by previous investigations with injury prevention, athletes' health, and performance optimization [2–6,9,10,22]. The various benefits of physical activities such as cycling, as opposed to physical inactivity, have been widely demonstrated in different age groups, including adolescents and young athletes [23–33]. However, considering the additional stressors to which these particular age groups are exposed, training load monitoring and management may represent important aspects.

Our results thus suggest the value of training load monitoring and in particular of fatigue perception assessment in young athletes, in order to potentially prevent overload and to ensure performance improvements.

We additionally observed how sRPE was negatively and largely correlated with both, pre- to post-exercise fluid loss (Δ) and carbohydrate consumption during exercise (CHO/h), independently from TRIMP training load categories. This confirms once more the importance of hydration status on fatigue perception and suggests the possible role of carbohydrate supply also in low intensity or low volume training (low TRIMP) in young athlete populations [8,11]. During physical activity, carbohydrate availability to the exercising muscle and central nervous system can be compromised due to the fuel cost of the athlete's training session or competition exceeding the endogenous stores and as a consequence of a lack of external supply [34,35]. The role of carbohydrates in the lower TRIMP training category can be associated with the reduction of fatigue onset and enhanced recovery from training rather than the ergogenic role mainly having an impact at higher training loads levels (i.e., 100–200 and >200 TRIMP point categories) [35–37].

This further underlines the role of nutritional education programs for young athletes in order to make them understand the importance of nutritional and fluid support, to preserve health and performance [8].

Kerksick et al. (2018) described water as the most important nutritional ergogenic aid for athletes and that limiting dehydration during exercise is one of the most effective ways to maintain exercise capacity [38]. In addition, it has been reported how dehydration may have a negative impact on mental fatigue accumulation and consequent cognitive performances as well as on psychological status of adolescent and young populations [39]. As suggested by our results and by previous observations, young athletes may experience fluid imbalances if some exercise conditions are met or liquids intake do not satisfy daily requirements, with possible consequences on their physical performance, fatigue accumulation, and health maintenance [11].

The results of the present study suggest thus the importance of fluid and nutrient supply during low to high training load sessions (e.g., low to high training intensity or volume) in young athletes' fatigue perception. The small sample size represents one limitation of this study; however, high-level young athletes represent a unique population that is slightly investigated, also due to the difficulty of involvement. This study was therefore carried out thanks to the possibility to work with a complete team (athletes and staff) for the entire duration of a season, which, however, at the same time represented the main limit on the sample size choice. The results of this study show the applicability of a non-invasive and easy-to-apply monitoring strategy. However, although it is recognized as a valid indicator, especially for athletes' self-assessments by the or for the in-field investigations, the utilization of the pre- and post-training Δ body mass as a marker of fluid loss is not free from limitations as previously reported (e.g., loss in body mass due to respiratory water losses and substrate oxidation) [40]. The present data described thus a monitoring model suitable for the in-field conditions that cycling team's staff normally face along the season and underlines the importance of previously described markers in a singular population as the high-level young cyclist (Figure 5).

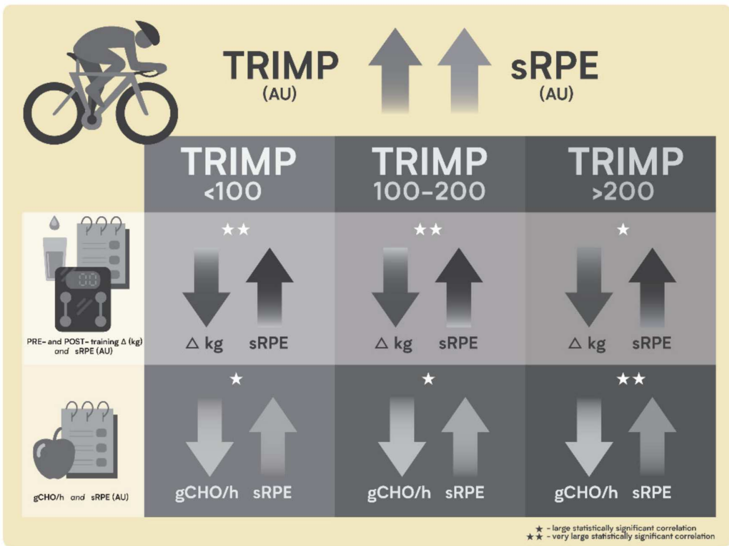


**Figure 5.** Graphical representation of the inter-relationships between training load markers, fluid balance and carbohydrate supply during exercise. Increased fluid loss (negative Δ) as well as lower or no carbohydrate consumption is related to an increased fatigue perception (sRPE) independently from training load category (TRIMP).

## 5. Conclusions

Young athletes' training load monitoring and nutritional support during exercise represent two important aspects for fatigue perception management. The importance of exercise-induced fatigue perception monitoring and the evaluation of a possible contributor of fatigue perception are important tools to support the young athlete. The results emerged from this research are aimed to young athletes' team staff as an example of a feasible approach to monitor and support the athlete. Future research may aim to further confirm our findings, involving a larger population of young athletes and involving a deeper evaluation on fatigue perception dynamics.

**Author Contributions:** Conceptualization, L.C.; methodology, L.C. and B.Y.; software, L.C. and B.Y; validation, L.C., B.Y. and G.M.; formal analysis, L.C. and B.Y.; investigation, L.C.; resources, L.C.; data curation, L.C. and B.Y.; writing—original draft preparation, L.C., B.Y. and G.M.; writing—review and editing, L.C, B.Y., G.M., D.Z., S.C., A.P. and A.I.; visualization, B.Y. and L.C.; supervision, G.M. All authors have read and agreed to the published version of the manuscript.

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**Institutional Review Board Statement:** The data collection presented in this study was conducted according to the guidelines of the Declaration of Helsinki, all details of the investigation have been previously discussed and approved by the investigators, the team principal and team's staff, and athletes' and/or athletes' responsible.

**Informed Consent Statement:** Informed consent was obtained from all subjects involved in the study.

**Data Availability Statement:** The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy restrictions.

**Conflicts of Interest:** The authors declare no conflict of interest.

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# Load Measures in Training/Match Monitoring in Soccer: A Systematic Review

**Mauro Miguel [1,2,3,*], Rafael Oliveira [2,3,4], Nuno Loureiro [2,3], Javier García-Rubio [1,*] and Sergio J. Ibáñez [1]**

1 Training Optimization and Sports Performance Research Group (GOERD), Sport Science Faculty, University of Extremadura, 10005 Caceres, Spain; sibanez@unex.es
2 Sport Sciences School of Rio Maior, 2040-413 Rio Maior, Portugal; rafaeloliveira@esdrm.ipsantarem.pt (R.O.); nunoloureiro@esdrm.ipsantarem.pt (N.L.)
3 Life Quality Research Centre (CIEQV), Polytechnic Institute of Santarem, 2040-413 Rio Maior, Portugal
4 Research Centre in Sport Sciences, Health Sciences and Human Development, 5001-801 Vila Real, Portugal
* Correspondence: mauromiguel@esdrm.ipsantarem.pt (M.M.); jagaru@unex.es (J.G.-R.); Tel.: +351-917752489 (M.M.)

**Abstract:** In soccer, the assessment of the load imposed by training and a match is recognized as a fundamental task at any competitive level. The objective of this study is to carry out a systematic review on internal and external load monitoring during training and/or a match, identifying the measures used. In addition, we wish to make recommendations that make it possible to standardize the classification and use of the different measures. The systematic review was carried out according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The search was conducted through the electronic database Web of Science, using the keywords "soccer" and "football", each one with the terms "internal load", "external load", and "workload". Of the 1223 studies initially identified, 82 were thoroughly analyzed and are part of this systematic review. Of these, 25 articles only report internal load data, 20 report only external load data, and 37 studies report both internal and external load measures. There is a huge number of load measures, which requires that soccer coaches select and focus their attention on the most useful and specific measures. Standardizing the classification of the different measures is vital in the organization of this task, as well as when it is intended to compare the results obtained in different investigations.

**Keywords:** soccer; training; match; internal load; external load

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## 1. Introduction

In recent years, soccer coaches, members of technical staff and sports scientists have given particular attention to training and match monitoring. The amount of work performed by soccer players in training and match, as well as the consequent individual responses, positively or negatively affect their performance, leaving them more or less vulnerable to injury. Thus, the load monitoring process should assist coaches' decision making about the players' availability for training and competition [1], having as main objectives the improvement of performance and injury prevention [2–4]. For this reason, and also because of technological and analytical method developments [2], nowadays there is a huge set of load measures obtained through the use of telemetry and global positioning systems (GPS), among other microtechnologies [5].

Load measures can be categorized as either internal or external [1], depending on whether they refer to measurable aspects occurring internally or externally to the athlete [6]. External loads are objective measures of work performed by the athlete during training or competition [1], which are determined by the organization, quality, and quantity of exercise (training plan) [6]. Most common measures of external load include power output, speed, acceleration, time–motion analysis [1], and deceleration. By contrast, internal loads are defined as the relative biological (both physiological and psychological) stressors imposed on the athlete during training or competition [1], reflecting the psychophysiological responses that the body initiates to cope with the requirements elicited by external load [6]. Measures such as heart rate (HR), blood lactate (BLa), and rated perceived exertion (RPE) are commonly used to assess internal load [1].

It is unanimously believed that an integrated approach, rigorous and consistent, combining the use of internal and external loads, provides more significant information about the stress caused in soccer players than interpretations based on isolated data [1,3,6], and it is also recognized that this information should be simplified, with reporting limited to a few key metrics [1].

Impellizzeri [6] clarifies the importance of integrating both types of load, exemplifying that the uncoupling between internal and external load may be used to identify how athletes are coping with their training program. Specifically, athletes who exhibit a lower internal load to standardized external load completed under similar conditions would be assumed to reflect increased fitness. By contrast, when the internal load is increased in this situation, the athlete may be losing fitness or suffering from fatigue.

Methods that directly quantify a unit of measure (e.g., HR, distance, speed, time) or are able to count occurrences or repetitions are easily interpretable and can be used to plan and prescribe training, as well as to evaluate demands of competition. The use of composite or derivate methods, usually measured in arbitrary units (AU) (e.g., training impulses derived from HR), metabolic power (derived from locomotor acceleration and deceleration), player load (derived from accelerometer acceleration) and session rated perceived exertion (sRPE) (derived from perception of effort), adds more complexity to the interpretation of results but may bring more insight if analyzed correctly [1].

However, there is currently no consensus as to which variables are most useful or, indeed, how to analyze the longitudinal data of a diverse squad of players [2]. Reina [7] reinforces the importance of conducting systematic reviews about training/match monitoring with increasing attention given to this task, and therefore, there are a lot of data to collect and organize.

The identification of internal and external load measures used by investigations that use training or match as environment of monitoring can provide answers about which variables to include in an integrated approach. Thus, this systematic review aims to compile and order all the load measures used in soccer training/match monitoring, systematizing them.

## 2. Methods

The systematic review was carried out according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. In the present study, the search strategy followed by Sarmento [8] was adopted. The research was conducted on November 8, 2019, through the electronic database Web of Science (WOS). We chose WOS database because it is a research engine that groups other databases such as (1) Web of Science Core Collection; (2) Current Contents Connect; (3) Derwent Innovations Index; (4) KCI—Korean Journal Database; (5) Medline; (6) Russian Science Citation Index; and (7) SciELO Citation Index. The keywords "soccer" and "football" were used, associating each of them with the terms "internal load", "external load" and "workload". Therefore, we did six searches: "soccer" + "internal load"; "soccer" + "external load"; "soccer" + "workload"; "football" + "internal load"; "football" + "external load"; and "football" + "workload".

### *2.1. Search Strategy: Inclusion Criteria and Process of Selection*

Our analysis elected to review experimental and descriptive studies that met the following inclusion criteria: (1) published in peer-reviewed journals; (2) written in English; (3) report data about load monitoring in training and/or a match; (4) participants are male soccer players competing at the regional and/or national level. Studies involving

(1) non-federated players, (2) female soccer players, (3) other sports, such as futsal, were excluded from the review, as well as studies that (4) did not present data collection of internal and/or external load, or that (5) reported exclusively data collected in specific exercises, such as small-sided games. If there was no agreement between the authors regarding the inclusion of any article, their inclusion/exclusion was discussed in order to reach a consensus.

It is necessary that there be reliability in the process of recording data in systematic reviews [9]. For this, consensus agreement between the coders was used. Two independent reviewers individually examined citations and abstracts to identify articles that potentially met the inclusion criteria. In these articles, a full-text analysis was carried out by the two reviewers to determine whether they met the inclusion criteria. Disagreements about the inclusion criteria were resolved through discussion between the authors, with all final decisions resulting from a joint analysis process.

### *2.2. Quality of the Studies and Data Extraction*

To assess the quality of the studies, the risk-bias quality form used by Gómez-Carmona [5], Reina [7], Sarmento [8] and García-Santos [10], adapted from the original version developed by Law [11], was adopted. This evaluation is composed of 16 items and was performed by two researchers, with valuable expertise on this topic.

Articles were evaluated according to their objectives (item 1), relevance of background literature (item 2), adequacy of study design (item 3), sample studied (item 4 and 5), use of informed consent procedure (item 6), outcome measures (items 7 and 8), description method (item 9), significance of results (item 10), analysis (item 11), practical importance (item 12), description of dropouts (item 13), conclusions (item 14), practical implications (item 15), and limitations (item 16). The 16 quality criteria were rated on a binary scale (0/1), of which one of these criteria (item 13) presented the option: "If not applicable, assume 3". The introduction of this option for item 13, "Were any dropouts reported?", as justified by Sarmento [8], occurred because in some studies the investigators were not required to report dropouts (item 13).

The introduction of the option "not applicable" allowed a correct score of the article, eliminating the negative effect of assuming the value 0 on a binary scale, when in fact that item was not applicable to that study. As in the studies by Gómez-Carmona [5], Reina [7], Sarmento [8] and García-Santos [10], to make a fair comparison between studies with different designs, the percentage score was calculated as a final measure of methodological quality. For this, the sum of the score of all items was divided by the number of relevant scored items for that specific research design. All articles were qualified according to their score: low methodological quality, with 50% or less; good methodological quality, between 51% and 75%; and excellent methodological quality, greater than 75%.

## 3. Results

### *3.1. Search Selection and Inclusion of Publications*

The initial research identified 1220 titles in the electronic database Web of Science and another 3 titles in the electronic database ResearchGate. All records were exported to a bibliography management software (Endnote Web), with the duplicates being eliminated automatically (533 references). The 690 existing articles were subject to evaluation of the title, resulting in 413 exclusions from the database, and the remaining 277 articles were analyzed in the abstract. The analysis of the abstracts resulted in the elimination of 147 studies, so the full text of 130 articles was read, of which 48 were rejected due to the lack of relevance to the objectives of this study. The lack of relationship between studies and training/match monitoring proved to be the main reason for exclusions ($n$ = 35). The integration of the female gender ($n$ = 4), non-federated athletes ($n$ = 6), and the other team sports ($n$ = 3) in the studies was the reason for excluding the remaining articles. After this procedure, 82 articles were thoroughly analyzed and are part of this systematic review (Figure 1).

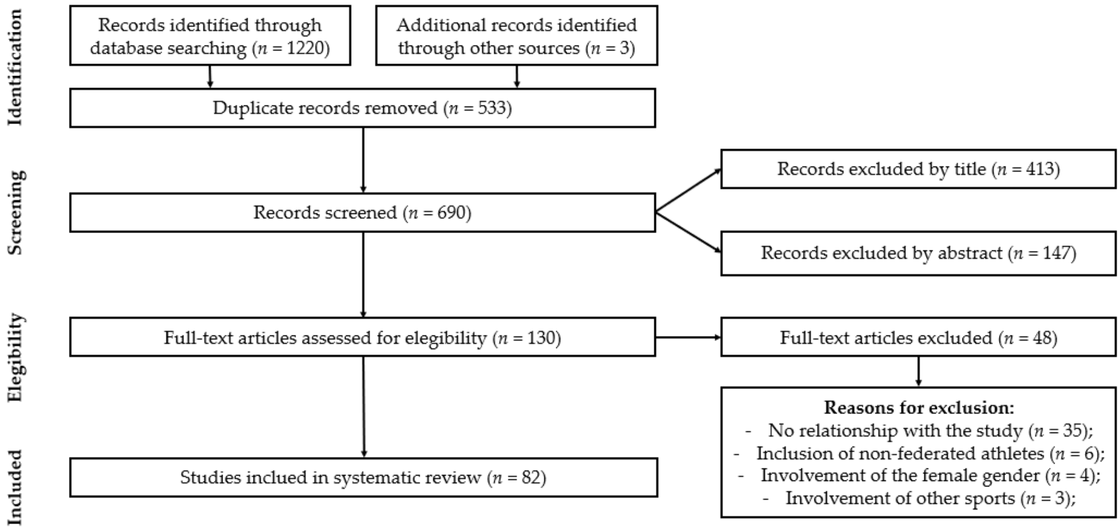


**Figure 1.** Article selection process flowchart.

### 3.2. Quality of the Studies

Through the kappa index, as used in other reviews [5,7,8,10], a value of 0.755 was obtained for interobserver reliability, indicating a substantial agreement between observers [12]. The quality of the articles included in this review is confirmed by the following indicators: the average quality score of the articles was 85.7%; 75 articles had a score above 75%, and below 100% (excellent methodological quality); 7 articles exposed scores between 51% and 75% (good methodological quality); and no article had a score equal to or less than 50% (low methodological quality). The main reasons for the absence of maximum scores were due to the non-detailed description of the sample, the non-justification of the sample size, and/or the non-detailed description of the intervention.

### 3.3. Characterization of Studies

Tables 1–3 describe the main characteristics of the 82 articles including the analysis, which were published between 2004 and 2019, and the sample varied between 6 and 1200 subjects. From a total of 82 articles, 25 articles report only internal load data (Table 1), 20 report only external load data (Table 2), and 37 studies report both internal and external load measures. Of these studies, 78 evaluated athletes who competed at the national level, and in the other study, the level of the respective participants is not clarified. The monitoring period varies between 3 and 460 training sessions, and between 2 and 79 matches, with some studies only indicating the monitoring period (e.g., 30 weeks).

**Table 1.** Characteristics of studies that evaluated only internal load measures.

| Study | Level | Sample | Age | Condition | Duration | Quality |
|---|---|---|---|---|---|---|
| Akubat [13] | National | 14 | 17.0 ± 1.0 year | Training<br>Competition | 24 Sessions<br>6 Matches | Excellent |
| Barrett [14] | National | 32 | 25.0 ± 8.0 year | Competition | 38 Matches | Excellent |
| Campos-Vasquez [15] | National | 9 | 26.7 ± 4.5 year | Training | 288 Sessions | Good |
| Campos-Vasquez [16] | National | 12 | 27.7 ± 4.3 year | Training<br>Competition | 21 Sessions<br>7 Matches | Excellent |
| Cetolin [17] | National | 18<br>12 | U15—14.7 ± 0.5 year<br>U19—18.9 ± 0.9 year | Training<br>Competition | 40 Sessions<br>3 Matches<br>45 Sessions<br>6 Matches | Excellent |

**Table 1.** *Cont.*

| Study | Level | Sample | Age | Condition | Duration | Quality |
|---|---|---|---|---|---|---|
| Clemente [18] | National | 35 | 25.7 ± 5.0 year | Training | 192 Sessions | Excellent |
| Delecroix [19] | National | 130 | N/D [1] | Training<br>Competition | 1 Season | Excellent |
| Freitas [20] | National | 11 | 16.5 ± 0.5 year | Training<br>Competition | 4 Weeks | Excellent |
| Freitas [21] | National | 26 | 15.6 ± 1.1 year | Competition | 4 Matches | Excellent |
| Gjaka [22] | National | 22 | 14.5 ± 0.3 year | Training<br>Competition | 12 Sessions<br>6 Matches | Excellent |
| Haddad [23] | National | 17 | 18.2 ± 0.5 year | Training | 21 Sessions | Excellent |
| Howle [24] | National | 42 | 26.4 ± 5.1 year | Competition | 37 Matches | Excellent |
| Impellizzeri [25] | N/D [1] | 19 | 17.6 ± 0.7 year | Training | 27 Sessions | Excellent |
| Leiper [26] | National | 79 | 18.0 ± 1.0 year | Training | 38 Sessions | Excellent |
| Los Arcos [27] | National | 40 | N/D [1] | Competition | 2 Seasons | Good |
| Los Arcos [28] | National | 24 | 20.3 ± 2.0 year | Training<br>Competition | 30 Weeks | Good |
| Malone [29] | National | 48 | 25.3 ± 3.1 year | Training | 460 Sessions | Excellent |
| Manzi [30] | National | 18 | 28.4 ± 3.2 year | Training | 8 Weeks | Excellent |
| McCall [31] | National | 171 | 25.1 ± 4.9 year | Training<br>Competition | 1 Season | Excellent |
| Pinto [32] | National | 20 | 16.8 ± 0.6 year | Competition | 2 Matches | Excellent |
| Raya-González [33] | National | 22 | 18.6 ± 0.6 year | Training<br>Competition | 141 Sessions<br>38 Matches | Excellent |
| Rowell [34] | National | 23 | 23.3 ± 4.1 year | Training<br>Competition | 1 Season<br>34 Matches | Excellent |
| Saidi [35] | National | 18 | 20.1 ± 0.4 year | Training | 26 Sessions | Excellent |
| Vahia [36] | National | 15 | 16.7 ± 1.0 year | Training | 160 Sessions | Excellent |
| Wrigley [37] | National | 8<br>8<br>8 | U14—13.0 ± 1.0<br>yearU16—15.0 ± 1.0<br>yearU18—17.0 ± 1.0 year | Training<br>Competition | 6–8 Sessions<br>2 Matches | Excellent |

[1] Not defined (N/D).

**Table 2.** Characteristics of studies that evaluated only external load measures.

| Study | Level | Sample | Age | Condition | Duration | Quality |
|---|---|---|---|---|---|---|
| Arruda [38] | National | 10 | 15.1 ± 0.2 year | Competition | 5 Matches | Excellent |
| Bacon [39] | National | 18<br>23 | 18.8 ± 1.2 year<br>17.0 ± 1.1 year | Training<br>Competition | 40 Weeks | Excellent |
| Barron [40] | Regional | 38 | 17.3 ± 0.9 year | Competition | 8 Matches | Excellent |
| Bendala [41] | National | 25 | 26.5 ± 4.1 year | Training<br>Competition | 41 Weeks<br>9 Matches | Excellent |
| Bowen [42] | National | 32 | 17.3 ± 0.9 year | Training<br>Competition | 2 Seasons | Excellent |
| Brito [43] | Regional | 66 | 13.4 ± 0.5 year | Competition | 9 Matches | Excellent |
| Casamichana [44] | National | 27 | 22.8 ± 4.5 year | Training<br>Competition | 9 Sessions<br>7 Matches | Excellent |

**Table 2.** *Cont.*

| Study | Level | Sample | Age | Condition | Duration | Quality |
|---|---|---|---|---|---|---|
| Chrismas [45] | National | 6 | 26.0 ± 2.0 year | Training | 247 Sessions | Excellent |
| Clemente [46] | National | 14<br>15 | 19.2 ± 1.0 year<br>25.1 ± 3.9 year | Training | 7 Weeks | Excellent |
| Clemente [47] | National | 23 | 24.7 ± 2.8 year | Training<br>Competition | 47 Sessions<br>12 Matches | Excellent |
| Clemente [48] | National | 18<br>24<br>23<br>24 | 25.4 ± 4.8 year<br>21.5 ± 2.5 year<br>23.0 ± 3.7 year<br>24.7 ± 2.9 year | Training<br>Competition | 5 Weeks | Excellent |
| Clemente [49] | National | 27 | 24.9 ± 3.5 year | Training<br>Competition | 22 Weeks | Excellent |
| Gonçalves [50] | National | 28 | 24.7 ± 4.7 year | Competition | 51 Matches | Excellent |
| Jones [51] | National | 37 | 23.0 ± 4.0 year | Competition | 79 Matches | Excellent |
| Martín-García [52] | National | 24 | 20.0 ± 2.0 year | Training<br>Competition | 42 Weeks<br>37 Matches | Excellent |
| Owen [53] | National | 29 | 26.7 ± 4.0 year | Training<br>Competition | 80 Sessions<br>20 Matches | Good |
| Owen [54] | National | 20 | 26.7 ± 4.1 year | Training<br>Competition | 88 Sessions<br>22 Matches | Excellent |
| Rago [55] | National | 14 | 27.6 ± 3.5 year | Competition | 6 Matches | Excellent |
| Reche-Soto [56] | National | 21 | N/D [1] | Competition | 12 Matches | Excellent |
| Wiig [57] | National | 75 | 20.4 ± 4.6 year | Competition | 3 Matches | Good |

[1] Not defined (N/D).

**Table 3.** Characteristics of studies that evaluated both internal and external load measures.

| Study | Level | Sample | Age | Condition | Duration | Quality |
|---|---|---|---|---|---|---|
| Abade [58] | National | 56<br>66<br>29 | U14—14.0 ± 0.2 year<br>U17—15.8 ± 0.4 year<br>U19—17.8 ± 0.6 year | Training | 12 Sessions<br>16 Sessions<br>10 Sessions | Excellent |
| Akenhead [59] | National | 33 | 24.0 ± 4.0 year | Training | 48 Sessions | Excellent |
| Aslan [60] | National | 47 | 17.6 ± 0.58 year | Competition | 4 Matches | Excellent |
| Azcárate [61] | National | 20 | 27.1 ± 3.1 year | Training<br>Competition | 46 Sessions<br>10 Matches | Excellent |
| Brink [62] | National | 16<br>15 | U15—14.3 ± 0.3 year<br>U17—16.3 ± 0.2 year | Training | 40 Sessions<br>48 Sessions | Excellent |
| Casamichana [63] | National | 28 | 22.9 ± 4.2 year | Training | 44 Sessions | Excellent |
| Castagna [64] | National | 1200 | 24.5 ± 0.8 year | Competition | 60 Matches | Good |
| Condello [65] | Regional | 17 | 24.9 ± 4.2 year | Training<br>Competition | 20 Sessions<br>4 Matches | Excellent |
| Coppalle [66] | National | 26<br>24 | 26.2 ± 5.1 year<br>25.9 ± 5.2 year | Training<br>Competition | 12 Weeks [1] | Excellent |
| Coutinho [67] | National | 56<br>66<br>19 | U15—14.0 ± 0.2 year<br>U17—15.8 ± 0.4 year<br>U19—17.8 ± 0.6 year | Training | 12 Sessions<br>11 Sessions<br>10 Sessions | Excellent |

**Table 3.** *Cont.*

| Study | Level | Sample | Age | Condition | Duration | Quality |
|---|---|---|---|---|---|---|
| Curtis [68] | National | 18 | 20.0 ± 1.0 year | Competition | 24 Matches | Excellent |
| Iacono [69] | National | 24 | 18.3 ± 1.1 year | Training<br>Competition | 8 Sessions<br>14 Matches | Excellent |
| Figueiredo [70] | National | 18 | 22.0 ± 2.0 year | Training | 4 Sessions | Good |
| Fitzpatrick [71] | National | 14 | 17.1 ± 0.5 year | Training<br>Competition | 23 Sessions<br>6 Matches | Excellent |
| Fullagar [72] | National | 15 | 25.5 ± 4.9 year | Training<br>Competition | 5 Sessions<br>2 Matches | Excellent |
| Gaudino [73] | National | 22 | 26.0 ± 6.0 year | Training | 38 Weeks | Excellent |
| Geurkink [74] | National | 46 | 25.6 ± 4.2 year | Training | 61 Sessions | Excellent |
| Giménez [75] | National | 14 | 23.2 ± 2.7 year | Competition | 2 Matches | Excellent |
| Jaspers [76] | National | 35 | 23.2 ± 3.7 year | Training<br>Competition | 2 Seasons | Excellent |
| Jaspers [77] | National | 38 | 22.7 ± 3.4 year | Training | 2 Seasons | Excellent |
| Malone [78] | National | 30 | 25.0 ± 5.0 year | Training | 45 Weeks | Excellent |
| Malone [79] | National | 48 | 25.3 ± 3.1 year | Training | 460 Sessions | Excellent |
| Malone [80] | National | 30 | 25.3 ± 3.1 year | Training | 240 Sessions | Excellent |
| Malone [81] | National | 37 | 25.0 ± 3.0 year | Training<br>Competition | 48 Weeks | Excellent |
| Noor [82] | National | 35 | 25.9 ± 3.8 year | Training<br>Competition | 16 Weeks | Excellent |
| Oliveira [83] | National | 13 | 26.2 ± 4.1 year | Training<br>Competition | 20 Sessions<br>9 Matches | Excellent |
| Oliveira [84] | National | 19 | 26.3 ± 4.3 year | Training | 189 Sessions | Excellent |
| Op De Beéck [85] | National | 26 | 23.2 ± 3.7 year | Training<br>Competition | 1 Season | Excellent |
| Owen [86] | National | 10 | 26.8 ± 4.1 year | Training | 8 Weeks | Excellent |
| Rago [87] | National | 17 | 27.8 ± 3.9 year | Training<br>Competition | 67 Sessions<br>17 Matches | Excellent |
| Rago [88] | National | 13 | 25.8 ± 3.5 year | Training<br>Competition | 42 Sessions<br>3 Matches | Excellent |
| Scott [89] | National | 15 | 24.9 ± 5.4 year | Training | 29 Sessions | Excellent |
| Silva [90] | National | 20 | 26.5 ± 3.9 year | Training | 15 Sessions | Excellent |
| Stevens [91] | National | 28 | 21.9 ± 3.2 year | Training<br>Competition | 76 Sessions<br>3 Matches | Excellent |
| Suarez-Arrones [92] | National | 30 | N/D [2] | Competition | 2 Seasons | Excellent |
| Torreño [93] | National | 26 | 27.3 ± 3.4 year | Competition | 2 Seasons | Excellent |
| Zurutuza [94] | National | 15 | 25.2 ± 3.0 year | Training<br>Competition | 20 Sessions<br>8 Matches | Excellent |

[1] Two seasons, 6 weeks in each season; [2] not defined (N/D).

Considering age groups, 53 studies were carried out evaluating only adult players, 10 studies only U19, 4 studies only U17, 3 studies exclusively U15, and in 4 studies the age of soccer players is not presented. Additionally, 8 studies evaluated players from two or more age groups. In 27 studies, training was used exclusively as a monitoring condition, in 19 studies only the competition was used and in 36 studies both conditions were assessed.

Of the 27 studies that only evaluate training load, 9 studies examined only internal load measures, 2 studies only external load measures, and 16 studies both internal and external load. Of the 19 studies that assessed only the match load, 6 studies analyzed both internal and external load measures, 8 studies monitored only the external load, and 5 studies examined only the internal load. Of the 36 articles that evaluated both conditions (training and match load), 11 studies examined only the internal load, 10 studies measured only the external load, and 15 studies included the internal and external load.

The load measures are divided into 8 categories: "Heart Rate" (Internal Load), "Questionnaires and Inventories" (Internal Load), "Biomarkers" (Internal Load), "Distances" (External Load), "Training and Match Participation" (External Load), "Metabolic Power" (External Load), "Impacts" (External Load), and "Accelerations and Decelerations" (External Load). Figure 2 shows the number of studies that used each category of load measures, establishing a relationship regarding the utilization of the different categories of measures.

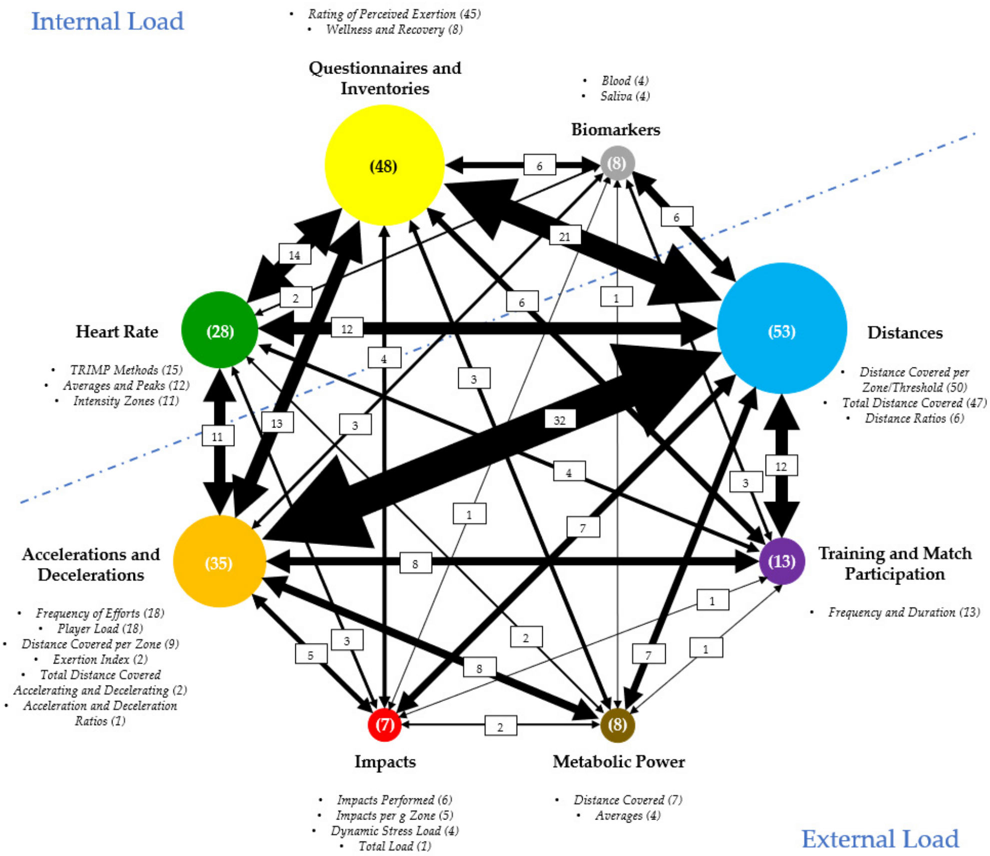


**Figure 2.** Load measures groups: quantities and relationships.

## 4. Internal Load Measures

The internal load measures were grouped according to their typology. Figure 2 shows the division of the different measures by each of the three categories.

### 4.1. Heart Rate

Heart rate (HR) is the number of heart beats per minute (bpm), and its monitoring has become a popular method for training control by measuring exercise intensity [95].

#### 4.1.1. Averages and Peaks

The average heart rate ($HR_{MEAN}$) is determined in absolute (bpm) [26,37,60] and relative values ($\%HR_{MAX}$) [15,26,37,68,69,72,78,87,90,92,93]. Additionally, Campos-Vázquez [15] also measured the peak heart rate ($HR_{PEAK}$) in relative values ($\%HR_{MAX}$) to assess the training sessions' intensity.

4.1.2. Intensity Zones

The intensity zones correspond to the division of the HR by intensity zones, measuring the activity time by zone. Several studies evaluate this measure, mostly in absolute values (min). However, there are differences regarding the division of the zones themselves. Wrigley [37] delimited HR assessment in six zones: $<50\%HR_{MAX}$, 51% to $60\%HR_{MAX}$, 61% to $70\%HR_{MAX}$, 71% to $80\%HR_{MAX}$, 81% to $90\%HR_{MAX}$, and $>90\%HR_{MAX}$, while Geurkink [74] evaluated the same zones with the exception of $<50\%HR_{MAX}$. Abade [58] and Coutinho [67] divided HR analysis into four zones: $<75\%HR_{MAX}$, 75% to $84.9\%HR_{MAX}$, 85% to $89.9\%HR_{MAX}$, and $\geq 90\%HR_{MAX}$. Zurutuza [94] differentiated three zones of intensity: 50% to $80\%HR_{MAX}$, 80% to $90\%HR_{MAX}$, and $>90\%HR_{MAX}$. Campos-Vázquez [15] only quantified uptime above $80\%HR_{MAX}$, Fullagar [72] exclusively measured uptime above $85\%HR_{MAX}$, while Akenhead [59], Campos-Vázquez [16], and Stevens [91] only analyzed the activity time above $90\%HR_{MAX}$. On the other hand, Silva [90] measured this measure in absolute (min) and relative values (%min), dividing the intensity in three zones: $>70\%HR_{MAX}$, $>80\%HR_{MAX}$, and $>85\%HR_{MAX}$.

4.1.3. TRIMP Methods

Banister training impulse [96], Banister TRIMP, was established to quantify the internal load of a training session. This method considers the intensity (maximum heart rate, $HR_{MAX}$; resting heart rate, $HR_{REST}$; and average heart rate, $HR_{MEAN}$) and exercise duration, $T$, using a coefficient, $y$, which relates heart rate and blood lactate during incremental exercise. The total load value, TRIMP, is expressed in arbitrary units (AU). This measure was used by Akubat [13], Impellizzeri [25], Scott [89], and Silva [90]. Since then, other authors developed methods for quantifying the total internal load that could provide more specific and individual responses:

Lucía's TRIMP [97] justifies the evaluation of training load according to ventilatory thresholds (VT). This method, which divides the exercise intensity according to the heart rate reference values obtained in the cycle ergometer test, considers three zones: "light intensity" ($<VT^1$), below $70\%VO2_{MAX}$; "moderate intensity" ($VT^1$–$VT^2$), between 70 and $90\%VO2_{MAX}$; and "high intensity" ($>VT^2$), superior to $90\%VO2_{MAX}$. Each zone is associated with a coefficient, 1, 2, and 3, respectively. The activity time, in minutes, in each zone is multiplied by the respective coefficient and added to obtain a total load value, expressed in AU. This measure was used by Impellizzeri [25].

Stagno TRIMP [98] directly evaluates the blood lactate profile instead of using a generic equation that reflects a hypothetical profile, obtaining a standard curve of response to increased exercise intensity. Five HR zones are then defined around the lactate threshold and onset of blood lactate accumulation (OBLA), $65–71\%HR_{MAX}$, 72–78%, 79–85%, 86–92%, and 93–100%, with the respective weights 1.25, 1.71, 2.54, 3.61, and 5.16. The activity time, in minutes, in each HR zone is multiplied by the respective weighting to determine the total internal load, expressed in AU. This measure was used by Campos-Vázquez [15], Leiper [26], and Brink [62]. Recently, this calculation was modified by Akubat [13], who through the use of an exponential formula generated from the pooled data of all players, but without breaking up the subsequent equation into zones, called it Team TRIMP.

Individualized TRIMP, TRIMPi [99], which, contrary to the methods used by Banister [96] and Stagno [98], had as a weighting factor the physiological response of each athlete to exercise. To evaluate this factor, all athletes are subjected to a maximum test to determine the individual blood lactate concentration profile—blood lactate concentrations were plotted against running speeds and fractional HR elevation, and individual blood lactate concentration profiles were identified via exponential interpolation. Thus, $TRIMPi = T \times [(HR_{MEAN} - HR_{REST})/(HR_{MAX} - HR_{REST})] \times yi$, where $yi$ reflects the profile of the standard curve of blood lactate response to increased exercise intensity. The *yi* values are calculated for each subject. The total load value, TRIMPi, is expressed in AU. This measure was used by Akubat [13] and Manzi [30].

Edward's training load [100] includes a modification in the calculation of training impulses that simplifies the quantification of interval training. The activity time, in minutes, in each of the five HR zones is calculated and multiplied by a factor responding to each zone (50–60%$HR_{MAX}$ = 1; 60–70% = 2; 70–80% = 3; 80–90% = 4; and 90–100% = 5). The results are then added together to determine a total internal load value, in AU. This measure was used by Campos-Vázquez [15], Impellizzeri [25], Leiper [26], Vahia [36], Casamichana [44], Condello [65], Fitzpatrick [71], Geurkink [74], Scott [89], Silva [90], and Zurutuza [94].

### *4.2. Biomarkers*

The term "biomarker", a portmanteau of "biological marker", refers to a broad subcategory of medical signs that can be measured accurately and reproducibly [101]. A joint venture on chemical safety, the International Programme on Chemical Safety, led by the World Health Organization (WHO) and in coordination with the United Nations and the International Labour Organization, has defined a biomarker as "any substance, structure, or process that can be measured in the body or its products and influence or predict the incidence of outcome or disease" [102].

#### 4.2.1. Blood

The lactate produced during high-intensity exercises is simultaneously oxidized or transported from the production places to various tissues such as the heart, liver, kidneys, and muscle fibres for later oxidation [103], so this biomarker has been used to measure physiological stress imposed on soccer players. Blood lactate concentration (BLa) has been proposed as a measure of endurance fitness, but also as a means of standardizing training intensity. The steady-state exercise intensity that elicits a lactate concentration of approximately 4 mmol/L has been suggested as the most favourable to induce optimal physiological adaptations for resistance events [104]; however, the number of factors that affect the way lactate accumulates, independent of exercise intensity, make the importance of the lactate threshold less definitive, thus limiting its usefulness in monitoring and prescribing training intensity [105]. Aslan [60] collected a blood sample to measure the BLa in the first minute of the match, while Iacono [69] obtained the sample three minutes after the end of the training session and match.

Creatine kinase (CK), or creatine phosphokinase (CPK), is an important enzyme in the energy metabolism of skeletal muscle, which is usually present in the blood only in small concentrations. In soccer, this biological marker is used as a measure of muscle damage [57]. Wiig [57] collected blood samples 1 h before, and 1 h, 2 h, 48 h, and 72 h after the end of the match, having analyzed the CK concentration. Oliveira [83] measured the CK concentration in the plasma 48 h before competition.

Myoglobin, a heme-containing globular protein, is found in abundance in myocyte cells of the heart and skeletal muscle and is often referred to as an oxygen storage molecule or as an extra reserve of oxygen [106]. Practically null in terms of assessing the internal load in soccer, this variable was used in the study by [57] to measure muscle damage, with blood samples taken 1 h before, and 1 h, 24 h, 48 h, and 72 h after the end of the match.

#### 4.2.2. Saliva

Saliva sampling has rapidly developed as a tool for the assessment of biomarkers associated with physical performance [107]. Participating in high-intensity activities, with high demands and/or volume over a long period, can cause reductions in salivary immunoglobulin (SIgA) concentrations. SIgA can be used as an additional objective tool in training monitoring and quantifying workload [3], in order to avoid infections in the upper respiratory tract (URTI) [86]. In addition, the results obtained by Freitas [20,21] suggest that the evaluation of SIgA, in conjunction with the sRPE method, can be an insightful approach for coaches and their technical staff to assess the magnitude of training loads and the demands of the competition, contributing to adjust training plans. Figueiredo [70] assessed the SIgA concentration of this antibody 10 min before warming up and 10–15 min after the end of the match. Owen [86] measured the SIgA concentration 30 min before the start of the training session and just after its end.

### *4.3. Questionnaires and Inventories*

The use of questionnaires to assess exercise and physical activity, particularly in large populations, is popular because its administration is easy and economical and does not affect training [105].

#### 4.3.1. Rating of Perceived Exertion

The perception of exertion is an important measure of an individual's degree of physical strain [108], with Borg's subjective rating of perceived exertion (RPE) being developed to allow the athlete, answering the question "How difficult/intense was the session?", to subjectively assess their feeling regarding exercise, considering their own levels of physical fitness and fatigue [109]. Currently, as stated by Pescatello [110], there are two widely used RPE scales: the original Borg scale, which classifies the exercise intensity from 6 to 20 [26,60,62,86], and the modified scale, which measures from 0 to 10 [22,23,73,75,82,88]. In an attempt to simplify the training load quantification, Foster [111] introduced the use of the session rating of perceived exertion (sRPE) instead of using HR data or measuring the intensity of the session, or the type of exercise performed. The sRPE, obtained after the completion of training and/or the match, classifies the general difficulty of the session by multiplying the RPE by the duration of the exercise, in minutes [111] and, based on the scale of 0 to 10, has been widely used in the evaluation of internal load, both in training and in competition [7,9,10,12–20,24,26,28–32,39,61,65–70,72,74,75,77–81,84,85]. On the other hand, Coppalle [66] and Owen [86] used the 6–20 scale to determine sRPE. The application of this inventory has often occurred shortly after the end of the training session and/or match (15 to 30 min); however, it was applied by Owen [86] in the morning after training, in order to ensure that the perceived exertion reflected the whole session and not the last effort.

Lately, some studies have separately assessed the perceived cardiorespiratory ($RPE_{RES}$) and muscular exertion ($RPE_{MUS}$) [14,27,28,61,62,94], and a scale of 0 to 100 has also been used for this purpose [14], in which the technical demand ($RPE_{TECH}$) is also assessed.

#### 4.3.2. Wellness and/or Recovery

One of the questionnaires that aims to assess the state of psychophysiological recovery of athletes is the Total Quality of Recovery (TQR) scale [112]. The use of a TQR scale makes it possible to monitor, and potentially accelerate, the recovery process simply by providing a more complete understanding of the actions necessary for achieving a total recovery [112]. Players perform TQR by answering the question "How recovered do you feel?" on one of two possible scales, 6 to 20 or 0 to 10. This questionnaire was applied by Campos-Vázquez [16] and Zurutuza [94] before the start of the training session and the match, and by Howle [24] 48 h after each match. Gjaka [22] modified this questionnaire to assess the level of recovery, having also submitted it to athletes before each training and match.

The Hooper Index is another questionnaire that subjectively assesses the feeling of well-being in relation to fatigue, stress level, muscle pain (DOMS), and quality of sleep [113]. Each of these parameters is measured separately before the training session or match, the index being the sum of the four indicators. These classifications use a scale of 1 to 7, from "very, very low/good" (point 1) to "very, very high/bad" (point 7) [114]. Clemente [18], Haddad [23], and Oliveira [84] applied this questionnaire before the beginning of each training session.

Recently, Howle [24] and Owen [86] customized this questionnaire to establish an image of individual daily well-being, modifying the scale used and some of the parameters evaluated. The questionnaire, with weightings from 1 (very poor) to 5 (excellent), includes questions about energy level, quality of sleep, readiness to train, and pain in lower body, allowing the sum of the partials to obtain an insight about the welfare state of the players before each training session. This questionnaire was applied before each training session, with Owen [86] trying to get answers about the previous training day.

Malone's well-being questionnaire [29] is also an adaptation of the Hooper Index, assessing the feeling of well-being in relation to muscle pain, sleep quality, fatigue, stress, and energy level, and is applied before each training session. Athletes respond on a 7-point Likert scale, from 1 (strongly disagree) to 7 (strongly agree). The five individual well-being responses are added together to obtain an overall well-being score perceived by the athlete, with a maximum well-being score of 35 AU [29].

The Recovery–Stress Questionnaire for Athletes (RESTQ–Sport) was developed to measure the frequency of current stress symptoms, along with the frequency of activities associated with recovery. Through the simultaneous assessment of stress and recovery, it is possible to obtain a differentiated image of the current state of recovery-stress [115]. In this questionnaire, the interviewee indicates, on a Likert scale with values ranging from 0 (never) to 6 (always), the frequency with which he participated in activities or experienced relevant recovery/stress states. The questionnaire considers 19 items: general stress, emotional stress, social stress, conflicts/pressure, fatigue, lack of energy, somatic complaints, success, social relaxation, somatic relaxation, general well-being, sleep quality, disturbed beaks, burnout/emotional exhaustion, fitness/injury, fitness/being in shape, burnout/personal accomplish, self-efficacy, and self-regulation. It was applied by Fullagar [72] before each training session.

## 5. External Load Measures

The external load measures were grouped according to their typology. Figure 2 shows the division of the different measures by each of the five categories.

### *5.1. Distances*

Locomotor activities, such as the total distance covered (TDC), high-speed running distance covered, or sprinting distance covered, are common external load metrics used by sport scientists [116]. The importance of studying locomotor activities was evidenced by McLaren [117] when he stated that the internal responses to training and match are strongly associated with the amount of running completed, rather than the myriad other external load measures typically monitored in team-sport athletes.

#### 5.1.1. Total Distance Covered

The total distance covered (TDC) is one of the most used external load measures in the evaluation of the amount of work developed by the players in training and competition, being measured in absolute (m) [29,32,38,39,42–53,55,57–60,64,66,68,70–74,76–78,80,83–91,93,94] and relative values (m/min [38,44,46,48,53,58,67–70,72,74,78,84,86,89,90], m/15 min [93], m/h [44], and %, represented as a % of the highest data reached in the match [54]).

#### 5.1.2. Distance Covered per Zone or Thresholds

The distance covered per speed zone is one of the preferred variables to assess the performance of soccer players. This measure, analyzed in absolute (m and min) [71,89] and/or relative values (m/min [38,53,69,80,90,92], %m [54,65,77,86,88], %m/min [54], and %min [44,50,65]), considers the division of the distance covered per speed zone, allowing a more detailed assessment of the work developed during training and/or the match. However, there is a great variability regarding the division and denomination of the zones. Aslan [60] delimited the distance covered in eight zones: "walking", 0.0 to 6.0 km/h; "jogging", 6.1 to 8.0 km/h; "low-intensity running", 8.1 to 12.0 km/h; "moderate-intensity running", 12.1 to 15.0 km/h; "high-intensity running", 15.1 to 18.0 km/h; "low-intensity sprint", 18.1 to 21.0 km/h; "moderate-intensity sprint", 21.1 to 24.0; and "high-intensity sprint", >24.0 km/h. Abade [58] and Coutinho [67] divided it into six zones: "zone 1", 0.0 to 6.9 km/h; "zone 2", 7.0 to 9.9 km/h; "zone 3", 10.0 to 12.9 km/h; "zone 4", 13.0 to 15.9 km/h; "zone 5", 16.0 to 17.9 km/h; and "zone 6", $\geq$18.0 km/h. Clemente [46,48] indicated four zones: "walking", 0.0 to 6.9 km/h; "jogging", 7.0 to 13.9 km/h; "running", 14.0 to 20.0 km/h; and "sprint", >20.0 km/h. Brito [43] also presented four zones: "low-intensity running", <13.0 km/h; "high-intensity running", 13.1 to 16.0 km/h; "very high intensity running", 16.1 to 19.0 km/h; and "sprinting", >19.1 km/h. Martín-García [52] exposed two zones: "high-speed running", >19.8 km/h; and "sprinting", >25.0 km/h. Giménez [75] demarcated six zones: "walking", <2.2 m/s; "jogging", 2.2 to 3.3 m/s; "low-speed running", >3.3 to 4.2 m/s; "moderate-speed running", >4.2 to 5.0 m/s; "high-speed running", >5.0 to 6.9 m/s; and "sprint speed running", >6.9 m/s. Jones [51] defined four zones: "low intensity", <4.0 m/s; "moderate intensity", 4.0 to 5.5 m/s; "high intensity", 5.5 to 7.0 m/s; and "sprinting", >7.0 m/s. Many other authors have presented different divisions and/or denominations [28,37,40,41,43,44,48,52–54,56,58,63,65–73,75–77,79,80,83–92]. In addition, the maximum distance [29,92] and average displacement [58,67,92] have been calculated at the "sprint" zone. The maximum speed reached by soccer players, in km/h [29,46,48,80] and in m/s [41,44,92], has also been evaluated.

Still in this category, the distance covered as a function of lactate thresholds is a measure used by Aslan [60], which consists of the individual assessment of running speed at lactate concentrations $FBL_2$, $FBL_{2–4}$, and $FBL_4$, <2 mmol/L, 2 to 4 mmol/L, and >4 mmol/L, respectively, and consequent determination of the distance covered in each of the speed zones.

Finally, Bacon [39], Iacono [69], Fitzpatrick [71], Rago [88], and Zurutuza [94] used an individualized method to define one or more speed zones: Bacon [39] assessed the distance covered above 75% of maximum speed; Iacono [69] determined the sprint zone using the equation (25.2 (in-game $PV$) $\times$ 100, where $PV$ stands for the peak speed achieved in match; Fitzpatrick [71] analyzed the distance covered above the maximal aerobic sprint (MAS) and $\geq$30% anaerobic sprint reserve (ASR), in meters and minutes (time spent at each zone); Rago [88] examined the distance covered $\geq$30% ASR, >80% MAS ("high-intensity activity"), 80.0% to 99.9% MAS ("moderate-speed running") and 100% MAS to 29% ASR ("high-speed running"), in m and in %m; and Zurutuza [94] measured the distance covered above 80% of maximum speed, in m and in %m.

In addition, the absolute ($n$) [38,41,44,58,59,67,73,74,86] and relative number of efforts ($n$/min) [41,46,48] per speed zone were evaluated, as well as the time spent in each sprint/effort [92] and between sprints/efforts [44,58,67,76,92], both in absolute (s) and relative (%) values.

#### 5.1.3. Distance Ratios

Work-to-rest ratios are used to describe soccer players' activity profiles [44,49,58,63,75,92]. To calculate this ratio, a speed zone is defined as "rest/recovery", and another as "work/activity", through which the distances covered in these zones are used to determine the ratio (division of the amount of work by the amount of rest). Casamichana [44,63] used a speed zone from 0.0 to 3.9 km/h as "rest/recovery" and a speed zone >4.0 km/h as "work/activity". Abade [58] constituted three levels of ratio: 0.0 to 6.9 as "rest" and 7.0 to 9.9 km/h as "work"; 0.0 to 6.9 as "rest" and 10.0 to 15.9 km/h as "work"; and 0.0 to 6.9 km/h as "rest" and a speed zone >16.0 km/h as "work". Giménez [75] indicated a speed zone from 0.0 to 2.0 m/s as "rest" and another >2.0 m/s as "work". Suarez-Arrones [92] defined a zone from 0.0 to 7.0 km/h as "rest" and another >7.0 km/h as "work".

Another ratio model is described by Clemente [49], who used the amount of distance covered in the microcycle and divided it by the load of the competition: "total distance ratio"; "running distance ratio", 14.0 to 19.9 km/h; "high-speed running distance ratio", 20.0 to 24.9 km/h"; and "sprinting distance ratio", >25.0 km/h.

### 5.2. Accelerations and Decelerations

Acceleration is based on the change in GPS speed data, and it is defined as a change in speed for a minimum of 0.5 s, with a maximum acceleration of at least 0.5 m/s. The acceleration is considered complete when the player stops accelerating. The classification of speed zones is based on the maximum acceleration achieved in the acceleration period. The same approach is used in deceleration [80].

#### 5.2.1. Total Distance Covered Accelerating and Decelerating

Total distance covered during acceleration and deceleration was collected by Rago [55] and Akenhead [59] to characterize physical demands imposed by competition in soccer players against opponents of higher and lower qualitative levels.

#### 5.2.2. Distance Covered per Zone

The measurement of the distance covered at each acceleration and deceleration zone allows to measure the intensity of the displacements, regarding the starting and braking actions. This metric is analyzed in absolute (m) and relative (m/min, m/effort, and %) values. However, there is variability in the definition of the acceleration and deceleration zones, as well as in the classification of those same zones. Barron [40] divided the analysis into four deceleration zones and four acceleration zones: "zone 1" (deceleration), $-5.0$ to $-20.00$ m/s$^2$; "zone 2" (deceleration), $-4.0$ to $-5.0$ m/s$^2$; "zone 3" (deceleration), $-2.0$ to $-4.0$ m/s$^2$; "zone 4"(deceleration), 0.0 to $-2.0$ m/s$^2$; "zone 5" (acceleration), 0.0 to 2.0 m/s$^2$; "zone 6" (acceleration), 2.0 to 4.0 m/s$^2$; "zone 7" (acceleration), 4.0 to 5.0 m/s$^2$; and "zone 8" (acceleration), 5.0 to 20.0 m/s$^2$. Castagna [64] delimited two zones of deceleration, "high-intensity decelerations" ($\leq$2.0 m/s$^2$) and "very high-intensity decelerations" ($\leq -3.0$ m/s$^2$), and two zones of acceleration, "high-intensity accelerations" ($\geq$2.0 m/s$^2$) and "very high-intensity accelerations" ($\geq$3.0 m/s$^2$). Akenhead [59] defined three zones of deceleration and three zones of acceleration: "low decelerating", $-1.0$ to $-2.0$ m/s$^2$; "moderate decelerating", $-2.0$ to $-3.0$ m/s$^2$; "high decelerating", $<-3.0$ m/s$^2$; "low accelerating", 1.0 to 2.0 m/s$^2$; "moderate accelerating", 2.0 to 3.0 m/s$^2$; and "high accelerating", >3.0 m/s$^2$. Other authors presented different divisions and/or denominations [49,54,71,94]. Chrismas [45] added to this variable (distance in acceleration and deceleration >2.0 m/s$^2$) the distance covered in high intensity (>5.5 m/s), in order to quantify the high-metabolic load (HML) that players experienced during training. The same method, in absolute (m) and relative (m/min) values, was used by Silva [90]; however, these authors considered the distance covered >14.4 km/h.

#### 5.2.3. Frequency of Efforts

The quantification of the number of accelerations and decelerations, total [70,75] or partial (by speed threshold), in absolute ($n$) and relative ($n$/min and %) [38,73,80,90], are measures used in recent studies.

In the division and denomination of these zones, there also is diversity. Curtis [68] indicated three zones of acceleration ("low intensity", 0.0 to 1.99 m/s$^2$; "moderate intensity", 2.0 to 3.99 m/s$^2$; and "high intensity", >4.0 m/s$^2$) and three of deceleration ("low intensity", 0.0 to $-1.99$ m/s$^2$; "moderate intensity", $-2.0$ to $-3.99$ m/s$^2$; and "high intensity", $<-4.0$ m/s$^2$). Stevens [91] divided the analysis of the number of accelerations and decelerations into four zones, two of acceleration ("medium efforts", 1.5 to 3.0 m/s$^2$ and "high efforts", >3.0 m/s$^2$) and two of deceleration ("medium efforts", $-1.5$ to $-3.0$ m/s$^2$ and "high efforts", $<-3.0$ m/s$^2$). Other authors have presented different divisions and/or classifications regarding these variables [38,52,73–77,85,87,90].

In addition to accelerations and decelerations above 2.0 m/s$^2$, Iacono [69] added the number of sprints in the calculation of high-intensity efforts per minute (HIE/min). By contrast, Owen [53] sums the number of accelerations and decelerations above 4.0 m/s$^2$ to define the amount of high-intensity efforts (HIE). Wiig [57] adopted the same strategy and summed the number of accelerations and decelerations above 2.5 m/s$^2$ to obtain the number of HIE. Casamichana [44] and Jaspers [77] assessed the number, average, average duration, and maximum duration of repeated HIE (at least 3 efforts at a speed >13.0 km/h [44] or at least 3 sprints, high-magnitude accelerations (>3.5 m/s$^2$), or a combination of both [77]—and with <21 s recovery between them).

#### 5.2.4. Accelerations and Decelerations Ratios

The acceleration and deceleration ratios were recently used by Clemente [49], who used the number of accelerations and decelerations (>3.0 m/s$^2$) in the microcycle and divided it by the load of the competition itself.

#### 5.2.5. Player Load

The player load (PL) is based on the acceleration data that are recorded by triaxial accelerometers [118] and is one of the most used metrics to describe the external load [29,40,44,56,57,59,63,68,75,77,85,89]. This variable is considered a vector of magnitude that represents the sum of the accelerations recorded in the anteroposterior, mediolateral, and vertical planes [119]. Lately, other metrics that derive from PL have been used. The PL Slow quantifies the accelerations performed at a speed below 2.0 m/s [29]; the PL 2D omits the vertical accelerometer from the calculation, allowing a more precise quantification in relation to actions over short distances [94]; and the PL 1D consists in assessment of each axis of the movement in isolation [51,77]. These are measured in absolute (AU and g) [48,49] and relative (UA/min [62,77], g/min [46], and UA/m [51,77]) values.

#### 5.2.6. Exertion Index

The exertion index (EI) derives from the speed of movements on the playing field and it is calculated using three equations. These equations are the sum of the weighted instantaneous speed, the weighted cumulative speed over 10 s, and the weighted cumulated speed over 60 s [44]. This variable is evaluated in absolute, EI [75], and relative, EI/min [44], values.

### *5.3. Impacts*

Impacts are often identified as values of maximum magnitude of the accelerometer, over 2 *g* over a period of 0.1 s, and they are reported as maximum and cumulative values over a specific period [120].

#### 5.3.1. Impacts Performed

The total (*n*) [38,58,80] and relative (*n*/min) [38,58,67,73,80,90] number of impacts is a variable used to measure the number of intense actions performed by soccer players.

#### 5.3.2. Impacts Performed per g Zone

In addition to the number of impacts, another measure is the distribution of the number of impacts by force zone, gArruda [38], Abade [58], and Coutinho [67] divided the impacts into six zones: "zone 1", 5.0 to 6.0 g; "zone 2", 6.1 to 6.5 g; "zone 3", 6.6 to 7.0 g; "zone 4", 7.1 to 8.0 g; "zone 5", 8.1 to 10.0 g; and "zone 6", ≥10.1 g. Gaudino [73] and Silva [90] analyzed only the number of impacts performed above 2.0 g. This division allows a more detailed analysis of the intensity of the body impacts.

#### 5.3.3. Dynamic Stress Load

Dynamic stress load is the total of the weighted impacts, which is based on accelerometer values of magnitude above 2.0 *g*. It weights the impacts using an approach similar to that used in the speed intensity or heart rate exertion calculations, with the key concept being that an impact of 4.0 *g* is more than twice as hard on the body as an impact of 2.0 *g* [120]. Weighted impacts are aggregated and organized at scale, expressed in AU to provide more useful values. This variable is quantified in absolute (AU) [70,73,80,90] and relative (AU/min) [73,80,90] values.

5.3.4. Total Load

The total load gives the total of the forces on the player over the entire activity period based on accelerometer data alone. It uses the magnitude of the accelerometer values taken in three directions, sampled 100 times per second [120]. This metric was used in the study of Figueiredo [70].

### *5.4. Metabolic Power*

Metabolic power (MP) has been proposed to provide an instant image of specific soccer activities [121]. This method considers acceleration and speed to define the profile of individual distances, and the time spent by players in power limits arbitrarily estimated and chosen [121,122]. This approach assumes that the energy produced by a player during a match is a direct result of the cost of the acceleration and the corresponding instantaneous speed [121]. Despite the name that implies metabolism of the athlete, it is mathematically derived from the speed–time profile and, therefore, remains as an external load measure [6].

5.4.1. Averages

The average MP (W/kg) is known as the energy spent by the players per second, per kilogram of body weight, and it has been evaluated by different authors [52,56,64,73] to obtain information about the metabolic requirement experienced by soccer players during training and/or a match.

5.4.2. Distance Covered per Zone

The assessment of the distance covered by the zone of MP exposes the amount of metabolic wear imposed by physical activity on the players. It was used by Martín-García [52], Gaudino [73], and Malone [80], who measured, in absolute (m) and/or relative (m/min) values, the distance covered in high metabolic power, >25.5 W/kg, as well as by Castagna [64] and Stevens [91], who determined the distance covered in "high power" and "high intensity", respectively, ≥20.0 W/kg. Additionally, the activity time (in %) at different power zones was also assessed by Iacono [69], who divided the analysis into five zones: "low power", 0.0 to 10.0 W/kg; "intermediate power", 10.0 to 20.0 W/kg; "high power", 20.0 to 35.0 W/kg; "elevated power", 35.0 to 55.0 W/kg"; and "maximum power", >55.0 W/kg.

In this category, the equivalent distance (ED) used in the study by Chrismas [45] represents the distance that the athlete would have covered at a constant pace using the total energy spent during the activity (training or match). $ED = W/ECcKT$, where $ED$ is expressed in meters, $W$ is the total energy expended (J/kg), $ECc$ is the energy cost of running at a constant speed, which is assumed as 3.6 J/kg, and $KT$ is a factor associated with the type of floor where soccer is played (=1.29) [121].

### *5.5. Training and Match Participation*

In soccer, the density of the competitive period requires a careful periodization by coaches and their staff. The number of training sessions per microcycle, the duration of each training session, and the time of participation in the competition are variables that affect, positively or negatively, the physical fitness of the soccer players.

Frequency and Duration

The total exposure time to the match [57,83,85,87] or to the training sessions [29,47,70,74,77,78,82–85,91], in minutes, as well as the number of training sessions and matches [82] is quantified to assess the external load imposed on athletes.

## **6. Discussion**

The purpose of the present study is to carry out a systematic review on internal and external load monitoring, in training/match, identifying the measures used. Simultaneously, we intend to order all the load measures used in soccer monitoring and systematizing them (describe them, grouping by categories, and standardize their structure/classification). In recent years, training and match load monitoring has received special attention from sports scientists, of which 55 articles included in this systematic review were published between 2017 and 2019. Through the analysis of all articles used in this systematic review, we verified, as stated in the Vanrenterghem [4] study, the existence of a colossal and increasing number of load measures at the disposal of soccer coaches. On the one hand, it increases the range of monitoring options, and on the other hand, it raises doubts about which measures are most valid, useful, and important to analyze. The technological evolution in the monitoring instruments not only allows improvements in the accuracy of the collected data, but also promotes the development of new measures and/or versions of existing measures. Moreover, as described by Akenhead [2], the multiplicity caused by the evaluation on the same load measure in terms of volume (absolute values) and intensity (relative values) of work is another reason that gives rise to the abundance of load measures. Foster [123] adds that the future of training monitoring might well be dominated by emerging technologies that allow new possibilities relative to the analysis of the external training load and, in that sense, there are very relevant works [1–4,6,123] in the theorization and conceptualization of monitoring purposes. However, there are few (practically non-existent) works that expose the load measures used in the training and match evaluation and that describe them systematically, providing those who start, or already work in this area of activity, a repository of basic knowledge.

The load categories most used to monitor training and match are “Distances” (53 studies), “Questionnaires and Inventories” (48 studies), “Accelerations and Decelerations” (35 studies), and “Heart Rate” (28 studies). Less used are the “Training and Match Participation” (13 studies), “Biomarkers” and “Metabolic Power” (both with 8 studies), and “Impacts” (7 studies). Regarding the load measures, the most used are “Distance Covered per Zone/Threshold” (50 studies), “Total Distance Covered (47 Studies), “Rating of Perceived Exertion” (45 studies), “Frequency of Efforts” and Player Load (both with 18 studies), “TRIMP Methods” (15 studies), “Frequency and Duration” (13 studies), “Average and Peaks” (12 studies), and “Intensity Zones” (11 studies). In these measures, the collected data are analyzed in absolute (e.g., m, AU, and min) and/or relative (e.g., %, m/min, and AU/min) values.

In agreement with Bourdon’s opinion [1] regarding the need to simplify the information for some main load measures, also corroborated by Akenhead [2], who verified that coaches, excluding match/training duration, record 7 $\pm$ 2 measurements in the monitoring tasks, we propose that the following measures should be considered: average heart rate (%$HR_{MAX}$) [14,25,36,67,68,71,77,86,89,91,92]; heart rate intensity zones (min and %min) [15,16,37,58,59,67,72,74,91,94]; sRPE (AU and AU/min) [7,9,10,12–20,24,26,28–32,39,61,65–70,72,74,75,77–81,84,85]; Edward’s training load (AU) [15,25,26,36,44,65,71,74,89,90,94]; Hooper index (AU) [18,23,24,29,84,86]; player load 3D (AU, AU/min, and %AU) [29,40,44,56,57,59,63,68,75,77,85,89]; total distance covered (m, m/min, and %m) [29,32,38,39,42–53,55,57–60,64,66,68,70–74,76–78,80,83–91,93,94]; distance covered by speed zone (m, m/min and %m) [29,38,41–46,48,49,51–55,57–60,64,66–78,80,81,84–93]; distance ratios [44,49,58,63,75,92]; accelerations and decelerations($n$, $n$/min and %$n$) [38,68,73–77,80,85,87,90,91]; and training/match duration (min) [29,47,57,70,74,77,78,82–85,87,91]. We identified five internal load and six external load measures among the most used in scientific articles included in this review, which include, as suggested by Bourdon [1], variables that directly quantify units of measurement, as well as composite methods, capable of globally evaluating the quantity and quality of training sessions and matches. When organizing a monitoring approach, we recommend that the inclusion of some of these measures should be considered. The importance attributed to the selected measures may vary from session to session, due to the alternation of physical regimes during the microcycle, or between the player positions that have different physical actions and demands during matches [14,40,43,54]. Altogether, the assessment of internal and external load measures will help coaches, sport scientists, and researchers to compare loads from different studies and to replicate different studies methodologies for their own exercise training sessions, planning, and periodization.

The internal load measures derived from biomarkers are not present among the most used mainly due to the constraints involved in their daily and systematic collection, both in training and in competition. This type of measures is useful and valid [60,69,105]; however, it is more appropriate for carrying out evaluations with less continuous nature.

We found that in some studies the term "training load" [16,17,20,22,28,33,65,83] is used as a parameter for assessing both the load suffered by athletes in training as in the match. However, we consider that this designation is not appropriate because it does not distinguish the medium of load monitoring, the training, or the match. Until a few years, training monitorization was only used in the context of training and the term "training load" was tolerable, nowadays, load monitorization is also used in competition and therefore, this designation becomes reductive. As applied by other studies [13,33,34,49,52,61,71,76,82,87], we recommend the use of the terms "training load" and "match load" (regardless of whether they are friendly or official) to differentiate where the load assessment is developed. When the assessed load corresponds to the sum of training and match load, we suggest applying the "workload" term [19,31,33,42,44,50,58,67,75].

All studies evaluating accelerations and decelerations use "$m/s^2$" as the unit of measurement; however, the same does not happen with respect to the distance covered by speed zones. Most studies use "km/h" [29,49,64,66–68,71,73,74,77,83,86,87,89] as the unit of measurement and a smaller number of studies use "m/s" [45,51,59,75]. We suggest the use of "m/s" as a unit of measurement in detriment of "km/h", and it is not just about converting "km/h" to "m/s". Notice that Owen [86] considers "jogging" the distance covered at a speed between 7.3 and 14.3 km/h (if we convert to m/s, ≈2.0 to 4.0 m/s); Clemente [46] considers "jogging" the distance covered between 7.0 and 13.9 km/h (if we convert to m/s, ≈1.9 to 3.9 m/s); Giménez [75] considers "jogging" the distance covered between 2.2 and 3.3 m/s (if we convert to km/h, ≈7.9 to 11.9 km/h). In these three studies, performed with professional soccer teams, there is no consensus regarding the "jogging" zone. What are the reasons for this? There are several, but one of them we consider to be the use of different units of measurement ("m/s" and "km/h"). We recognize that the standardization of the unit of measurement used will allow us to improve the existing consensus regarding speed zones, just as the "m/s" unit also fits much better to what is used by soccer coaches when preparing their plans and when they intervene. For example, when a coach planning an exercise to improve "sprint" speed, where the exercise space is 20 m long, does it become simpler to control if he sets a goal to reach in 7.0 m/s or in 25.2 km/h? The issue is not the simple conversion from "km/h" to "m/s"; it is the utility and functionality of the unit of measurement. In summary, we suggest using the "m/s" unit when evaluating the distance covered by speed zone, and the "$m/s^2$" unit when evaluating the acceleration/deceleration zones.

Furthermore, there are inconsistencies in the denomination and categorization of some measures, which may indicate uncertainties about the validity and usefulness of what is being examined, and they make it difficult to compare results between different investigations. Consequently, we consider its uniformity and systematization to be critical. Regarding heart rate, we observe that are differences with respect to the definition of heart rate intensity zones. Wrigley [37] found lower values of average HR ($\%HR_{MAX}$) for U18 compared to U16 and U14: in training, U18—69 ± 2%, U16—74 ± 1%, and U14—74 ± 2%; and in match, U18—81 ± 3%, U16—84 ± 2%, and U14—83 ± 2%. In the monitorization carried out by Iacono [69] in U19, mean HR values ($\%HR_{MAX}$), 84.5 ± 2.8%, were found in UEFA Youth League matches. Malone [78] assessed the average HR ($\%HR_{MAX}$) of the training sessions in the preparatory period and identified values of 70 ± 7%, with Silva [90] finding similar values in the same period of the season, 71.2 ± 5%. Torreño [93] measured, in an elite senior team, the average HR ($\%HR_{MAX}$) during the matches and obtained values of 86 ± 4.9%. Thus, considering the analysis of $\%HR_{MAX}$ and the permanent existence of variables that affect the intensity of training/match, we recommend the definition of four zones of intensity: <60.0%$HR_{MAX}$ (Wrigley [37] and Geurkink [74] define 60% as the upper limit of one of their intensity zones), 60.0% to 74.9%$HR_{MAX}$ (Wrigley [37] and Geurkink [74] define an intensity zone above 60%, while Abade [58] and Coutinho [67] define one below 75%), 75.0% to 89.9%$HR_{MAX}$ (sum of two intensity zones presented by Abade [58] and Coutinho [67]), and ≥90%$HR_{MAX}$ [15,37,58,59,67,74,91,94]. Additionally, in Abade [58] and Coutinho [67] studies, the intensity zones are called "zone 1, 2, 3, and 4"; however, this type of denomination does not clarify the intensity involved. We suggest, for the indicated intensity zones, to name them as "low intensity", "moderate intensity", "high intensity", and "maximum intensity", respectively. When we propose the use of these four zones, our intention is to standardize the evaluation parameters. How can we compare two studies performed in similar conditions [37,58] and the results obtained by them if, for example, one uses an intensity zone of 71.0% to 80.0%$HR_{MAX}$ [37] and the other of 75.0% to 84.9%$HR_{MAX}$ [58]? If the heart rate intensity zones are not consensual between studies, we will lose detail in the analysis and, consequently, the practical applications of the studies become dubious as there are different configurations regarding the definition of the intensity zones.

Concomitantly, when analyzing the speed zones, we verified that the distance covered above 4.0 m/s is called both "high-speed running" [80] and "high-intensity activity" [88]. In professional soccer, the distance covered above 5.5 m/s is defined as "high-speed running" [45]. Previously, we suggest the use of "intensity" for variables related to heart rate (e.g., intensity zones) or accelerations and decelerations (distance covered or number of efforts performed), and the use of "speed" when related to distance covered by different speed thresholds. Then, we propose the definition of six speed thresholds: "walking distance", 0.0 to 2.0 m/s; "jogging distance", 2.0 to 3.0 m/s; "running speed distance", 3.0 to 4.0 m/s; "high-speed running distance", 4.0 to 5.5 m/s; "very high-speed running distance", 5.5 to 7.0 m/s; and "sprint distance", a speed greater than 7.0 m/s. Subsequently, we recommend, as defined by Giménez [75], that a speed zone <2.0 m/s should be considered as a "rest" in the assessment of ratios related to the distance covered. If an elite European soccer player covers 107 ± 12 m/min [124], approximately 1.78 ± 0.2 m/s, the definition of a speed zone >2.0 m/s as "rest" includes a speed usually higher than the average running speed presented in competition by national teams and, therefore, can hide the part of the "work" developed. Furthermore, with regard to accelerations and decelerations, we recommend the definition of three zones used by Curtis [68]: "low intensity", 0.0 to 2.0 $m/s^2$; "moderate intensity", 2.0 to 4.0 $m/s^2$; and "high intensity", greater than 4.0 $m/s^2$.

## 7. Limitations

Some limitations were addressed when considering this research on the training/match load monitoring in soccer. Only 3 of 82 studies are based on the regional level. In this sense, the conclusions obtained mainly portray the load measures in elite soccer (in different age groups) and cannot be generalized to any competitive level. Finally, 65% of the articles included in this review present a sample exclusively composed of adult soccer players, which influences the choice and definition of the load measures evaluated in the training and/or match, and we do not differentiate the analysis by age group.

## 8. Conclusions and Practical Applications

In soccer, training and match load monitoring is recognized as a relevant task at any competitive level. Through this monitorization, the coaches and other members of the technical staff can base part of their decision making about the periodization, design, and application of the different types of planning (training exercise, training session, microcycle and mesocycle), and the individual and collective management of the team in training process and in the competition.

However, due to the inconsistencies examined in the criteria for identifying and systematizing various measures, it is critical to standardize their structure and classification. This will allow to have confidence about the validity and usefulness of what is being analyzed, as well as to promote the possibility of comparing the results of different investigations and, consequently, to increase and improve knowledge about this very sensitive subject.

This systematic review reveals the measures used in scientific articles that focus on internal and/or external load monitoring in training sessions and/or matches and it could be used as an instrument for the reorganization and standardization of various load measures. From the findings of the present systematic review, relevant practical applications should be considered:

(a) Nomenclature and Organization—"Training load" only represents the load assessed in the training sessions. "Match load" represents the evaluation of the load imposed by the games, with an official or friendly nature. "Workload" corresponds to the sum of training and match load. Additionally, to clarify the structure and classification of this activity, it is essential to use a standard nomenclature and order. The use of different names, or values, for the same variable causes entropy. We specifically indicate the nomenclature to be used, as well as the range of values that define each speed, acceleration/deceleration, and heart rate intensity zone;
(b) Identification of Load Measures—Our study systematically describes all the load measures used by the articles included in this review, providing those who start, or already work in this area of activity, a repository of basic knowledge;
(c) Selection of Load Measures—Due to the existence of an extraordinary number of load measures, it is essential that soccer coaches and/or sport scientists select and focus their attention on the most useful and specific measures. Based on the measures most used by the articles included in this review, we suggest a set of internal and external load measures to be considered in that selection;
(d) Units of Measure—The use of the "m/s" unit when evaluating the distance covered by the speed zone, to the detriment of "km/h", will improve the existing consensus regarding speed zones, as well as take on a more functional character;
(e) Intensity vs. Speed—The use of "intensity" to variables related to heart rate or accelerations and decelerations, and the use of "speed" when related to distance covered by different speed thresholds.

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# Kinematic Analysis of Water Polo Player in the Vertical Thrust Performance to Determine the Force-Velocity and Power-Velocity Relationships in Water: A Preliminary Study

**Giuseppe Annino [1,2], Cristian Romagnoli [2,3], Andrea Zanela [4], Giovanni Melchiorri [1,5], Valerio Viero [5], Elvira Padua [6,*] and Vincenzo Bonaiuto [2]**

1 Department of Medicine Systems, "Tor Vergata" University of Rome, via Montpellier 1, 00133 Rome, Italy; g_annino@hotmail.com (G.A.); gmelchiorri@libero.it (G.M.)
2 Sport Engineering Lab, Department of Industrial Engineering, "Tor Vergata" University of Rome, via del Politecnico 1, 00133 Rome, Italy; cristian.romagnoli2@unibo.it (C.R.); vincenzo.bonaiuto@uniroma2.it (V.B.)
3 Department for Life Quality Studies, University of Bologna, 47900 Rimini, Italy
4 Robotics and Artificial Intelligence Lab, ENEA "Casaccia" Research Centre, via Anguillarese, 00301 Rome, Italy; andrea.zanela@enea.it
5 Italian Swimming Federation, Stadio Olimpico Curva Nord, 00135 Rome, Italy; valerio.viero@gmail.com
6 Department of Human Science and Promotion of Quality of Life, San Raffaele Open University of Rome, via di val Cannuta 247, 00166 Rome, Italy
* Correspondence: elvira.padua@uniroma5.it

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**Abstract:** Background: To date, studies on muscle force and power-velocity (F-v and P-v) relationships performed in water are absent. Aim: The goal of this study is to derive the F-v and P-v regression models of water polo players in water vertical thrust performance at increasing load. Methods: After use of a control object for direct linear transformation, displacement over the water and elapsed time was measured, by using a high-speed 2D-videoanalysis system, on 14 players involved in the study. Results: Intra-operator and player's performance interclass correlation coefficient (ICC) reliability showed an excellent level of reproducibility for all kinematic and dynamic measurements considered in this study with a coefficient of variation (CV) of less than 4.5%. Results of this study have shown that an exponential force-velocity relationship seems to explain better the propulsive force exerted in the water in lifting increasing loads compared to the linear one, while the power and velocity have been shown to follow a second-order polynomial regression model. Conclusion: Given the accuracy of the video analysis, the high reliability and the specificity of the results, it is pointed out that video analysis can be a valid method to determine force-velocity and power-velocity curves in a specific environment to evaluate the neuromuscular profile of each water polo player.

**Keywords:** water polo; biomechanics; video analysis; force-velocity relationship; power-velocity relationship

## 1. Introduction

Water polo is characterized by a complex number of movements: swim with speed changes, faster counterattack actions, frequents changes from horizontal to vertical positions, shots, blocks and fight to gain or maintain the position in water [1]. Most of these actions (handlings, shots, fight) performed at high intensity require a vertical position in water [2]. There are two actions in movement of lower limbs of the water polo player that can be identified: the eggbeater kick (cyclic movement) [3,4] and the breaststroke kick (ballistic movement) [5]. The latter skill, involving maximal lower limbs muscle power, is usually adopted in trunk vertical thrust over the water level to complete the pass, in overall shots and in goalkeeper save actions. Indeed, some studies have found in elite female water polo players a significant correlation between the shot speed and the vertical thrust over the water level performed with breaststroke kick [6,7]. Net of sex differences, it is plausible to consider the vertical thrust one of the main skills also for men's water polo.

From a biomechanical point of view, the maximal vertical thrust is obtained through the breaststroke kick techniques performed with quick movements on horizontal foot plan in extensive abduction, hip in flexion position and fast flexion-extension of knee [8]. Relative to muscular power and strength of lower limbs, it is common practice to test and condition the water polo players directly in the gravitational environment [1,9] without taking into account the specificity principle of neuromuscular and biomechanical performance that has to be transferred directly to the vertical thrust performed in water [10]. Relative to exercises performed on dry land, some authors showed a poor relationship between ground vertical jump and vertical thrust in water [11,12]. Recently, some authors, using different strength and power training methods performed on dry land or combined (dry-land and in-water) or in water only, showed a positive effect on some of the water polo skills performance with different results related to the method used [12–14]. Nevertheless, to date, studies on muscle force and power-velocity (F-v and P-v) relationships performed in water are absent [15]. In fact, the relationship between force and muscular contraction velocity has been determined in athletes to evaluate the dynamic neuromuscular characteristics in isotonic or ballistic conditions [15–17]. For this reason, individual power load-based training is difficult be carry out in the water taking into account that this is not specific if performed in a gravitational field.

Usually, in gravitational field, the most used devices for their practical applications in determining the mentioned above curves are linear encoders that, through a derivation process of measured space-time values, are able to calculate force and power parameters in relation to displaced mass [16,18]. Therefore, also taking into account the logistical difficulties in applying whatever isoinertial dynamometer in an aquatic environment, it remains mandatory to find a reliable and non-invasive assessment system. The practical goal of this study has been to verify an easy and reliable method, through a 2-D motion analysis approach, whose validity on kinematic measurements has already been shown [19], to assess the vertical displacement reached over the water level—net of the submerged breaststroke kick technique—and the related derivate kinematic as well as dynamic parameters. Furthermore, this needs to determine the accuracy of the measurement system together with the intra-rater and neuromuscular performance reliability of the assessment method used. In order to obtain in the aquatic environment F-v and P-v relationships like those obtained in gravitational field, it a test protocol was used at increasing loads performing the vertical thrust with a breaststroke technique.

## 2. Materials and Methods

### *2.1. Subjects*

Fourteen male sub-elite level water polo players, (age 22.7 ± 5; Body Weight, 72.9 ± 8.2 kg; height 178.9 ± 5.2 cm, Body Mass Index 22.8 ± 2.2 kg/m$^2$) participating in the regional championships (Serie C level) organized by the Italian Swimming Federation participated in this study. The body mass and height of the subjects were measured to the nearest 0.5 kg and 0.5 cm, respectively (Seca Beam Balance-Stadiometer, Germany). The players with physical problems (pain or injuries) or with low compliance training were excluded from the study. Written informed consent was obtained from participants (n = 14) before being tested. The research was approved by the Internal Research Board of "Tor Vergata" University of Rome. All procedures were carried out in accordance with the Declaration of Helsinki.

### *2.2. Experimental Design*

This study requires the subjects to perform in the water vertical thrust tests at increasing load. This has been applied to the subjects by using the Water polo Overload Test/Training (WOT) [1] equipment, shown in Figure 1, that consists of a harness made of belts that are worn by the player and a load which can be fastened to its lower extremity, and does not interfere in any way with the legs' movements.

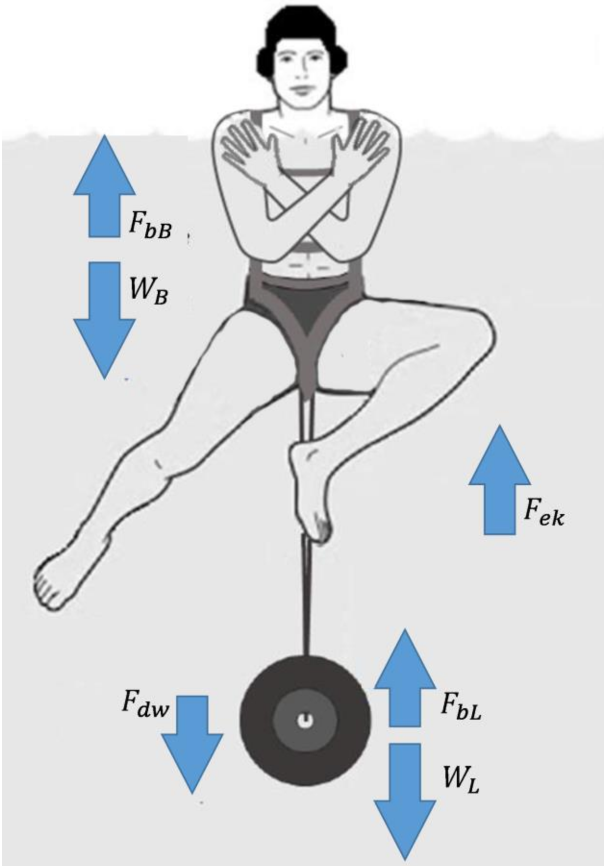


**Figure 1.** Frontal view of water polo overload test (WOT) conditions and acting forces. Buoyancy force of the subject ($F_{bB}$), Body weight of the subject ($W_B$), eggbeater kick force ($F_{ek}$), buoyancy force of the load ($F_{bL}$), weight of the load ($W_L$), force relative to power that is wasted to accelerate water downwards ($F_{dw}$).

The subjects, once they reached the position between the posts, spent a few seconds floating with the eggbeater kick technique to achieve and to maintain the optimal start position keeping the acromion at the same water level as before to perform, by using the breaststroke kick technique, an explosive boost to raise vertically the body as high as possible. In addition, to avoid any coordinative influence, the subjects held their upper limbs to their shoulders during the performance. Then, wearing the WOT system, they started to perform the increasing load test starting from free load condition which represents the reference trial for the test specificity. The player performed vertical thrusts increasing the load by 5 kg at each step (5, 10, 15, 20, 25 kg) where the 25 kg was the maximum load vertically raised at the limit of the buoyancy. The best trial of three measurements in terms of displacement and verticality at each increased load performance was selected for statistical analysis. Each subject completed raised load test with almost three-minute rest time between the trials enough to recovery from single boost performance.

In order, to determine day-to-day reliability, the subjects underwent the same protocol after two rest days. The measurements were performed in the same swimming pool where the subjects usually train with the water temperature of 29 °C, pH of 7.2–7.6, and an environmental temperature that ranges between 24–26 °C at a humidity of 75%. These parameters remained unchanged in both the test days. One week before the test administration, the subjects performed some simulations for familiarization with the equipment. On the first test day, the anthropometric data were recorded and the subjects performed, after a warm-up, an incremental loads protocol test with the WOT. The warm-up exercises were completed in 15 min and consisted general to specific skills performed with a progressive increase intensity.

The subject, to maintain the assigned start position must produce, properly moving his limbs (eggbeater kick), an upward floating force ($F_{ek}$) equal to the difference between the sum of his body weight ($W_B$) plus the weight of the eventual additional load ($W_L$) and the sum of the respective buoyant forces ($F_{bB}$ and $F_{bL}$) [20]. Equation (1) takes into account a further force ($F_{dw}$) related to the power that is wasted to accelerate the water downwards and that does not contribute to the thrust.

$$F_{ek} - F_{dw} = (W_B - F_{bB}) + (W_L - F_{bL}) \tag{1}$$

Considering that the body weight and the buoyant force, respectively ($V_B$ [m$^3$] is the volume of the body, $\rho_s$ its density [kg/m$^3$], $\rho_w$ the water density (995.96 kg/m$^3$ at 29 °C), $g$ [m/s$^2$] the acceleration due to the gravity and $f$ the fraction of the submerged body), are $W_B = gV_B\rho_B$ and $F_{bB} = gfV_B\rho_w$. The Equation (1) can be written as follow

$$F_{ek} = W_B\left(1 - f_0\frac{\rho_w}{\rho_B}\right) + (W_L - F_{bL}) + F_{dw} \tag{2}$$

where $f_0$ is the fraction of the submerged body at starting position (i.e., the volume of the whole body without the head and neck).

Conversely, when the subject has to perform the vertical thrust, he has to provide, by moving his legs with a breaststroke kick, an upward force ($F_{bk}$) greater than the sum of the weight force of both load $W_L$ and body $W_B$, the friction forces $F_{fr}$, the buoyant forces $F_b$ and the losses $F_{dw}$ as reported in the follow expression:

$$F_{bk} > \left(W_B - F_{bB} + F_{frB}\right) + \left(W_L - F_{bL} + F_{frL}\right) + F_{dw} \tag{3}$$

where $F_{bB}$ and $F_{bL}$ represent, respectively, the buoyant force of the subject and the load, while $F_{frB}$ and $F_{frL}$ are the respective friction forces [20].

The buoyant and friction forces of the load have been evaluated starting from manufacturing features (material, shape and dimensions). Moreover, because the load remains entirely immersed during the whole test, the relative buoyant force always presents the same value. Furthermore, since the friction depends on the displacement velocity, it will be possible, due to the features of the WOT, to use the same value of the vertical thrust velocity computed for the subject.

A different approach is required for the calculation of the same forces for the human body. Indeed, the buoyant force depends on the fraction of the volume of the immersed body that tends to vary during each test because the height of the vertical thrust changes at different loads. Therefore, the accuracy on the computation of such a term depends on a proper estimation of both the volumes of the different parts of the body and its density. In this study, this value of density $\rho_B$ has been simply estimated, for each subject, starting from his weight and height by using the procedure suggested in [21,22]. Moreover, in order to identify the right fraction of the submerged body volume, we used the mean relative percentage values of the volumes of the different segments of the human body [23,24]. Finally, we chose to evaluate the upward force performed with the breaststroke kick considering the buoyant force ($F_{bB0}$) at the start position only (i.e., when it presents its maximum level) and where the estimation of the immersed body volume shows the minimum error. Consequently, the calculation of the upward force will be underestimated, in the same way, for all the subjects.

In this context, to avoid the difficulties in evaluating the body volumes at different vertical thrust height, we consider this force minus the relative body weight (i.e., $F'_{bk} = F_{bk} - W_B$). Therefore, neglecting the skin friction drag of the body $F_{frB}$ and the losses $F_{dw}$, the breaststroke force equation to lift the loads becomes

$$F'_{bk} = m_L(a+g) - F_{bB0} - F_{bL} + F_{frL} \quad (4)$$

where $a$ is value of the acceleration in the thrust and $m_L$ the mass of the load. Thus, the corresponding mechanical power $P'_{bk}$ relative to the force exerted with the breaststroke kick during the vertical thrust can be computed as:

$$P'_{bk} = F'_{bk} \cdot v \quad (5)$$

### 2.3. Experimental Procedure

Each trial was recorded at 240 fps (time resolution ~4 ms) with a high-speed camera (Casio Exilim EX-ZR 3700—Japan) that was positioned at a distance of 2.30 m perpendicular at the sagittal plan of the subject in water. To verify the verticality of upper body displacement over the water level, a second camera was placed orthogonally (and at the same distance) to the first one so that the subject lay in the center of view angles of both cameras. No subject that performed a jump too far from his vertical was considered in this study.

The video analysis procedure allows, by processing the acquired videos, the value of the displacement $\Delta d$ of the vertical jump to be obtained and the time $\Delta t$ required by the subject to reach the maximum elevation. In detail, the duration of the rising phase of each thrust was obtained by multiplying the frame time by the number of frames between the start of the movement (i.e., the frame where is observed the starting vertical movement) from the buoyance position and the point where the subject reaches the higher position. The starting position was identified where the subject stands stably with the acromion at the water level.

Moreover, the height of each thrust has been evaluated by measuring (in number of pixels) the distance between the position, in the two different frames of start and top position, of the marker placed on the center of the subject's headgear with respect to the level of the water (Figure 1). The values of mean velocity, force and power were calculated starting from these values while the muscular force and the relative power produced by the subject were computed starting from the maximum displacement reached in the jump by using Equations (4) and (5) respectively. A single operator provided the acquisition of these values, by using specific tools available inside the video analysis software BioMovie *ERGO*© (by Infolabmedia, Italy).

### 2.4. Video Analysis System Accuracy

The size of the images obtained by the camera was 432 × 320 pixels. The calibration factor $K_C$ [pix/cm] has been evaluated by using a 2D-DLT (2D-direct linear transformation) [25] with vertical (post) and horizontal (crossbar) reference objects in the picture placed at the same distance of the subject (i.e., the subject and reference object are in the same calibration plane). Considering as negligible the horizontal displacement of the athletes during vertical jump performance, the post height (86 cm) only was considered for the calculation of the factor $K_c$ that has been evaluated as 0.717 cm/pix.

Moreover, the relative errors (in percentages) of measured displacement ($\varepsilon_{d\%}$) and of measured time ($\varepsilon_{t\%}$) can be evaluated as:

$$\varepsilon_{d\%} = \frac{\varepsilon_u \; K_C}{d_{0\text{kg}}} \cdot 100 \quad (6)$$

where $d_{0\text{kg}}$ is the average of the height reached by the subjects during the trials at free load and $\varepsilon_u$ is the uncertainty error, due to the motion blur [26] in the estimation of the maximum reference point in the vertical displacement.

The time absolute error of the camera can be assumed as equal to a frame time ($\varepsilon_t$ = 4 ms) with a negligible jitter considering that the inaccuracy of the internal clock oscillator of the camera can be estimated at less than 0.1 μs. The percentage errors for the forces as well as the power were evaluated according to the usual methodologies for the error propagation [27].

The estimation of the error for the buoyancy force relative to the different subjects was computed to take into account a value equal to 3.5% for the percentage error in the measure of the body volumes ($\varepsilon_{VB\%}$) as reported by [22].

### 2.5. Statistical Analysis

Data in text, tables and figures are expressed as mean ± standard deviation (SD). The Kolmogorov-Smirnov test was used to validate the assumption of normality. Since no significant deviations from normality were detected, the coefficient of variation (CV), interclass correlation coefficients (ICC), standard error of measurement (SEM) and 95% confidence interval (95% CI) were calculated to determine the day-to-day reliability for displacement, time, velocity, acceleration, force and power. Moreover, the ICC was used as assessment test of consistency, repeatability of quantitative measurements made by same operator and to evaluate the athlete's performance in two different days. Paired *t*-tests with Bonferroni adjustment and the Pearson correlation coefficient (r) were used for between-group comparisons, for test-re-test measurements repeatability and to determine the level of specificity among selected variables of the test. In addition, the effect sizes (ES) were also calculated using Cohen's d between the pre-test and post-test means [28], where small effect was 0.1, moderate 0.3 and large was 0.5 [29]. The level of statistical significance was set at $p < 0.05$. The IBM-SPSS 20.0 (SPSS, Inc., Chicago, IL, USA) was used for statistical analysis.

## 3. Results

### 3.1. System Accuracy

In order to evaluate the displacement relative error we apply Equation (2) where $d_{(0\text{kg})}$ is equal to 68 cm and the uncertainty error $\varepsilon_u$ set to 3 pixels, the $\varepsilon_{d\%}$ is equal to 3.11% while the percentage errors for the velocity, acceleration, force and power can be estimated as $\varepsilon_{v\%} = 3.37\%$, $\varepsilon_{a\%} = 4.25\%$, $\varepsilon_{Fbk\%} = 6.89\%$, $\varepsilon_{Pbk\%} = 7.58\%$ respectively.

### 3.2. Reliability

Test-retest values of Mean, SD, SEM, ICC, Pearson correlation coefficient (r) and the CV relative to the displacement, velocity, acceleration, force and power performed in the same day and day-to-day are reported in Table 1. The average displacement decreases from 0.69 m (without load) to 0.15 m (load 25 kg), with r ranging from 0.87 at 5 kg to 0.99 at 0, 10 and 25 kg respectively. The thrust performance time (s) decreases at increasing loads with r ranging from 0.86 at 15 kg to 0.99 at 25 kg. Also, the vertical velocity (m/s) decreases as the loads increase with r ranging from 0.95 at 5 kg to 0.99 at 25 kg. Also, the acceleration ($m/s^2$) decreases at increase load with r ranging from 0.93 at 20 kg to 0.99 at 5 kg with high correlation values. By contrast with the kinematic parameters, the force increases proportionally to the load ranging from 20.31 N at 5 kg to 304.35 N at 25 kg with high r values ranging from 0.95 at 20 kg to 0.99 at 5 kg. The power increases progressively from 5 kg (r = 0.99) to reach its maximal value at 20 kg (442.70 W with r = 0.94) and then decreases at 25 kg (313.80 W). The ICC of all parameters, expressed in detail in Table 1, showed an excellent level of reproducibility for all measurements. The CV, while remaining low in the kinematic parameters, tends to increase in the dynamic ones reaching its maximum value of 4.32 at the $P_{bk}$ 10 kg. In addition, the SEM values observed in day-to-day trials are very low in all kinematic parameters considered for each load. The effect size (ES) calculated between pre-test and post-test means, showed a magnitude ranging from small to moderate in all kinematic and dynamic observed parameters (Table 1). The level of statistical significance was set at $p < 0.05$. An IBM-SPSS 20.0 (SPSS, Inc., Chicago, IL, USA) was used for statistical analysis.

**Table 1.** Day-to-day repeatability of average displacement (m), time (s), velocity (m/s) and acceleration (m/s$^2$), force and power ± Standard Deviation (SD) of the vertical thrust exercise (in water) performed by 14 water polo players with increasing loads, r Pearson correlation coefficient; CV, Coefficient of Variation for repeated measurements; ICC, Interclass Correlation Coefficient; 95% Confidence Interval (CI); SEM, Standard Error of Measurement; and ES, Effect Size, for each load.

| **Different Day** | **Day 1** | **Day 2** | **r** | **CV** | **ICC** | **95% CI** | **SEM** | **ES** |
|---|---|---|---|---|---|---|---|---|
| **Parameters** | **Mean ± SD** | **Mean ± SD** | | | | | | |
| Displacement (m) | | | | | | | | |
| $D_{0\,kg}$ | 0.69 ± 0.02 | 0.69 ± 0.01 | 0.99 | 0.31 | 0.99 | 0.941 to 0.998 | 0.0013 | 0.004 |
| $D_{5\,kg}$ | 0.55 ± 0.04 | 0.57 ± 0.05 | 0.87 | 1.61 | 0.85 | 0.315 to 0.978 | 0.0103 | 0.147 |
| $D_{10\,kg}$ | 0.49 ± 0.05 | 0.50 ± 0.05 | 0.99 | 1.09 | 0.98 | 0.910 to 0.998 | 0.0031 | −0.093 |
| $D_{15\,kg}$ | 0.44 ± 0.04 | 0.43 ± 0.04 | 0.94 | 2.43 | 0.94 | 0.718 to 0.992 | 0.0061 | 0.091 |
| $D_{20\,kg}$ | 0.35 ± 0.03 | 0.34 ± 0.04 | 0.97 | 1.72 | 0.95 | 0.595 to 0.993 | 0.0034 | 0.219 |
| $D_{25\,kg}$ | 0.15 ± 0.05 | 0.15 ± 0.05 | 0.99 | 0.94 | 0.99 | 0.983 to 0.999 | 0.0013 | 0.004 |
| Time (s) | | | | | | | | |
| $T_{0\,kg}$ | 0.258 ± 0.009 | 0.257 ± 0.010 | 0.95 | 0.89 | 0.94 | 0.713 to 0.992 | 0.0013 | 0.134 |
| $T_{5\,kg}$ | 0.244 ± 0.008 | 0.245 ± 0.010 | 0.91 | 1.28 | 0.94 | 0.648 to 0.991 | 0.0018 | −0.173 |
| $T_{10\,kg}$ | 0.235 ± 0.009 | 0.237 ± 0.013 | 0.90 | 1.82 | 0.93 | 0.561 to 0.990 | 0.0025 | −0.191 |
| $T_{15\,kg}$ | 0.225 ± 0.010 | 0.225 ± 0.011 | 0.86 | 1.78 | 0.93 | 0.494 to 0.991 | 0.0023 | 0.017 |
| $T_{20\,kg}$ | 0.205 ± 0.008 | 0.206 ± 0.011 | 0.96 | 1.31 | 0.93 | 0.627 to 0.991 | 0.0015 | −0.015 |
| $T_{25\,kg}$ | 0.141 ± 0.023 | 0.143 ± 0.023 | 0.99 | 0.73 | 0.99 | 0.878 to 0.999 | 0.0008 | −0.075 |
| Velocity (m/s) | | | | | | | | |
| $V_{0\,kg}$ | 2.68 ± 0.17 | 2.69 ± 0.17 | 0.98 | 0.90 | 0.98 | 0.891 to 0.997 | 0.0013 | −0.062 |
| $V_{5\,kg}$ | 2.30 ± 0.20 | 2.30 ± 0.23 | 0.95 | 2.13 | 0.95 | 0.733 to 0.994 | 0.0283 | −0.023 |
| $V_{10\,kg}$ | 2.11 ± 0.23 | 2.12 ± 0.25 | 0.98 | 1.41 | 0.98 | 0.916 to 0.998 | 0.0173 | −0.022 |
| $V_{15\,kg}$ | 1.95 ± 0.18 | 1.94 ± 0.21 | 0.97 | 1.98 | 0.96 | 0.808 to 0.995 | 0.0222 | 0.066 |
| $V_{20\,kg}$ | 1.71 ± 0.14 | 1.65 ± 0.12 | 0.96 | 1.63 | 0.93 | 0.403 to 0.990 | 0.0159 | 0.279 |
| $V_{25\,kg}$ | 1.03 ± 0.17 | 1.02 ± 0.17 | 0.99 | 1.38 | 0.98 | 0.903 to 0.999 | 0.0122 | 0.073 |
| Acceleration (m/s$^2$) | | | | | | | | |
| $Acc_{0\,kg}$ | 10.41 ± 1.04 | 10.51 ± 1.11 | 0.97 | 1.72 | 0.97 | 0.843 to 0.996 | 0.1041 | −0.094 |
| $Acc_{5\,kg}$ | 9.46 ± 1.09 | 9.43 ± 1.23 | 0.99 | 1.53 | 0.98 | 0.912 to 0.998 | 0.0839 | 0.025 |
| $Acc_{10\,kg}$ | 8.99 ± 1.21 | 8.96 ± 1.40 | 0.96 | 3.11 | 0.96 | 0.752 to 0.994 | 0.1616 | 0.024 |
| $Acc_{15\,kg}$ | 8.69 ± 0.95 | 8.66 ± 0.95 | 0.97 | 2.94 | 0.95 | 0.712 to 0.993 | 0.1472 | 0.031 |
| $Acc_{20\,kg}$ | 8.34 ± 0.78 | 8.15 ± 0.79 | 0.93 | 2.37 | 0.92 | 0.552 to 0.988 | 0.1132 | 0.241 |
| $Acc_{25\,kg}$ | 7.33 ± 0.46 | 7.15 ± 0.59 | 0.94 | 1.82 | 0.89 | 0.234 to 0.992 | 0.1061 | 0.323 |
| Force $_{Bk}$ (N) | | | | | | | | |
| $F_{5\,kg}$ | 20.31 ± 11.39 | 19.63 ± 11.74 | 0.99 | 2.37 | 0.99 | 0.976 to 0.999 | 0.3083 | 0.058 |
| $F_{10\,kg}$ | 103.55 ± 17.01 | 103.39 ± 14.00 | 0.98 | 2.76 | 0.97 | 0.809 to 0.997 | 2.0393 | 0.009 |
| $F_{15\,kg}$ | 183.20 ± 19.31 | 182.55 ± 18.17 | 0.98 | 2.16 | 0.97 | 0.750 to 0.996 | 2.8066 | 0.030 |
| $F_{20\,kg}$ | 257.43 ± 18.51 | 253.36 ± 17.95 | 0.95 | 1.53 | 0.98 | 0.787 to 0.996 | 2.1082 | 0.223 |
| $F_{25\,kg}$ | 304.35 ± 14.59 | 300.41 ± 17.15 | 0.96 | 1.02 | 0.93 | 0.431 to 0.995 | 2.5036 | 0.248 |
| Power $_{Bk}$ (W) | | | | | | | | |
| $P_{5\,kg}$ | 48.27 ± 29.35 | 47.01 ± 30.06 | 0.99 | 3.47 | 0.99 | 0.978 to 0.999 | 0.9558 | 0.042 |
| $P_{10\,kg}$ | 221.99 ± 58.20 | 222.95 ± 64.92 | 0.98 | 4.32 | 0.97 | 0.862 to 0.997 | 5.5571 | −0.015 |
| $P_{15\,kg}$ | 361.15 ± 70.34 | 358.17 ± 84.30 | 0.97 | 4.30 | 0.96 | 0.784 to 0.995 | 8.9433 | 0.038 |
| $P_{20\,kg}$ | 442.70 ± 62.11 | 421.90 ± 55.86 | 0.94 | 3.30 | 0.89 | 0.239 to 0.985 | 8.2565 | 0.353 |
| $P_{25\,kg}$ | 313.80 ± 55.93 | 306.06 ± 55.89 | 0.97 | 2.47 | 0.97 | 0.733 to 0.998 | 6.5053 | 0.138 |

### 3.3. Specificity

For the specificity of the method analyzed in this study, the vertical thrust without overloads was considered as a specific water polo skill and, therefore, correlated with the same skill performed at increasing loads. The analysis of correlation between displacement and the force, power and velocity at each load showed a strong correlation with low load (until 20 kg). As the loads increase, these correlations tend to decrease until it becomes not significant at 20 and 25 kg for velocity while for the force and power became non-significant at 25 kg only (Figure 2).

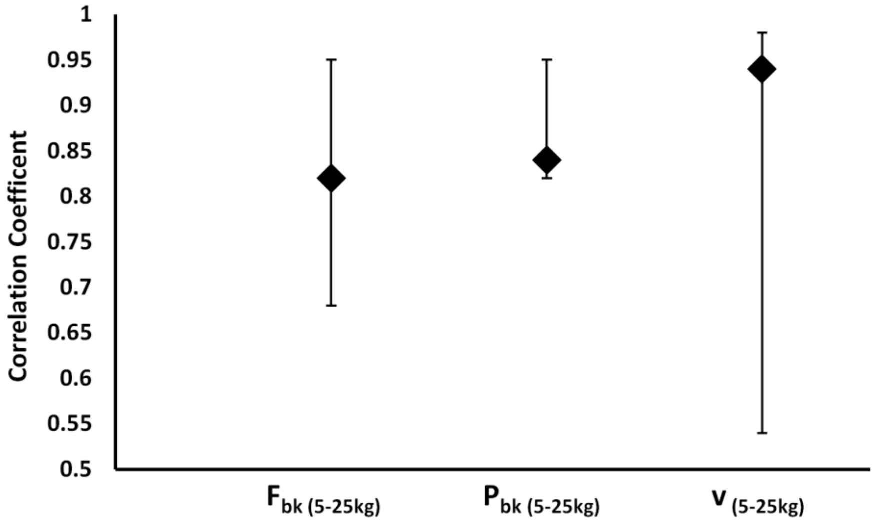


**Figure 2.** Median correlation coefficients and their ranges obtained comparing the vertical thrust's height free load with individual $F_{bk}$, $P_{bk}$ and $v$ at 5–25 kg.

### 3.4. Force-Velocity and Power-Velocity Relationships

Taking in account the means and SD values of force, power and velocity obtained by the measurements showed in Table 1, it was possible to determine a linear relationship between force and velocity and a quadratic curve between power and velocity (Figure 3).

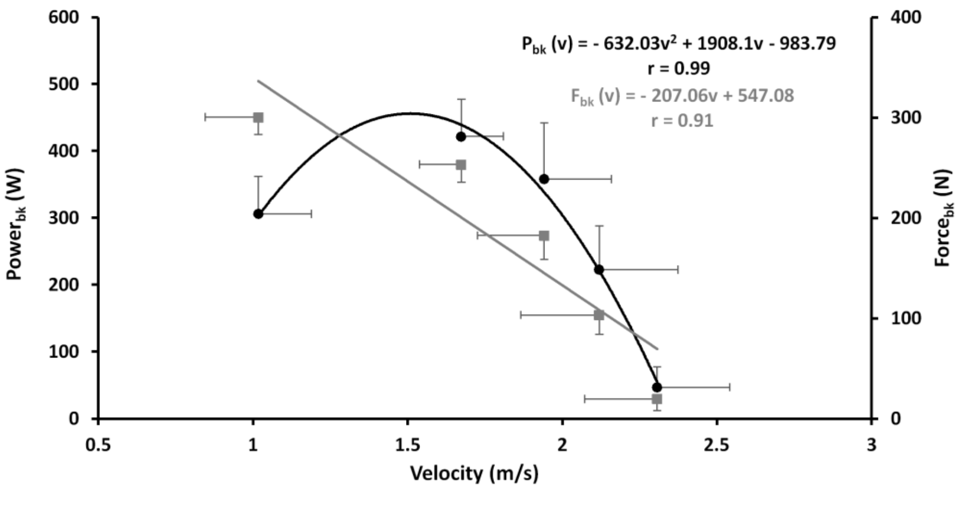


**Figure 3.** Linear F-v (grey line and squares) and second-order polynomial regression P-v (black line and dots) with the relative regression equations building on vertical thrust performed at incremental loads (from 5 to 25 kg). Both curves are depicted according the average and SD of velocity, force and power at different load as shown in Table 1.

It is worth noting that force and velocity values presented an inverse trend at increasing loads while the power reached the minimum value at 5 kg condition, reached a higher value at 20 kg, and then decreased again at 25 kg load. Both curves, depicted in Figure 2, show the linear and quadratic equation with a high correlation value (r = 0.92 and 0.99 for F-v and P-v curves respectively). Moreover, with a more accurate analysis of the F-v curve, it is interesting to highlight that the values recorded up to 20 kg maintain a linear relationship while at 25 kg the curve tends to assume an exponential like shape (Figure 4).

Therefore, the following exponential equation (Equation (7)) seems to fit better the behavior of the F-v relationship of the incremental loads test (r = 0.99; $p < 0.001$) than the previous linear one (r = 0.92):

$$F_{bk}(v) = F_0\, e^{-\frac{1}{2}(v-a)^b} \quad (7)$$

where $F_0$ is the maximum value of the force recorded at the lowest value of velocity (constant $a$) of the vertical thrust performed in the test, $v$ is the velocity value recorded at each load while the constant $b$ allows us to model the growth in the exponential rate.

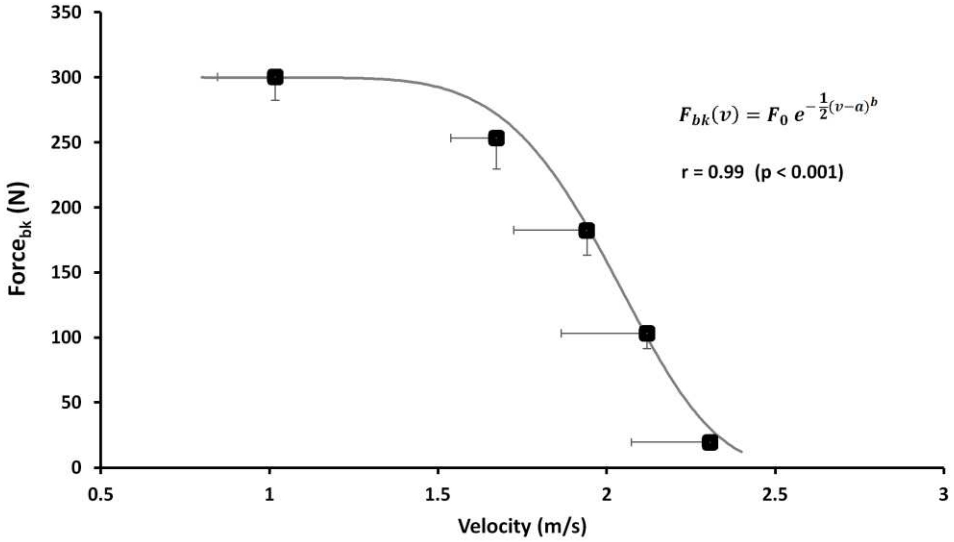


**Figure 4.** Exponential F-v with the relative regression equations building on vertical thrust performed at incremental loads (from 5 to 25 kg). The curve is depicted according to the average and SD of velocity and force with the different loads as shown in Table 1.

## 4. Discussion

The results of this study confirm the accuracy of the kinematic parameters measured with the video analysis system. Displacement, time and the calculated parameters as velocity and acceleration showed error values contained below 4.5% in any ballistic performance (breaststroke kick) load conditions, while the dynamic derivate as force and power showed the maximum error below 8%. It needs to be underlined that, for each parameter (measured or calculated), the relative error was less than the mean differences observed among athletes in each load condition performance.

The level of reproducibility of all parameters assessed in this study was very high between the two trials performed in two different days (Table 1) in terms of correlation (r from 0.86 to 0.99) and CV (<4.5%). Thus, the intra-rater reliability on the video analysis system used in this study and the water polo player's performance provide a consistent result, with an excellent level of ICC, satisfying the basic requirement of any assessment method [16].

Usually, the methods used to determine the F-v and P-v curves of leg extensor muscles are the half-squat weightlifting or jumping test performed at increasing load in gravitational environment. Considering that the specificity represents the most important discriminant criterion of a test [30], it should be emphasized there is scant specificity from biomechanical and neuromuscular points of view between dry half squat, vertical jump and vertical thrust on the water performance [11]. The strong significant correlation showed in this study between the free load vertical displacement and the other kinematic and dynamic parameters obtained at increasing loads (Figure 2), gave to this method a high level of specificity from biomechanical and neuromuscular points of view. Biomechanically, lifting the upper body over the water level means apply a lift force able to counteract the drag force. Indeed, by using the breaststroke kick technique, Sanders [8] showed that the lift forces in the water polo boots are developed through the synergic action of feet where their velocity action is obtained using the anteroposterior and mediolateral directions, followed by the knee extension and trunk straightening from their start angle with respect to the horizontal plane. In this context, squat weightlifting or dry-land jump involves the neuromuscular system in a different biomechanics condition [31]. In addition, Platanou [11] observed no correlation between the vertical thrust on water and the vertical jump on dry land (r = 0.25). From a neuromuscular point of view, in this study the relationship between vertical thrust tends to decrease at increasing load just to become minimal in correspondence of the maximal strength (25 kg) (Figure 3). Furthermore, in the water the muscle contraction does not use the same strategies related to the stretching-shortening cycle and the performance is not characterized neither by the use of elastic energy nor by stretch reflex, typical features of natural gravity movements on developing the ground reaction force. Currently, the methods used to assess the power and strength of the leg extensor and arm muscles are performed in a gravity environment [32]. This study represents the first tentative, in aquatic environment, able to determine the linear F-v and parabolic P-v relationship of lower limb muscles during a vertical thrust performance directly on the water. Both curves maintain the same characteristics of the F-v and P-v relationship observed on an athlete's performance made in a gravitational environment using a leg or arm extensors isotonic [16,18] or isokinetic devices [33] or ballistic movement [34]. According to Jaric [32], the linear relationship of F-v and consequent parabolic P-v relationship performed in a multi-joint performance showed a strong correlation revealing a high reliability of all the parameters considered in this study as reported in Table 1. Moreover, the second-order polynomial regression of P-v has shown a $P_{max}$ in correspondence with 20 kg that represents the optimal load averagely expressed by the analyzed subjects. In this context, also the high values of specificity observed with low loads tend to decrease becoming not significant after the $P_{max}$ load, probably due to a different neuromuscular pattern. In fact, according to the motor unit size recruitment principle of Henneman [35], by using an increasing loads protocol, the water polo players exhibited a decreasing heights and muscle contraction velocity on vertical thrust in relation to increasing muscular strength (increased loads) (Figure 3). Although the force and velocity values satisfy the linearity of the relationship, it is worth noting that, as shown in Figure 4, these values recorded at 25 kg tend to lose this linearity. Indeed, it can be presumed that the force exerted by the lower limbs in holding and lifting very heavy loads reached a saturation level (plateau) without ever reaching the maximum isometric force, which is impossible to obtain in a water environment, as instead it is observed in a gravitational field. In this condition, it seems conceivable to consider that the F-v curve could switch its linearity in an exponential like relationship with heavy loads (i.e., when the vertical displacement will become negligible to the further increasing load without muscular force increase). In this case, the eggbeater and breaststroke kick are performed alternatively to maintain buoyancy, as happens in games during the hard attacks and blocks between centre forward and defender. Indeed, it is feasible to assume that the limiting factor of the maximal force exerted by a breaststroke kick is based upon the maximal buoyant force sustained with eggbeater kick performance [36]. In this context, the exponential model represented by Equation (7), with the strongest relationship (r = 0.99) compared with the previous linear curve (r = 0.92; $p < 0.001$), seems to better explain the development of the propulsive force exerted in the water by water polo players with the breaststroke kick technique [8,11]. Furthermore, the P-v curve (Figure 3) is not influenced by the linear or exponential F-v curve maintaining the same parabolic trend. The scant correlation observed between the maximal strength and boots performance shows that $P_{max}$ load could be considered as a reference load to plan strength or velocity conditioning training in water polo players.

Then, in accordance with the incremental load method for eggbeater kick used by Melchiorri [1] the method for breaststroke kick used in this study, seems to be able to overcome the specificity limits of all strength and power monitoring and training method performed on the land for water polo players.

As a limitation, the use of a more performing camera or a new sensor system able to detect the space-time variations of players on the water, should allow the improvement of such a measure with a consequent reduction of the error. In addition, the indirect assessment of the volumes of the different sections of the human body could lead to a less accurate estimation than the real buoyant force of the body players at the different heights reached during the vertical thrust.

## 5. Conclusions

Considering the accuracy and the reliability recorded between two consecutive trials and two days' video analysis measurements and the high specificity of the breaststroke kick performed at increasing loads, it is reasonable to consider the validity of this method. Thus, the kinematic assessment of the water polo player performing specific neuromuscular and biomechanical patterns in specific environments could reduce the bias in the assessment and training. In line with these considerations, this easy and practical method could provide coaches and trainers specific indications of the individual linear (especially at light loads) or exponential F-v and quadratic P-v relationships of each water polo player, useful for strength and power monitoring and conditioning to perform directly on the water without time spent in a non-specific regimen. Future studies should be required to verify these preliminary results calculating more accurately the human volumes and densities. Moreover, the same method should be also verified on female water polo players.

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# Effects of Ballroom Dance on Physical Fitness and Reaction Time in Experienced Middle-Aged Adults of Both Genders

**Valerio Bonavolontà [1,*,†], Francesca Greco [2,†], Umberto Sabatini [3], Francisco J. Saavedra [4], Francesco Fischetti [1], Carlo Baldari [5], Laura Guidetti [6], Maria Grazia Vaccaro [7] and Gian Pietro Emerenziani [2]**

1 Department of Basic Medical Sciences, Neurosciences and Sense Organs, School of Medicine, University of Bari "Aldo Moro", 70124 Bari, Italy; francesco.fischetti@uniba.it
2 Department of Experimental and Clinical Medicine, "Magna Graecia" University, 88100 Catanzaro, Italy; francescagreco1997@gmail.com (F.G.); emerenziani@unicz.it (G.P.E.)
3 Department of Medical and Surgical Sciences, Institute of Neuroradiology, Magna Græcia University, 88100 Catanzaro, Italy; sabatini@unicz.it
4 Research Centre for Sports Sciences, Health and Human Development Sport Sciences Department, University of Trás-os-Montes e Alto Douro, 5000-801 Vila Real, Portugal; fjfsaave@utad.pt
5 Department of Theoretical and Applied Sciences, eCampus University, 22060 Novedrate, Italy; carlo.baldari@uniecampus.it
6 "Niccolò Cusano" University, 00166 Rome, Italy; laura.guidetti@unicusano.it
7 Neuroscience Centre, Magna Graecia University, 88100 Catanzaro, Italy; mg.vaccaro@unicz.it
* Correspondence: valerio.bonavolonta@uniba.it; Tel.: 0039-080-5351126
† The contribution of the first two authors must be considered equal.

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**Abstract:** Ballroom dance practice might play a pivotal role for successful aging, but its effects could differ depending on dancers' experience level. The aim of this study was to investigate the effects of six months of ballroom dance (three times/w) on physical fitness and reaction time (RT) in 24 middle-aged adults who are experienced dancers (age: 59.4 ± 11.6 years). Body composition, handgrip test (HG), standing long-jump test (SLJ), step test (ST), one-legged stance balance test (OLSB), and RT were assessed before ($T_0$) and after six months ($T_6$) of dance practice. RT was re-evaluated four months later ($T_{10}$). RT was significantly ($p < 0.05$) lower at $T_6$ (221.2 ± 20.3 ms) and $T_{10}$ (212.0 ± 21.9 ms) than $T_0$ (239.1 ± 40,7 ms); no significant differences were found between $T_6$ and $T_{10}$. No significant differences were observed for all the other parameters between $T_0$ and $T_6$: weight and muscle mass were significantly lower ($p < 0.01$) in females than in males, and percentage of fat mass was significantly higher ($p < 0.01$) in females than in males. HG was significantly higher in males than females ($p < 0.01$). Results suggest that in experienced middle-aged adults of both genders, ballroom dance may positively influence RT, and this result could be maintained for four months.

**Keywords:** cognitive functions; aging; partnered dances; fall prevention; physical activity

## 1. Introduction

Aging is a life-long process characterized by a progressive loss in cognitive function and physical fitness (PF) [1]. As the mean age of the population is increasing, there is a greater proportion of older adults at risk for developing non-communicable disorders (NCDs) such as cardiovascular, respiratory diseases, diabetes, and some types of cancers [2]. It is also known that aging is associated with a progressive reduction in brain volume, especially in the prefrontal and temporal cortices [3]. Resnick et al. [4] have found that individuals who remain medically and cognitively healthy show a slower rate of brain atrophy compared to non-demented older individuals. Recently, it has become clear that the aging brain could regain neuroplasticity, confirming that these changes are age-related, but not entirely unavoidable. These brain age-related changes might influence subjects' reaction time that is closely associated with the risk of multiple falls in older adults [5].

Moreover, low PF, such as lower limb strength and balance, and cognitive impairments might increase the risk of falls [6]. Therefore, it is important to participate in regular physical activity (PA), which leads to positive outcomes on PF increasing individuals' quality of life [7,8] and help to contrast cognitive decline and neurodegenerative diseases [9,10]. Although regular PA has been shown to have many health benefits in older adults, this population remains physically inactive [11]. In particular, to improve the strength of the lower limbs, various relatively fast and stability-challenging movements should be suitable, such as dance movements [12]. Dance could be an easy access PA practice with high levels of enjoyment that increase the exercise adherence and improve individuals' PF [13,14]. Thus, dance practice requires a considerable cognitive, physical, and emotional engagement that could induce positive functional adaptations potentially promoting health-related benefits in inexperienced older dancers [15,16]. Indeed, six months of dance practice is additionally recommended as a successful measure to counteract unfavorable effects of aging on the brain in the elderly [3]. Waltz, Tango, Viennese Waltz, Slow Foxtrot, and Quickstep (standard dances) belong to the ballroom dances characterized by different movements alternating musical rhythms given by sudden accelerations with instant pauses. Each of them has its peculiar characteristic necessary to perform the correct technique, and all of them are danced in pairs [17]. Males and females perform different movements according to their role during dancing, and this could result in different effects on their PF.

In particular, ballroom dance practice leads to improvements in perceived PF and cognitive functioning in novice (<1 year of dance) and experienced (>2 years of dance) dancers [18]. However, Lakes et al. [18] assessed both PF and cognitive functions using a survey. Kattenstroth et al. [19] showed that expert dancers had better performance than sedentary subjects in terms of expertise-related domains such as posture, balance, and reaction times. In addition to this previous article, the same authors [20] demonstrated that regular dance practice promoted postural, sensorimotor, and cognitive performances without affecting cardio-respiratory functions in older dancers who have not been involved in any regular dancing activity for 5 years. However, Kattenstroth et al. [20] did not study the effects of partnered ballroom dance but a dance that could be performed alone without a partner (Agilando$^{TM}$), and no data regarding body composition and muscle strength were assessed.

In inexperienced dancers, scientific evidence showed that dance practice could induce brain plasticity, at both structural and functional levels [21,22]. Given the positive effects of dance on PF and cognitive functions in novel dancers, it could be possible that different results could appear in experienced dancers [23]. Indeed, different volume dance practice (years of expertise) might differently influence PF and cognitive functions in older adults. Consequently, subjects might reach a plateau on PF and cognitive functions at different times. Therefore, the aim of this study was to investigate the effects of six months of ballroom dance (from November 2018 to May 2019 and then after summer season) on PF and reaction time in experienced middle-aged dancers of both genders.

## 2. Materials and Methods

### 2.1. Participants

Thirty-one experienced middle-aged adults were enrolled for the study. Twenty-four participants (age: 59.4 ± 11.6. years, 11 females and 13 males) were evaluated at $T_6$ and 18 participants at $T_{10}$. All participants were recruited from the Dance School "Free Dance" of Catanzaro. Written informed consent was obtained from the participants before study participation. For this single-arm trial study, only healthy experienced dancers were enrolled (dance average years = 11 years). Indeed, all participants were clinically evaluated before participation to exclude any contraindication to PA by a medical doctor (e.g., functional inabilities, cardiovascular diseases, or prosthesis). None of the participants were assuming any drugs that could interfere with the intervention effects, nor they did perform other types of physical exercise in addition to ballroom training.

*2.2. Procedures*

Participants carried out their dance protocol three days a week for six months. Each dance class lasted one hour and half and consisted of different choreographies, which include various rhythmic and simple movements typically of ballroom/standard dances (Waltz, Tango, Viennese Waltz, Slow Foxtrot, and Quickstep). All these dance styles were performed during each class session. Therefore, the rhythms of the music were different within the same dance class (File S1).

Each dance class was composed of 15 min of warm-up at low intensity (1.6–2.9 METs), followed by 60 min of dance practice and 15 min of cool-down. Dance training was performed at moderate intensity (subjects' average heart rate during dance practice equal to 68% of their maximum heart rate calculated as 220 minus age) and was measured by subjects' heart rate (HR) using a HR monitor (RS 400, Polar Electro™, Kempele, Finland). Before ($T_0$) and after six months ($T_6$) of intervention, anthropometric characteristics, physical fitness (PF), and reaction time (RT) were evaluated. Moreover, RT was re-evaluated four months after the end of dancing practice (summer season) ($T_{10}$). During the summer season, subjects were allowed to practice unsupervised free dance without being involved in any organized class. Prior to the first testing session, all participants took part in a rehearsal session to familiarize themselves with the PF tests. To increase the reliability of measurements, all subjects were tested at $T_0$, $T_6$, and $T_{10}$ in the evening from 5.00 pm to 8.00 pm by the same qualified sport scientists; fasting time was two hours before the measurements. This study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Regional Ethics Committee (protocol code 395/2020). All participants gave their written informed consent before inclusion in the study.

*2.3. Anthropometric Characteristics, Body Composition, and Physical Fitness Assessments*

Height was measured by using a stadiometer to the nearest 0.1 cm. Weight, muscle mass (MM), fat mass (FM) body mass index (BMI), and basal metabolic rate (BMR) were measured by hand-to-foot bioelectrical impedance instrument in upright position (InBody R20, Seoul, Korea): for each measurement, subjects' age, gender, and height were settled on the hand-to-foot bioelectrical monitor. Subjects' physical fitness (PF) was evaluated using the following tests: handgrip strength test (HG), standing long-jump test (SLJ), YMCA 3-minute bench step test (ST), one-legged stance balance test (OLSB), and reaction time test (RT).

Handgrip test (HG) [24]: Handgrip strength was measured using a Jamar hydraulic hand dynamometer to evaluate muscle strength. Subject was seated on a chair without armrests and held the dynamometer in the hand to be tested, with the arm at right angles and the elbow by the side of the body without touching it. The subject should be strongly encouraged to give maximum effort. The measurement was repeated three times on the dominant hand, with a recovery of 30 seconds from the first measurement to the next one. The average of the three measurements was considered.

Standing long-jump test (SLJ): This test was performed to measure the lower extremity power. The subject stands behind a line marked on the ground with feet slightly apart. A two-foot take-off and landing were used, with bending of the knees to provide forward drive. The subject attempted three times to jump as far as possible, landing on both feet without falling backwards maintaining the arms on the hips. The best of three attempts was considered.

YMCA 3-minute bench step test (ST): This test was administered according to the YMCA step test procedure (12-inch bench height, step frequency at 96 beats/min). The stepping frequency was indicated by the metronome, and the trial lasted for three minutes. During and three minutes after the test, heart rate was continuously measured using a chest belt device (RS400, POLAR Electro, Germany). After, test subjects were seated. The one-minute heartbeat count (1 min-HBC) as defined by the original YMCA step test was approximated, calculating the mean of twelve consecutive POLAR heart rate records in

5 s intervals, starting 5 s after workload termination. $VO_{2max}$ (ml/kg/min) was then calculated as previously reported [25].

One-legged stance balance test (OLSB) [26]: Subjects, without shoes, had to stand unassisted on one leg with closed eyes and were recorded in seconds from the time one foot was flexed off the floor to the time when it touched the ground or the standing leg or an arm left the hips. Two measurements were taken for each limb, and the best attempt was recorded.

Reaction time test (RT): Reaction time was assessed as previously reported by Eckner et al. [27]. The subject was seated with the arm resting on a table in a comfortable position, and they then caught the apparatus as quickly as possible after it began to fall. The fall distance was measured and then converted into a reaction time (in milliseconds) using the formula for a body falling under the influence of gravity (d 5 $\frac{1}{2}gt^2$), where *d* is distance, *g* is acceleration due to gravity, and *t* is time.

### 2.4. Statistical Analysis

The sample size of 24 was used for the statistical power analyses. The effect sizes and the alpha level used for this analysis were 0.3 and 0.05, respectively. The post hoc analyses revealed that statistical power for this study was 0.8 for detecting a medium effect (G*power 3.1). All descriptive data are reported as mean ± SD. Correlation analysis was used to explore the relationships between RT, body composition, and physical fitness variables. A repeated measures ANOVA (RM-ANOVA) was used for RT and PF variables with time as within-participants factor ($T_0$ and $T_6$) and gender as between-participant factors (males vs. females). Seeing that RT was significantly different after dance practice ($T_6$), a RM-ANOVA was used for RT with time as the within-participants factor ($T_0$, $T_{6,}$ and $T_{10}$) and gender as the between-participant factor (males vs. females). Post hoc analysis with Bonferroni correction was performed to assess differences in RT between $T_0$, $T_6$, and $T_{10}$. Statistical analyses were conducted using SPSS v. 23 (IBM International, Chicago, IL, USA), and the level of significance was established at $p \leq 0.05$.

## 3. Results

The drop-out rate was 22.6% at $T_6$ and 42% at $T_{10}$. The significant main effect of time was found for RT ($F_{1,22}$=16.8, $p < 0.01$, $\eta p^2 0.43$). In detail, RT at $T_6$ was 9% faster than $T_0$. No gender differences were found between males and females in the RT parameter. (Table 1). No significant time x gender interaction was found for all the variables. Moreover, significant gender differences were found in weight ($p$ = 0.003), muscle mass ($p < 0.01$), percent of fat mass ($p < 0.01$), and hand grip ($p < 0.01$) (Table 2). Indeed, females showed lower weight, muscle mass, and hand grip values, while a higher percentage of fat mass compared to males (Table 2). Moreover, RT was significantly correlated to $VO_{2max}$ and OLSB at $T_0$ and to $VO_{2max}$, OLSB, and SLJ at $T_6$ as reported in Table 3. Seeing that RT was significantly different between $T_0$ and $T_6$, this variable was the only one re-evaluated after four months ($T_{10}$) in 18 subjects. A significant effect of time was found for RT ($F_{2,16}$ = 6.59). Post hoc analysis showed that RT was significantly higher at $T_0$ (239.1 ± 40,7 ms) than $T_6$ (221.2 ± 20.3 ms) and $T_{10}$ (212.0 ± 21.9 ms) as shown in Figure 1.

**Table 1.** Subjects' body composition and physical fitness variables pre ($T_0$) and after ($T_6$) dance intervention.

| Variables | T0 | | | T6 | | |
|---|---|---|---|---|---|---|
| Weight (kg) | 71.1 | ± | 13.3 | 71.5 | ± | 13.7 |
| MM (kg) | 26.6 | ± | 6.0 | 27.1 | ± | 6.3 |
| %FM (%) | 32.4 | ± | 6.8 | 31.4 | ± | 6.4 |
| BMI (kg/m$^2$) | 26.3 | ± | 4.0 | 26.4 | ± | 4.0 |
| $VO_{2max}$ (ml/kg/min) | 37.0 | ± | 4.8 | 36.8 | ± | 5.1 |
| HG ($Kg_f$) | 33.8 | ± | 9.6 | 33.6 | ± | 9.5 |
| OLSB (s) | 4.2 | ± | 3.0 | 4.9 | ± | 2.9 |
| SLJ (cm) | 68.4 | ± | 22.7 | 69.6 | ± | 21.5 |
| RT (ms) | 238.7 | ± | 43.1 | 217.3 | ± | 27.9 * |

MM = muscle mass; %FM = percentage of fat mass; BMI = body mass index; $VO_{2max}$ = maximum oxygen consumption; HG = handgrip test; OLSB = one-legged stance balance test; SLJ = standing long-jump test; RT = reaction time test. * $p < 0.05$ vs $T_0$.

**Table 2.** Gender differences in body composition and physical fitness variables.

| Variables | Males | | | Females | | |
|---|---|---|---|---|---|---|
| Weight (kg) | 78.3 | ± | 3.1 | 63.0 | ± | 3.4 * |
| MM (kg) | 31.2 | ± | 1.0 | 21.7 | ± | 1.1 * |
| %FM (%) | 28.4 | ± | 1.4 | 36.0 | ± | 1.6 * |
| BMI (kg/m$^2$) | 27.4 | ± | 1.1 | 25.1 | ± | 1.2 |
| $VO_{2max}$ (ml/kg/min) | 37.9 | ± | 1.3 | 35.7 | ± | 1.4 |
| HG ($kg_f$) | 40.3 | ± | 1.7 | 25.9 | ± | 1.8 * |
| OLSB (s) | 4.9 | ± | 0.8 | 4.1 | ± | 0.8 |
| SLJ (cm) | 74.3 | ± | 5.7 | 62.7 | ± | 6.1 |
| RT (ms) | 220.8 | ± | 9.2 | 236.5 | ± | 10.0 |

MM = muscle mass; %FM = percentage of fat mass; BMI = body mass index; $VO_{2max}$ = maximum oxygen consumption; HG = handgrip test; OLSB = one-legged stance balance test; SLJ = standing long-jump test; RT = reaction time test. * $p < 0.05$ vs males.

**Table 3.** Correlation between reaction time (RT) and physical fitness variables at $T_0$ and $T_6$

| | | Weight (kg) | MM (kg) | %FM (%) | $VO_{2max}$ (ml/kg/min) | HG ($kg_f$) | OLSB (s) | SLJ (cm) |
|---|---|---|---|---|---|---|---|---|
| RT ($T_0$) | r | −0.053 | −0.140 | 0.086 | −0.417 * | −0.014 | −0.415 * | −0.381 |
| | p | 0.806 | 0.516 | 0.690 | 0.042 | 0.949 | 0.043 | 0.066 |
| RT ($T_6$) | r | 0.012 | −0.103 | 0.191 | −0.454 * | 0.030 | −0.587 * * | −0.698 * * |
| | p | 0.957 | 0.631 | 0.370 | 0.026 | 0.888 | <0.01 | <0.01 |

MM = muscle mass; %FM = percentage of fat mass; $VO_{2max}$ = maximum oxygen consumption; OLSB = one-legged stance balance test; SLJ = standing long-jump test; RT = reaction time test. * $p < 0.05$ and ** $p < 0.01$; r = Pearson's correlation.

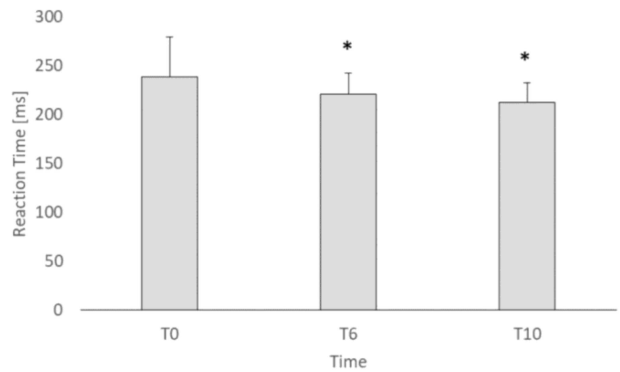


**Figure 1.** Subjects' reaction time (ms) pre ($T_0$) and post ($T_6$) dance intervention and after summer season ($T_{10}$). * $p < 0.05$ vs $T_0$.

## 4. Discussion

The aim of the present study was to investigate the effects of six months of ballroom dance on physical fitness (PF) and reaction time (RT) in middle-aged dancers. Results showed that dance training had a significant effect on RT, while no differences were found for the other dependent variables. Specifically, RT values were statistically lower at $T_6$ and $T_{10}$ than $T_0$.

Results showed gender differences regarding anthropometric measures. In particular, females had lower weight, muscle mass, HG, and higher percent of fat mass than males. Flanagan and colleagues [28] highlighted that sex-specific differences in PF are already noticeable before pubescence. Regarding HG values, subjects showed higher values than those reported by Emerenziani et al. [29] and Vaccaro et al. [16]. This difference could depend on the younger age of the subjects involved in the present study compared to those involved in Vaccaro et al. [16]. Indeed, the latter study [16] showed that experienced older adults had a value of HG equal to 23.2 $kg_f$ at pre and 23.8 $kg_f$ after dance intervention.

Regarding cardiorespiratory fitness, $VO_{2max}$ values of enrolled male and female dancers were good and excellent according to the ACSM Health-Related Physical Fitness Assessment Manual [30]. These values were higher than those reported by Kattenstroth et al. [20] and by Huang et al. [31]. These differences could be justified by the different age and different expertise between the studies considered. Indeed, Fleg et al. [32] showed that maximum oxygen consumption has an accelerated rate of decline after the age of 60, while our dancers mean age was 59.1. In addition, in the study by Kattenstroth et al. [20], the non-significant effect of dance practice on cardio-respiratory functions might be justified by the limited amount of weekly training of the intervention (1h/wk.) Although, in the present study, the amount of training was 4.5 h/w, no significant improvements on PF were found as well. We might hypothesize that our experienced dancers had previously reached their PF plateau due to their multi-year practice dancing activities. Thus, to elicit further improvements, a greater exercise intensity and volume than that proposed should be necessary.

OLSB results indicate no differences after the intervention in contrast with Rehfeld et al. [33] and Sohn et al. [34], who reported improved balance and sensorimotor abilities and improved static and dynamic balance in healthy and active older adults. As previously suggested [16], this difference may account on the higher technical ability of our dancers compared to the beginners and/or unhealthy ones.

RT showed a significant and negative correlation with $VO_{2max}$ and OLSB at $T_0$ and with $VO_{2max}$, OLSB, and SLJ at $T_6$. Therefore, we could hypothesize that better cardiorespiratory fitness, balance, and lower limbs muscle power lead to a better RT result. Results are in agreement with those reported by Ando S et al. [35] showing that the increase in the RT is negatively correlated with maximal oxygen uptake $VO_{2max}$. Moreover, it has been showed that balance training improves RT in healthy older adults [36], highlighting the positive correlation between balance and RT. Last, as previously reported [37], muscle power might influence RT positively. However, in the present study, this correlation was found only at $T_6$. Further studies with a higher number of participants will deeply investigate these correlations.

Regarding the RT, a significant improvement was found after dance intervention. Indeed, the average RT was 239 at $T_0$ and 217 ms at $T_6$, suggesting that experienced dancers also present faster RTs at baseline than inexperienced dancers due to multi-year dance practice. These results are in agreement with those reported by Kattenstroth and colleagues [20] who found an improvement in RT after non-partnered dance in older dancers. However, Kattenstroth et al. [20] did not evaluate whether the positive effects of dance practice on RT would also be maintained after a period of unstructured activity. Conversely, since RT was the only variable that improved after dance intervention, we re-evaluated RT 4 months after the end of dancing practice (summer season) ($T_{10}$) to verify whether this improvement had been maintained. Faster RT was maintained at $T_{10}$ (as shown in Figure 1), suggesting that the unstructured dance practice during summer season might have maintained the positive effects of dance. Teixeira-Machado et al. [21] suggested that dance can improve functional brain plasticity, integrating different brain areas that induce both structural and functional changes. In addition, Hänggi et al. [38] proposed that anatomical differences between dancers and non-dancers are a consequence of the relative duration and intensity experience of professional dancing. Thus, it could be hypothesized that our dancers have maintained faster RT after a 4-month period of break because of their ability to maintain dance practice adaptations. In this regard, it would be interesting to evaluate specific brain areas in future studies to monitor long-lasting ability to retain positive neural adaptations even with a low-impact activity after a break from practice.

Moreover, according to Müller al. [22], a long-term dancing intervention (18 months) in healthy elderly individuals could be better than tedious physical exercise in inducing neuroplasticity in the aging brain, due to the multimodal idea of moving. In addition, the simultaneous training of cognitive and physical abilities, which is proper for dancing, may offer greater benefits on daily life functioning.

The authors are aware of some study limitations. First of all, the number of subjects involved in this intervention study could be extended to a wider population with the presence of a control group. Additionally, adherence to dance classes was not collected as dancers were all experienced showing high levels of participation. However, the significant effect on RT observed in our population, in both $T_6$ and $T_{10}$ compared to $T_0$, reinforces the strength of the study. It would be of interest to monitor the subjects' PF for a longer period of dance practice, such as two years, to better evaluate the duration of the effects of ballroom dance on RT. Finally, functional magnetic resonance imaging (fMRI) on the primary ($M_1$) and secondary (premotor and supplementary motor areas) cortex could provide useful information on functional changes underlying RT improvements after a long period of dance practice.

## 5. Conclusions

A six-month ballroom dance practice had positive effects on reaction time but no effects on subjects' PF in experienced middle-aged adults. Moreover, the improvement in RT was maintained four months later. Thus, dance practice could represent an effective strategy for a successful aging. Further studies are needed to investigate different types of dances on PF outcomes and on RT.

**Supplementary Materials:** The following are available online at https://www.mdpi.com/1660-4601/18/4/2036/s1, List S1: list of songs for one dance session.

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# The Effects of Short-Term Visual Feedback Training on the Stability of the Roundhouse Kicking Technique in Young Karatekas

**Stefano Vando [1,†], Stefano Longo [2,†], Luca Cavaggioni [2], Lucio Maurino [3], Alin Larion [4], Pietro Luigi Invernizzi [2] and Johnny Padulo [2,*]**

1 Fiamme Oro, Polizia di Stato, 00128 Rome, Italy; stefanovando@gmail.com
2 Department of Biomedical Sciences for Health (SCIBIS), Università degli Studi di Milano, 20133 Milan, Italy; stefano.longo@unimi.it (S.L.); luca.cavaggioni@unimi.it (L.C.); pietro.invernizzi1@unimi.it (P.L.I.)
3 CONI-Italian Olympic Committee, Campania, 80127 Napoli, Italy; info@luciomaurino.com
4 Faculty of Physical Education and Sport, Ovidius University of Constanta, 900527 Constanta, Romania; alinlarion@yahoo.com
* Correspondence: johnny.padulo@unimi.it
† These authors share first authorship.

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**Abstract:** The aim of this study was to assess the efficacy of using real-time visual feedback (VF) during a one-week balance training intervention on postural sway parameters in young karatekas. Twenty-six young male karatekas (age = 14.0 ± 2.3 years) were randomly divided into two groups: real-time VF training (VFT; $n$ = 14) and control (CTRL; $n$ = 12). Their center of pressure (COP) displacement (path length, COPpl; distance from origin, COPod) was assessed pre- and post-training on a Wii Balance Board platform in two positions (Flex: knee of the supporting leg slightly bent, maximum hip and leg flexion of the other leg; Kick: knee of the supporting leg slightly bent, mawashi-geri posture for the kicking leg). Both groups trained twice a day for seven days, performing a one-legged stance on the non-dominant limb in the Kick position. During the training, VFT received real-time VF of COP displacement, while CTRL looked at a fixed point. No interaction effect was found ($p > 0.05$). VFT exhibited greater changes pre- and post-training in Flex COPpl (−25.2%, $g$ = 1.5), Kick COPpl (−24.1%, $g$ = 1.3), and Kick COPod (−44.1%, $g$ = 1.0) compared to CTRL (−0.9–−13.0%, $g$-range: 0.1–0.7). It is possible that superimposing real-time VF to a week-long balance training intervention could induce a greater sport-specific balance-training effect in young karatekas.

**Keywords:** intensive training; proprioception; postural sway; testing

## 1. Introduction

Karate is a martial art where postural stability is of great importance for performance [1]. Indeed, many actions are performed on a single leg stance at maximum speed using different postures (e.g., kicking and transitions between postures). One of the main kicking techniques employed during kumite competitions (free sparring against an opponent) is a roundhouse kick named mawashi-geri [2]. Its execution requires a coordinated body segment sequence performed at the highest possible speed:

i. Flexing the hip of the kicking leg with a flexed knee while standing on the supporting leg;
ii. Extra-rotating the supporting leg while aligning the kicking leg with the target and stabilizing balance, slightly arching the torso;
iii. Extending the knee to reach the target with the foot without a damaging impact; and
iv. Flexing the knee of the kicking leg [3]. Given this complex interaction between the supporting leg, speed, trunk stability, and circular trajectory, training to achieve correct postural control is crucial for mawashi-geri efficacy.

To optimize and develop an athlete's fundamental motor skills, static (i.e., stationary body) and dynamic (i.e., while moving) balancing ability is of great importance [4]. It has also been reported that sport disciplines requiring skilled, fast actions improve postural control [5–8]. In this context, karate has been demonstrated to represent an effective stimulus for balance control improvement [9], most likely due to a combination of practicing intense complex motor tasks and a substantial load being placed on the ankle joint. However, several studies concerning karate and postural control have been conducted in adults [9]. Therefore, there is great interest in finding training methods that aim to improve the postural stability of young karate athletes, bearing in mind that maturity and biological age may have a direct influence on balance system organization. Indeed, the somatosensory afference seems to be developed at 3–4 years of age and the visual system, as well as the vestibular component, reaches complete maturation at 15–16 years of age [10].

In sports where motor control is essential, such as karate [11,12], improvements in performance can be achieved by receiving external feedback about the movement features—so-called augmented feedback [13]. This method can be effective in both individual and team sports, and allows athletes to adjust for possible movement errors through instructions given about technical ability [13]. One particular type of augmented feedback involves vision (real-time visual feedback), which can provide this sensory information to the central nervous system, helping to reduce motor output variability [14]. Visual feedback training (VFT) has been successfully employed in different sports; for example, to help athletes improve the mechanical work against gravity in runners [15], the mechanical effectiveness of pedaling during steady-state cycling [16], or the explosive leg press maneuver [17]. VFT has been employed for improving stance stability [18]. The positive effects of VFT seem to refer to enhanced motor guidance, better focus on the task, and motivation as a result of task accomplishment (e.g., training at a higher intensity) [13]. In the context of karate, it has been shown that one session of VFT could acutely improve postural sway in young karatekas [19]. However, it is unclear whether this effect could be reflected in better performance during a more complex task, such as standing on one leg and performing a kicking action.

Recently, the Wii Balance Board (WBB, Nintendo, Kyoto, Japan) has been employed in different fields as a simple, accessible, and reliable device for assessments of bipedal balance [20,21], single-leg stance postural control [22], and muscle asymmetries [23], as well as a tool for balance training in clinical and exercise fields, with and without visual feedback [21,24,25]. The low cost and reliability of this equipment are the main advantages of its broad application in both clinical and performance-related settings.

Therefore, the aim of this study was to assess if superimposing real-time visual feedback on a one-week balance training program performed by young karatekas on the WBB could improve postural stability during a sport-specific kicking action.

## 2. Materials and Methods

### 2.1. Participants

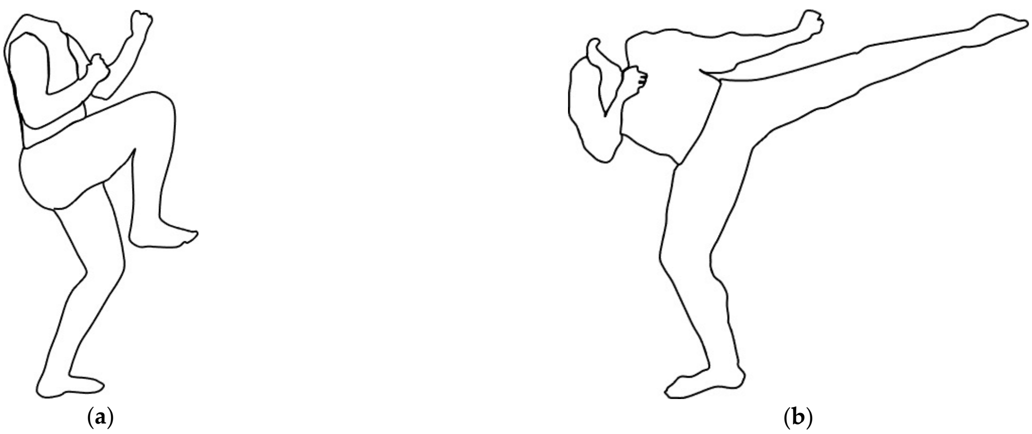
A total of 38 young male karatekas (mean ± SD: age 13.4 ± 2.4 years; stature 156.5 ± 12.8 cm; body mass 53.0 ± 15.1 kg) participating in a one-week intensive karate training camp volunteered to take part in this study. Participants were randomly divided into two groups: real-time visual feedback training (VFT; $n$ = 19, age 14.1 ± 1.8 years, stature 161.4 ± 11.2 cm, body mass 58.4 ± 11.3 kg), and a control condition, in which participants stood in front of a wall looking at a fixed point (CTRL; $n$ = 19, age 13.2 ± 2.6 years, stature 154.4 ± 12.2 cm, body mass 54.1 ± 17.0 kg). Members of both groups had at least four years of karate training experience with at least two karate training sessions per week (~3 h per week), and were familiar with exercises involving a single-leg stance. During the training camp, all the athletes lived together and followed a diet provided by a sports nutritionist [26]. None of the participants underwent any specific balance training, strenuous endurance activity, or resistance training outside of their normal training program. The study conformed to the Declaration of Helsinki and subsequent updates, and it was conducted after the approval of the Ethics Committee of Ovidius University of Constanta (23/2020). The procedures, risks, and goals were explained to the participants' tutor. In addition to receiving consent from the subjects, written parental consent was also obtained prior to subjects' participation.

### 2.2. Experimental Setup

Participants reported to the experimental room (average temperature: 23 °C, min: 22 °C, max: 24 °C; relative humidity: 55 ± 2.3%) three times for testing procedures in the afternoon (2–4 p.m.) to avoid any circadian effects [27]. For the reliability of measurements and familiarization with procedures, all participants were assessed on a stabilometric platform on the first and second days of testing, with two days in between. The second testing day was used as a baseline measure (Pre). The stabilometric test was performed on the third testing day using the same procedure as for Pre (i.e., post-training—Post). The postural stability tests of the single-legged stance lasted 20 s on a Nintendo$^{TM}$ WBB, with the non-dominant leg (supporting leg) and open eyes; trials were performed in random order (Latin square design) with 1 min of recovery in between [28]. The CoreMeter$^{TM}$ software was employed to analyze the center of pressure (COP) from the point of origin of the Cartesian plane.

Two positions were assessed before and after training:

i. Knee of the supporting leg slightly bent, maximum hip and leg flexion of the other leg (Flex, Figure 1a);
ii. Knee of the supporting leg slightly bent, mawashi-geri posture for the kicking leg (Kick, Figure 1b).
iii. For each position, the upper limbs were positioned in guard (i.e., both closed hands close to the head). A manual goniometer was used to standardize the knee angle of the supporting leg ~155° of knee flexion (with 180° = full extension) [3].



(**a**) (**b**)

**Figure 1.** Testing position for single-leg balance. (**a**) Flex: knee of the supporting leg slightly bent, maximum hip and leg flexion of the other leg; (**b**) Kick: knee of the supporting leg slightly bent, mawashi-geri posture for the kicking leg. Note: training was performed as in (**b**).

### 2.3. Data Collection and Analysis

The WBB, validated by Clark et al. [20], contains four micro foil-type strain-gauge transducers (sampling rate = 100 Hz) located in each of the four corners of the board. The WBB was interfaced with a laptop computer via Bluetooth® using custom software (CoreMeter$^{TM}$ 0.9, Latina, Italy) and calibrated by placing a variety of known loads at different positions on the platform. Once paired successfully, the device can be accessed through the standard Bluetooth® stack. The device can be interrogated at any time to read the current settings from the four strain-gauge sensors on the board, which are delivered as 16-bit integers. By taking into account the position of the sensors and the recorded values, the position of the COP can be easily calculated [26]. The WBB sensors have an internal fixed sampling rate, which we determined to be 100 Hz. Raw calibration data and raw sensor values were stored in a relational database on the local machine. This allows for flexible post-test data processing. A report-generation tool analyzed the collected data from the database and produced summary reports. The outcome measure used in this study was total COP displacement. Therefore, total COP displacement was chosen as the primary outcome measure because it is known to be a reliable and valid measure of standing balance [20].

The COP coordinates ($X$, $Y$) were calculated using the data from the four sensors on the WBB using the following equation:

$$\begin{pmatrix} X \\ Y \end{pmatrix} = \frac{\sum_{i=1}^{4} \mathrm{Wght_i} \cdot \begin{pmatrix} x_i \\ y_i \end{pmatrix}}{\sum_{i=1}^{4} \mathrm{Wght}_i} \quad (1)$$

where ($x_i$, $y_i$) = coordinates of each pressure sensor ($i$) in the Wii Balance Board's reference frame; $\mathrm{Wght_i}$ = weight recorded on each sensor ($i$); and ($X$, $Y$) = coordinates of the COP [25]. After determination of the COP, its path length (COPpl) and distance from origin (COPod) were calculated automatically by the CoreMeter$^{\mathrm{TM}}$ software.

### 2.4. Training Protocol

The training protocol was composed of two sessions per day for seven days. The first session was performed in the morning and alternated between 1 min of balance training and 1 min of passive recovery, for a total of 5 min. The second session was held in the afternoon using the same procedure. Both groups performed a one-legged stance on the non-dominant limb while keeping the kicking leg in mawashi-geri posture on the WBB (as in Figure 1b). The VFT group could see the COP displacement in real-time and their goal was to keep it as centered as possible [19,26]. CTRL performed the same protocol as VFT without receiving any COP displacement feedback while staring at a fixed point, trying to stay as steady as possible.

### 2.5. Statistical Analysis

Data were tested for normality using the Shapiro–Wilk test. The Student's *t*-test for independent samples was used to detect any initial differences between groups pre-test. The reliability of COPpl and COPod measurements was assessed in a randomly selected sub-sample of 15 participants by intra-class correlation coefficient (ICC) with 95% confidence interval (95% CI:), and classified as follows: very high if >0.90, high if between 0.70 and 0.89, and moderate if between 0.50 and 0.69 [29]. Moreover, the standard error of measurement as percentage (SEM%) was calculated for each variable as a measure of absolute reliability [30,31]. The between-group differences in COPpl and COPod changes over time were analyzed using a two-way analysis of variance (ANOVA) with time as a repeated-measure factor (two levels: Pre- and Post-training) and group as a between-factor (two levels: VFT and CTRL). The ANOVA effect size was evaluated with partial eta squared ($\eta_p^2$) and classified as follows: small, <0.06; medium, 0.06–0.14; and large, >0.14 [32]. The Hedge's *g* effect size with 95% CI: was also calculated and interpreted as follows: trivial, 0.00–0.19; small, 0.20–0.59; moderate, 0.60–1.19; large, 1.20–1.99; and very large, >2.00 [33]. The level of statistical significance was set at $p \leq 0.05$ in all comparisons. Data were analyzed using XLSTAT 12.3.01 (Addinsoft, SARL, Long Island City, NY, USA) and SPSS (IBM SPSS Statistics v. 19, Armonk, NY, USA) statistical software packages. Descriptive statistics were expressed as mean $\pm$ standard deviation (SD). Percentage differences were shown with 95% CI: of the change.

## 3. Results

There were no baseline differences between the groups in age, stature, body mass, training experience, and all other variables studied ($p > 0.05$). During the experimental week, eight participants withdrew from the study (three from VFT and five from CTRL) due to personal reasons not linked to the experimental procedures. Four participants (two from

VFT and two from CTRL) were deemed as outliers and removed from the study. Therefore, the sample size was reduced to $n$ = 14 in VFT (age 14.4 ± 2.5 years, stature 159.2 ± 10.4 cm, body mass 54.2 ± 11.7 kg) and $n$ = 12 in CTRL (age 13.5 ± 1.9 years, stature 156.9 ± 9.2 cm, body mass 52.2 ± 16.0 kg).

### 3.1. Reliability

In Flex, reliability was high for both COPpl (ICC = 0.86, 95% CI: = 0.60 to 0.95; SEM% = 5.4%) and COPod (ICC = 0.96, 95% CI: = 0.88 to 0.99; SEM% = 7.9%). Likewise, reliability of the Kick position was high for both COPpl (ICC = 0.91, 95% CI: = 0.74 to 0.97; SEM% = 6.1%) and COPod (ICC = 0.97, 95% CI: = 0.90 to 0.99; SEM% = 7.7%).

### 3.2. VFT-Induced Effects

The training-induced effects in VFT and CTRL are reported in Table 1 for both COPpl and COPod. The ANOVA did not reveal any interaction effects in the parameters analyzed ($p$ range: 0.07 to 0.49, $\eta_p^2$ range: 0.02 to 0.15, small to medium). There was a significant effect of time in all analyzed variables ($p$ range: 0.02 to <0.001, $\eta_p^2$ range: 0.24 to 0.56, large).

**Table 1.** Comparison of stabilometric data between the Pre- and Post-training in the two groups by two-way analysis of variance (ANOVA).

| | | | | | | **ANOVA** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Condition** | **Group** | | | | | **Time** | | | **Group × Time Interaction** | | |
| | | COPpl (mm) | | | | | | | | | |
| Flex | | Pre | Post | Δ% | 95% CI: (%) | F | $p$ | $\eta_p^2$ | F | $p$ | $\eta_p^2$ |
| | VFT | 166.7 ± 32.7 | 123.7 ± 23.3 | −25.2 | −31.8 to −18.6 | 6.22 | 0.02 | 0.24 | 2.69 | 0.12 | 0.12 |
| | CTRL | 176.1 ± 67.6 | 167.2 ± 63.8 | −0.9 | −22.6 to 20.8 | | | | | | |
| | | COPod (cm) | | | | | | | | | |
| | | Pre | Post | Δ% | 95% CI: (%) | F | $p$ | $\eta_p^2$ | F | $p$ | $\eta_p^2$ |
| | VFT | 4.9 ± 2.5 | 2.8 ± 1.3 | −35.2 | −49.9 to −20.6 | 16.70 | 0.001 | 0.45 | 1.46 | 0.24 | 0.07 |
| | CTRL | 5.3 ± 1.8 | 4.1 ± 1.3 | −11.9 | −40.7 to 17.0 | | | | | | |
| | | COPpl (mm) | | | | | | | | | |
| Kick | | Pre | Post | Δ% | 95% CI: (%) | F | $p$ | $\eta_p^2$ | F | $p$ | $\eta_p^2$ |
| | VFT | 174.8 ± 33.4 | 125.0 ± 26.9 | −24.1 | −32.9 to −15.3 | 25.86 | <0.001 | 0.56 | 0.49 | 0.49 | 0.02 |
| | CTRL | 177.9 ± 60.5 | 146.0 ± 29.7 | −13.0 | −26.3 to 0.3 | | | | | | |
| | | COPod (cm) | | | | | | | | | |
| | | Pre | Post | Δ% | 95% CI: (%) | F | $p$ | $\eta_p^2$ | F | $p$ | $\eta_p^2$ |
| | VFT | 5.2 ± 2.7 | 2.8 ± 1.7 | −44.2 | −55.8 to −32.6 | 18.15 | <0.001 | 0.48 | 3.67 | 0.07 | 0.15 |
| | CTRL | 4.9 ± 2.3 | 4.0 ± 1.1 | −5.6 | −31.3 to 20.1 | | | | | | |

Values are expressed as mean ± SD for the visual feedback training (VFT) and control group (CTRL). Flex: knee (~155°) of the supporting leg slightly bent, flexed hip and knee of the kicking leg; Kick: knee (~155°) of the supporting leg slightly bent, mawashi-geri posture for the kicking leg; COPpl: center of pressure path length; COPod: center of pressure distance from origin; Δ%: percentage difference between Pre- and Post-training; 95% CI: (%): 95% confidence interval of the Pre–Post percentage difference; $\eta_p^2$: partial eta-squared.

In VFT, COPpl changed by −25.2% in Flex ($g$ = 1.5, 95% CI: = 0.6 to 2.3, large) and by −24.1% in Kick ($g$ = 1.3, 95% CI: = 0.5 to 2.2, large) after intervention. COPod changed by −35.2% in Flex ($g$ = 1.0, 95% CI: = 0.2 to 1.8, moderate) and by −44.2% in Kick ($g$ = 1.0, 95% CI: = 0.3 to 1.8, moderate) compared to Pre values.

In CTRL, COPpl changed by −0.9% in Flex ($g$ = 0.1, 95% CI: = −0.7 to 0.9, trivial), and by −13.0% in Kick ($g$ = 0.6, 95% CI: = −0.2 to 1.5, moderate) after intervention. COPod changed by −11.9% in Flex ($g$ = 0.7, 95% CI: = −0.1 to 1.6, moderate), and by −5.6% in Kick ($g$ = 0.5, 95% CI: = −0.33 to 1.3, small) positions.

## 4. Discussion

This study was designed to investigate the efficacy of a one-week balance training program combined with visual feedback in improving stability during a sport-specific kicking action in young karate athletes. The main results showed that all together, COPpl and COPod changed between Pre- and Post-intervention in all tests. Despite no group × time interaction, the effect size analysis evidenced a greater impact of real-time visual feedback training compared to the control condition in COPpl and in COPod in Kick. These findings indicate that a short-time balance intervention was effective in improving specific balance in young karatekas. It is possible that this type of visual feedback could influence the magnitude of the results within such a short-time intervention.

### *4.1. Preliminary Considerations*

It is worth mentioning that the WBB (combined with CoreMeter$^{TM}$ software) could be an easy, accessible, and feasible device to assess standing balance in different environments than a laboratory setting. It could be advantageous to study different populations, as previously shown [20,26]. However, force in the horizontal axes cannot be assessed on the WBB, thus representing an inherent limitation of the device. Nonetheless, Clark et al. [20] highlighted that the force levels in the horizontal axes were quite low (rarely exceeding 5 N). Moreover, excellent concurrent validity of the WBB compared to the gold standard has been demonstrated [20,28], suggesting that, despite the inherent limitations, this device can be used effectively to assess standing balance.

COPpl and COPod provide indirect information about the balance control process and strategy. The reduction found in these values indicate an improvement in postural control during a single-leg specific-task balance test. These results suggest that young karatekas can adapt quickly to balance stimuli even within a one-week training performed twice a day, as previously demonstrated in a younger group (~10 years of age) [26].

### *4.2. Effects of VFT*

The main finding of this investigation was that short-term, sport-specific balance training was able reduce COP displacement (COPpl and COPod). Despite the lack of an interaction effect, the effect size analysis evidenced a greater impact of real-time visual feedback in almost all variables. According to the present results, previous findings showed that VFT was effective in enhancing postural control [18,34,35]. Furthermore, a recent study showed significant improvements in postural sway following one session of real-time visual feedback practice in ~16 year old young karate athletes [19]. Moreover, Shin et al. [36] showed that visual feedback can be crucial in optimizing postural control in young people, which improves until 15–16 years of age due to growth and maturation per se [10].

We tested our participants in two single-leg stance positions, which are crucial for the correct execution of the mawashi-geri kick: Flex (i.e., the "loading" of the kick, with both hip and knee in a flexed position of the kicking leg) and Kick (i.e., the actual mawashi-geri posture, with the knee in an extended position). The VFT group obtained a marked decrease in both COPpl and COPod compared to CTRL. Therefore, it can be speculated that training with real-time visual feedback can be more effective than simply staring at a fixed point. We can hypothesize that in a simple task, such as being in the Flex position, the attentional demand for keeping the posture required in the CTRL group was not as high as when receiving a real-time visual feedback of COP displacement. Indeed, it has been demonstrated that the presence of an external cue (e.g., real-time COP displacement) could act as a constant reminder to keep the focus on the task during the training [37]. Interestingly, in the Kick position (i.e., complex task), both groups reduced COPpl values with a similar effect size. Since this testing position reflects the training position performed by both groups, this finding can be interpreted as training–testing specificity (i.e., equal training and testing positions).

The ANOVA did not evidence an interaction effect in any of the variables. It is likely that data variability accounted for this result. As a future perspective, in light of the different Pre–Post effect sizes, it would be interesting to assess whether, with a longer training period, the VFT and CTRL groups would exhibit similar results, or if VFT would superimpose a greater training stimulus compared to balance training alone.

For young karatekas, the improvement of basic and specific motor abilities are key features for the achievement of top fighting results [1]. Training balance with visual feedback, either real-time or at a fixed point, seems to be effective in managing better postural control during a mawashi-geri kick. Therefore, it can be suggested that incorporating these types of exercises during daily practice, particularly when the time for balance training is limited, would be beneficial. As mentioned previously, vision certainly played a great role in the training-induced adaptations seen in the present study. However, it is difficult to differentiate the effective contribution of each sensory system (visual, vestibular, somatosensory) to the final outcomes, and whether or not these systems adapted to the training stimuli. Nevertheless, the consistency between the improvements in postural sway parameters as a consequence of this short-time intervention is encouraging. Future studies may explore the effects of different balance training conditions, conducted over a long time period, and analyzing their effects on both performance parameters and on a competitive karate level.

This study has several possible limitations to be pointed out; firstly, the small sample size of participants. Nonetheless, we tried to recruit as many participants as possible during the one-week training camp, and we observed a significant reduction in the parameters measured. This point highlights that the sample size was probably sufficient for this kind of study design. Secondly, the training period was short in duration. Therefore, longer and more detailed intervention studies are needed to clarify the mechanisms responsible for the training-induced adaptations. Thirdly, the WBB is not a platform created for data collection. Nonetheless, its validity against a gold-standard reference has been demonstrated, as previously mentioned. Finally, no potential asymmetries between legs in the training-induced response were examined. It would be interesting to assess if balance training while standing on the preferred kicking leg would have led to different results.

## 5. Conclusions

Superimposing real-time visual feedback to a one-week balance training intervention improved sport-specific balance performance in young karatekas, with a greater effect size compared to balance training alone. These results highlight the potential of using the VFT method in this population of athletes.

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# Summated Hazard Score as a Powerful Predictor of Fatigue in Relation to Pacing Strategy

**Sylvia Binkley [1], Carl Foster [1,*], Cristina Cortis [2], Jos J. de Koning [3], Christopher Dodge [1], Scott T. Doberstein [1], Andrea Fusco [2], Salvador J. Jaime [1] and John P. Porcari [1]**

[1] Department of Exercise and Sport Science, University of Wisconsin-La Crosse, La Crosse, WI 54601, USA; sylbink@gmail.com (S.B.); cdodge@uwlax.edu (C.D.); sdoberstein@uwlax.edu (S.T.D.); sjaime@uwlax.edu (S.J.J.); jporcari@uwlax.edu (J.P.P.)
[2] Department of Human Sciences, Society and Health, University of Cassino and Lazio Meridionale, 03043 Cassino, Italy; c.cortis@unicas.it (C.C.); andrea.fusco@unicas.it (A.F.)
[3] Department of Human Movement Science, Movement Sciences Amsterdam, Vrije Universiteit, 1081BT Amsterdam, The Netherlands; j.j.de.koning@vu.nl
* Correspondence: cfoster@uwlax.edu

**Abstract:** During competitive events, the pacing strategy depends upon how an athlete feels at a specific moment and the distance remaining. It may be expressed as the Hazard Score (HS) with momentary HS being shown to provide a measure of the likelihood of changing power output (PO) within an event and summated HS as a marker of how difficult an event is likely to be perceived to be. This study aimed to manipulate time trial (TT) starting strategies to establish whether the summated HS, as opposed to momentary HS, will improve understanding of performance during a simulated cycling competition. Seven subjects (peak PO: 286 ± 49.7 W) performed two practice 10-km cycling TTs followed by three 10-km TTs with imposed PO (±5% of mean PO achieved during second practice TT and a self-paced TT). PO, rating of perceived exertion (RPE), lactate, heart rate (HR), HS, summated HS, session RPE (sRPE) were collected. Finishing time and mean PO for self-paced (time: 17.51 ± 1.41 min; PO: 234 ± 62.6 W), fast-start (time: 17.72 ± 1.87 min; PO: 230 ± 62.0 W), and slow-start (time: 17.77 ± 1.74 min; PO: 230 ± 62.7) TT were not different. There was a significant interaction between each secondary outcome variable (PO, RPE, lactate, HR, HS, and summated HS) for starting strategy and distance. The evolution of HS reflected the imposed starting strategy, with a reduction in PO following a fast-start, an increased PO following a slow-start with similar HS during the last part of all TTs. The summated HS was strongly correlated with the sRPE of the TTs (r = 0.88). The summated HS was higher with a fast start, indicating greater effort, with limited time advantage. Thus, the HS appears to regulate both PO within a TT, but also the overall impression of the difficulty of a TT.

**Keywords:** pacing; cycling; time trial; RPE; performance

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## 1. Introduction

Pacing is most simply defined as the distribution of energy expenditure over time intended to accomplish a desired goal without excessive fatigue or negative health effects [1,2]. A variety of evidence suggests that appropriate pacing contributes to optimizing performance in time-based athletic events [3–6]. In head-to-head competition, less successful athletes often follow the pacing pattern of the eventual winner, until they are compelled to change to more individually realistic pacing patterns [7,8]. In events where athletes, either elite or recreational, are improving their own best performances, the same pacing pattern is often adopted [9]. In non-athletic individuals, health complications are associated with unaccustomed heavy exercise [10]. Additionally, training sessions that start out too hard, are often associated with poor adherence in persons training for health and fitness [11]. Therefore, for optimizing performance, preventing health complications and improving adherence with training, proper pacing of exercise bouts is critical.

The basis of pacing reaches back to a hunter–gatherer society, where hunters had to make effort/reward decisions when pursuing game [12]. This problem was shared by migrant groups and armies, with the challenge of achieving goals while avoiding exhaustion. For example, Roman legionnaires were trained to march over twenty miles in a "full step", while carrying up to 27 kg (~50% body weight) [13]. Since inability to sustain the march pace was punishable by death, managing energy expenditure was critical. Even athletes, performing very challenging tasks such as the grand tours in cycling [14] and systematic training for competition, distribute the relative effort during training such that only 10–20% of training is performed at high intensities [15–17]. Similarly, a normal practice for older industrial workers is to "pace" tasks in order to make the workload acceptable [18].

The concept of pacing highlights the importance of controlling intensity throughout an exercise bout in order to avoid unacceptably large homeostatic disturbances [1–6,19–21]. Further, pacing in athletics may represent the difference between a first-place win and an early-race burnout or between a pleasant [22] exercise session and one that is likely to be perceived as too difficult and is unlikely to be repeated [23]. Robinson et al. [24] performed the first controlled studies of pacing in relation to exercise performance as early as 1958, although there was not widespread interest in pacing until the 1990s. They studied homeostatic disturbances during differently paced middle-distance races with the intent of understanding optimal pacing. This early study laid the groundwork for future pacing strategies, suggesting that for middle distance events it is important to follow a relatively even pace and conclude the event with an "end spurt" in order to optimally utilize energetic reserves [1–3].

Contemporary studies have extended this concept by looking at changes in energy expenditure relative to the details of specific athletic competitions. During shorter events, particularly when the primary retarding factor is air resistance (cycling/skating), it appears best to utilize anaerobic energy quickly to compensate for the short race duration, as velocity at the end of a race can be viewed as wasted kinetic energy [25]. The opposite appears to be true in middle and longer distance events, particularly where gravity or water provide the retarding factor (running/swimming), where it is possible to have a large slowdown that negatively impacts performance [4]. Similar results were found by Tucker et al. [26] when analyzing world record performances in 800 m, 5000 m, and 10,000 m running. In the 800 m, greater running speeds were reached during the first lap with a typical slowdown in the second lap. In the 5000 m and 10,000 m, an end spurt was possible because of the maintenance of energy reserves during the middle portion of the race. Similar results were noted in the 2008 Beijing Olympic track races [7]. Noakes et al. [27] noted that in 1-mile running world records, there was a distinct pacing pattern of starting fast, slowing through the middle of the race, and then running faster during the last lap. However, Foster et al. [28] noted that 1-mile running world records had evolved to become much more "even paced" during the last 25 years. Further, Foster et al. noted that when an individual athlete, whether elite or recreational level, bettered their own best performance, they typically used the same relative pacing pattern [9]. Abbiss and Laursen [1] noted the importance of an all-out strategy in shorter races, a positive or gradual decrease in pace after reaching maximum velocity in middle distance events, and an even pacing strategy in longer distance events. Similar evidence was presented by Foster et al. [29] showing that events of different durations had unique pacing profiles. Joseph et al. [30] and Faulkner et al. [31] showed that when time trials (TTs) were normalized to relative distance, all events had a similar structure. This is further supported by the observation that depletion of anaerobically attributable energetic reserves, represented by W′, is responsible for failures to maintain power output (PO) during fatiguing tasks with complete depletion of W′ at exhaustion [32].

The process through which athletes spontaneously select their pacing strategy is called teleoanticipation [20]. Teleoanticipation can be characterized as the internal "negotiation" an athlete conducts with themselves, based on the presence of a pre-determined and well-practiced pacing template, their current level of fatigue, and the anticipated distance or time remaining [19]. This internal negotiation is an almost entirely subconscious "risk analysis" that allows for PO regulation throughout a competition [1–3].

While objective physiological measures can be used to measure homeostatic disturbance, exercise intensity can also be appreciated through the rating of perceived exertion (RPE) [33]. RPE has been used in various settings as a subjective measure of exercise intensity at any given moment throughout an exercise bout. A higher RPE usually reflects a higher level of homeostatic disturbance (either from intensity or progressive fatigue related to the duration of an event) [2,21,22,30,31,34,35], while a lower RPE reflects a relative maintenance of homeostasis. When RPE is compared to distance of an event there is a scalar, linear growth pattern despite the occurrence of various modifiers (muscle glycogen depletion, distance, hypoxia-hyperoxia, temperature, mode of exercise) [2,8,9,19–21,29–31,34–38]. The association between RPE versus modulation of PO demonstrates a reciprocal relationship between transiently above-normal PO and RPE [36–38], supported by studies where the length of a TT was deceptively changed [37,38]. Following working at an intensity greater than normal (such as during a break away effort during a race), there is usually a reciprocal decrease in PO in order to counteract dramatic changes in homeostatic disturbance [36,38]. Similarly, if the momentary RPE is lower than expected for that point during a competition, it is likely that PO will increase.

This reciprocal relationship between RPE and changes in PO, and the abrupt decrease in PO after the starting segment of track cycling races [36,38] led to the concept of the Hazard Score (HS) which describes the likelihood that athletes will change their PO during competition, with the twin goals of avoiding catastrophic collapse during an athletic competition while optimizing performance [39,40]. The HS combines the momentary RPE and the percent distance of the race remaining as a predictor of change in PO (e.g., velocity). When an individual begins a race too quickly, they will reduce the speed in order to sustain a rate of growth of RPE [30] that will allow to finish the race without "collapsing". The HS can also be used to calculate a potentially more powerful predictor, the summated HS, throughout an event in order to better understand the effect of accumulated fatigue on pacing during competition. Accordingly, the intent of this study was to evaluate how the summated HS grows during a simulated competitive event in relation to the starting strategy. The hypothesis was that PO would be regulated after an enforced starting strategy in a way designed to control the final value of the summated HS toward a common final value.

## 2. Materials and Methods

The subjects for this study were seven well-trained (7–10 h per week), recreational level, cyclists, age 25–61 years. The subjects were mostly long distance "tourists", and performed limited competitive cycling, but regularly participated in "tours" of up to 160 km. Within the classification scheme of De Pauw et al. [41] and Delcroix et al. [42], they were in categories 2–3. The Physical Activity Readiness Questionnaire was completed by each subject to identify contraindications (e.g., exclusion criteria) to exercise testing. Written informed consent was provided by each subject prior to testing and the protocol was approved by the Institutional Review Board for the Protection of Human Subjects at the University of Wisconsin-La Crosse (Protocol 20.SB.080).

For subject characterization, each subject performed maximal incremental exercise on an electronically braked cycle ergometer (Lode, Groningen, Netherlands). Tests were conducted to provide peak PO, maximal oxygen uptake, ventilatory threshold, maximal heart rate, and maximal RPE. After a warm-up stage of 3-min at 25 W, PO was increased of 25 W/min until pedaling cadence could not be maintained within the range of 70–90 rpm.

Following the maximal test each subject performed a total of five 10-km (km) cycling TTs on a Velotron cycle ergometer (Velotron Electronic Bicycle Ergometer, Elite Model, Racer Mate, Seattle, WA, USA). Prior to all TTs, there was a self-selected warm-up of 15–30 min, which included 2–3 bursts of 30–60 s at the anticipated starting velocity. The first two TTs were practice 10-km TTs to allow the athletes to become habituated to the 10-km cycling TT [6]. The subsequent, randomly ordered, three TTs, were conducted in a manner in which the initial PO (3-km) was manipulated, based on the average PO of the first 3-km of the 2nd practice TT ($PO_{init}$). During the self-paced TT, the subject was only instructed to finish the TT as quickly as possible. During the fast-start TT, the PO during the initial 3-km was 5% greater than $PO_{init}$. During the slow-start TT, the PO during the initial 3-km was 5% less than $PO_{init}$. This was reinforced by a visual display visible to the rider and verbal feedback from the investigator. The remaining 7-km were finished as rapidly as possible. A small monetary reward ($10), based on improving final TT performance versus the 2nd practice TT, was offered to provide a "competitive incentive" during TTs 3–5. PO was measured continuously by the ergometer, and integrated every 0.5-km. The RPE was measured every 1-km using the Category Ratio (0–10) RPE scale [33]. Blood lactate was measured every 2-km in fingertip blood using dry chemistry (Lactate Pro, Arkray, Japan). Heart rate (HR) was measured using radio telemetry with data averaging every 5 s (T31, Polar Electro Oy, Kempele, Finland). Session RPE (sRPE) was measured ~30 min after the cool-down [43].

Descriptive characteristics of subjects were calculated as mean ± standard deviation. Time and average PO of the three experimental TTs (self-paced, fast-start and slow-start) were compared using a one-way Analysis of Variance (ANOVA) with repeated measures. The HS was calculated by multiplying momentary RPE by the remaining fraction of the race [39]. Summated HS was calculated by adding the HS values from each km. Two-way ANOVA with repeated measures was used to analyze differences in lactate, RPE, PO, and HR between the three experimental TTs. Pairwise comparisons were made using Tukey's post-hoc tests. Significance was set at $p < 0.05$ to achieve statistical significance.

## 3. Results

Descriptive data from the maximal tests are presented in Table 1. Table 2 shows differences in time, average PO, and sRPE between the three TTs. There were no statistically significant differences in finish time, average PO, and sRPE between the three experimental TTs ($p > 0.05$). On average, the self-paced TT was 15.6 s faster than the slow-start TT and 12.6 s faster than the fast-start TT. sRPE, which included the warm-up, the TT, and cool-down, was the greatest for the fast-start TT and least for the slow-start TT.

**Table 1.** Means ± standard deviations of the descriptive characteristics of men and women during maximal incremental exercise testing.

| Characteristic | Male (n = 5) | Female (n = 2) |
|---|---|---|
| Age (years) | 39.0 ± 3.71 | 45.0 ± 11.31 |
| Height (cm) | 176.8 ± 3.90 | 166.4 ± 1.80 |
| Weight (kg) | 81.6 ± 11.48 | 62.0 ± 5.66 |
| $VO_{2max}$ (L/min) | 4.1 ± 0.39 | 3.1 ± 0.82 |
| Peak PO (W) | 305 ± 44.7 | 237 ± 17.7 |
| PO at VT (W) | 165 ± 22.4 | 138 ± 17.7 |
| $HR_{max}$ (bpm) | 170 ± 7.4 | 163 ± 0.0 |

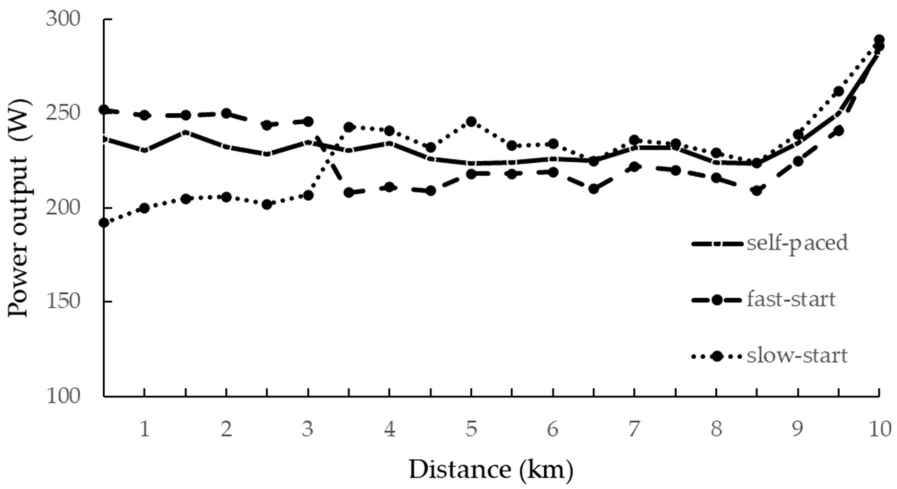
$VO_{2max}$: maximal oxygen uptake; PO: power output; VT: ventilatory threshold; $HR_{max}$: maximal heart rate.

**Table 2.** Means ± standard deviations of time, average power output (PO), and session rating of perceived exertion (sRPE) of self-paced, fast-start, and slow-start trials.

| Variable | Self-Paced | Fast-Start | Slow-Start |
|---|---|---|---|
| Time (min) | 17.51 ± 1.41 | 17.72 ± 1.87 | 17.77 ± 1.74 |
| Average PO (W) | 234 ± 62.6 | 230 ± 62.0 | 230 ± 62.7 |
| sRPE | 7.1 ± 1.94 | 7.4 ± 1.97 | 6.8 ± 1.70 |

The pattern of PO, RPE, blood lactate concentration, and HR within the three TTs is shown in Figure 1.

(**a**)




(**b**)

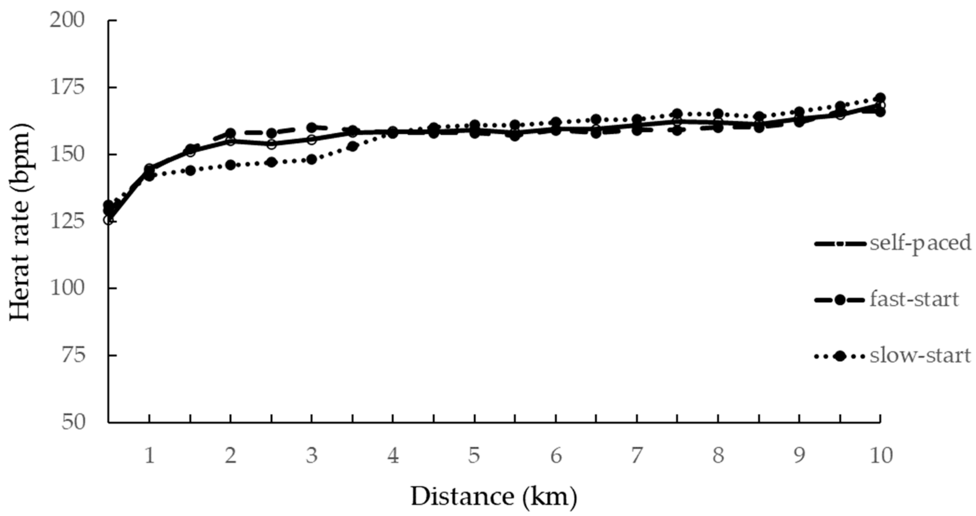
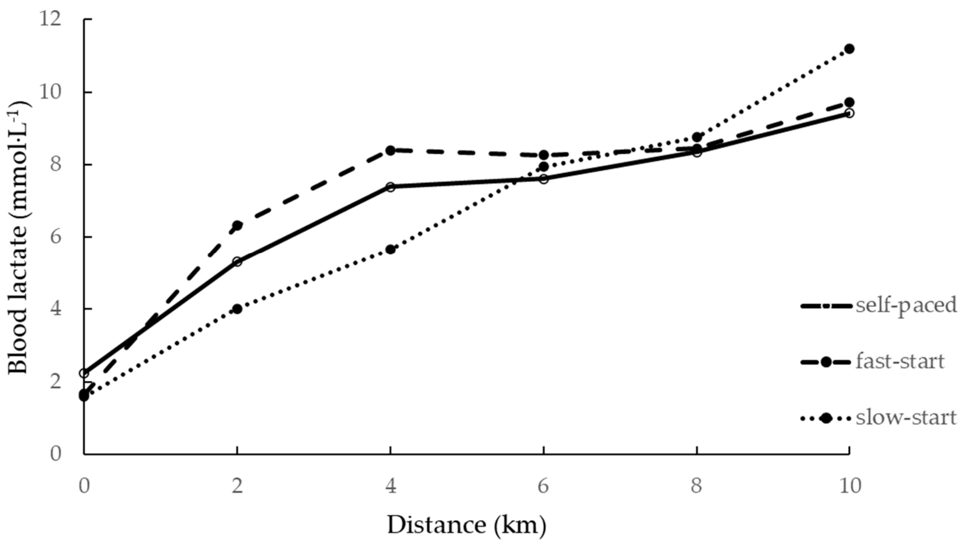



**Figure 1.** *Cont.*

(**c**)




(**d**)

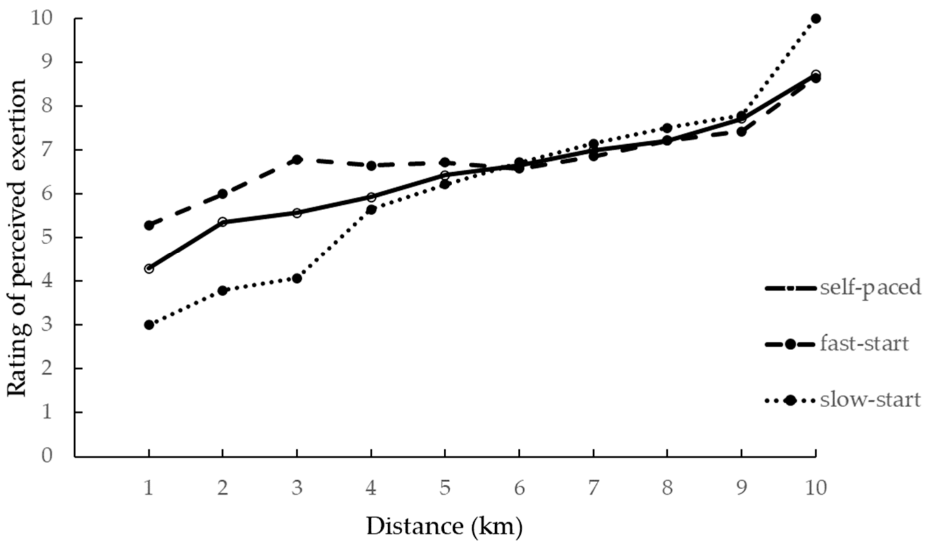



**Figure 1.** Power output (**a**), heart rate (**b**), blood lactate (**c**), and rating of perceived exertion (**d**) responses in relation to starting strategy.

A significant interaction between the starting strategy and the distance covered was shown for PO ($p = 0.034$), RPE ($p = 0.027$), blood lactate concentration ($p = 0.043$), and HR ($p = 0.046$).

As per design of the study, the PO for the fast-start TT was significantly greater than the slow-start TT for the first 3-km. PO for the self-paced TT was significantly greater than the slow start trial at the 500-m mark (Table 3). RPE for the fast-start TT was significantly greater than the slow-start TT at kilometers 1, 2, and 3 (Table 4.). Blood lactate for the fast-start TT was significantly greater than the slow-start TT at the 4 km time point (Table 5). HR for the fast-start TT was significantly greater than the slow-start TT at kilometers 2, 2.5, and 3 (Table 6).

**Table 3.** Means ± standard deviations of power output (W) during self-paced, fast-start, and slow-start time trials.

| Distance (km) | Self-Paced | Fast-Start | Slow-Start |
|---|---|---|---|
| 0.5 | 237 ± 76.4 * | 252 ± 50.6 * | 192 ± 68.7 |
| 1.0 | 231 ± 60.0 | 249 ± 57.2 * | 200 ± 59.5 |
| 1.5 | 240 ± 54.8 | 249 ± 57.2 * | 205 ± 53.1 |
| 2.0 | 232 ± 62.0 | 250 ± 56.5 * | 206 ± 53.4 |
| 2.5 | 229 ± 56.5 | 244 ± 52.1 * | 202 ± 54.0 |
| 3.0 | 235 ± 68.1 | 246 ± 51.7 * | 207 ± 53.0 |
| 3.5 | 230 ± 68.4 | 208 ± 79.8 | 243 ± 61.0 |
| 4.0 | 234 ± 68.1 | 211 ± 82.4 | 241 ± 60.0 |
| 4.5 | 226 ± 52.5 | 209 ± 78.2 | 232 ± 57.2 |
| 5.0 | 224 ± 62.6 | 218 ± 76.6 | 246 ± 66.7 |
| 5.5 | 224 ± 68.6 | 218 ± 78.4 | 233 ± 73.8 |
| 6.0 | 226 ± 71.9 | 219 ± 76.1 | 234 ± 70.4 |
| 6.5 | 225 ± 61.7 | 210 ± 63.0 | 225 ± 63.5 |
| 7.0 | 232 ± 68.8 | 222 ± 72.6 | 236 ± 70.1 |
| 7.5 | 232 ± 72.4 | 220 ± 73.9 | 234 ± 72.9 |
| 8.0 | 224 ± 66.5 | 216 ± 69.6 | 229 ± 61.1 |
| 8.5 | 223 ± 61.5 | 209 ± 64.6 | 224 ± 68.1 |
| 9.0 | 235 ± 65.6 | 225 ± 72.2 | 239 ± 81.7 |
| 9.5 | 250 ± 62.4 | 241 ± 73.3 | 262 ± 71.7 |
| 10.0 | 283 ± 83.0 | 286 ± 96.8 | 289 ± 87.4 |

* Significantly greater than slow-start trial.

**Table 4.** Means ± standard deviations of rating of perceived exertion (RPE) during self-paced, fast-start, and slow-start time trials.

| Distance (km) | Self-Paced | Fast-Start | Slow-Start |
|---|---|---|---|
| 1 | 4.3 ± 1.38 | 5.3 ± 1.38 * | 3.0 ± 0.82 |
| 2 | 5.4 ± 1.75 | 6.0 ± 1.83 * | 3.8 ± 1.15 |
| 3 | 5.6 ± 1.90 | 6.8 ± 1.63 * | 4.1 ± 1.30 |
| 4 | 5.9 ± 2.21 | 6.6 ± 1.97 | 5.6 ± 1.49 |
| 5 | 6.4 ± 1.99 | 6.7 ± 2.06 | 6.2 ± 1.58 |
| 6 | 6.6 ± 2.17 | 6.6 ± 2.44 | 6.7 ± 1.80 |
| 7 | 7.0 ± 2.08 | 6.9 ± 2.12 | 7.1 ± 1.49 |
| 8 | 7.2 ± 1.91 | 7.2 ± 2.16 | 7.5 ± 1.55 |
| 9 | 7.7 ± 1.89 | 7.4 ± 2.30 | 7.8 ± 1.82 |
| 10 | 8.7 ± 1.50 | 8.6 ± 1.55 | 10.0 ± 4.42 |

* Significantly greater than slow-start trial.

**Table 5.** Means ± standard deviations of blood lactate concentration (mmol·$L^{-1}$) during self-paced, fast-start, and slow-start time trials.

| Distance (km) | Self-Paced | Fast-Start | Slow-Start |
|---|---|---|---|
| 0 | 2.2 ± 1.24 | 1.7 ± 0.46 | 1.6 ± 0.54 |
| 2 | 5.3 ± 2.60 | 6.3 ± 3.22 | 4.0 ± 1.12 |
| 4 | 7.4 ± 2.60 | 8.4 ± 2.88 * | 5.7 ± 1.26 |
| 6 | 7.6 ± 3.25 | 8.3 ± 2.64 | 7.9 ± 2.02 |
| 8 | 8.3 ± 3.37 | 8.4 ± 2.70 | 8.8 ± 2.21 |
| 10 | 9.4 ± 2.53 | 9.7 ± 2.61 | 11.2 ± 2.06 |

* Significantly greater than slow-start trial.

**Table 6.** Means ± standard deviations of heart rate (bpm) during self-paced, fast-start, and slow-start time trials.

| Distance (km) | Self-Paced | Fast-Start | Slow-Start |
|---|---|---|---|
| 0.5 | 126 ± 19.2 | 129 ± 23.0 | 131 ± 26.0 |
| 1.0 | 145 ± 11.8 | 144 ± 17.0 | 142 ± 15.8 |
| 1.5 | 151 ± 9.0 | 152 ± 8.5 | 144 ± 10.1 |
| 2.0 | 155 ± 8.0 | 158 ± 6.7 * | 146 ± 8.5 |
| 2.5 | 154 ± 6.9 | 158 ± 7.9 * | 147 ± 9.5 |
| 3.0 | 156 ± 5.4 | 160 ± 8.0 * | 148 ± 5.8 |
| 3.5 | 158 ± 6.5 | 159 ± 4.9 | 153 ± 5.1 |
| 4.0 | 159 ± 6.5 | 158 ± 3.8 | 158 ± 5.4 |
| 4.5 | 158 ± 7.1 | 158 ± 6.1 | 160 ± 4.0 |
| 5.0 | 159 ± 7.0 | 158 ± 5.3 | 161 ± 4.6 |
| 5.5 | 158 ± 6.6 | 157 ± 5.7 | 161 ± 4.9 |
| 6.0 | 159 ± 6.9 | 159 ± 6.2 | 162 ± 4.9 |
| 6.5 | 159 ± 6.7 | 158 ± 5.3 | 163 ± 4.2 |
| 7.0 | 161 ± 7.5 | 159 ± 4.0 | 163 ± 4.7 |
| 7.5 | 162 ± 6.4 | 159 ± 4.4 | 165 ± 3.6 |
| 8.0 | 162 ± 6.2 | 160 ± 4.9 | 165 ± 3.8 |
| 8.5 | 161 ± 7.1 | 160 ± 3.9 | 164 ± 4.8 |
| 9.0 | 163 ± 5.5 | 162 ± 4.5 | 166 ± 6.0 |
| 9.5 | 165 ± 5.2 | 166 ± 6.4 | 168 ± 5.9 |
| 10.0 | 168 ± 5.4 | 166 ± 6.4 | 171 ± 6.7 |

* Significantly greater than slow-start trial.

The pattern of changes in the HS and summated HS within the three TTs is shown in Figure 2.

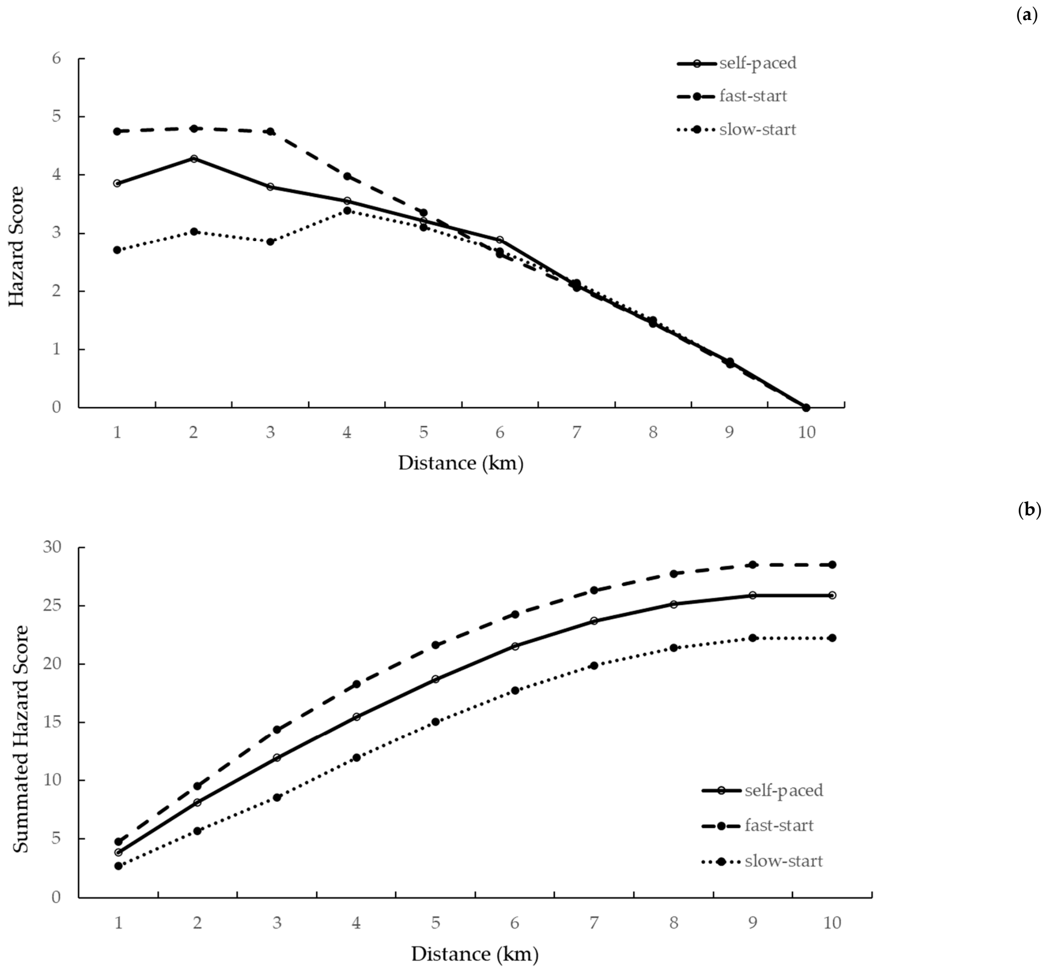



**Figure 2.** Growth of Hazard Score (**a**) and summated Hazard Score (**b**) in relation to distance during self-paced, fast-start, and slow-start time trials.

There was a significant interaction between the starting strategy and the distance covered for HS ($p$ = 0.022) and summated HS ($p$ = 0.031). HS during the fast-start TT was significantly greater than the self-paced TT at kilometers 1 and 3. HS during the fast-start TT was significantly greater than the slow-start TT at kilometers 1 and 2. HS during the self-paced TT was significantly greater than the slow-start TT at kilometers 1, 2, and 3 (Table 7). Summated HS during the fast-start TT was significantly greater than the self-paced TT from kilometers 3–10. Summated HS during the fast-start TT was significantly greater than the slow-start trial for kilometers 1–10. Summated HS during the self-paced TT was significantly greater than the slow-start trial for kilometers 2–10 (Table 8).

**Table 7.** Means ± standard deviations of the Hazard Score during self-paced, fast-start, and slow-start time trials.

| Distance (km) | Self-Paced | Fast-Start | Slow-Start |
|---|---|---|---|
| 1 | 3.9 ± 1.24 *# | 4.8 ± 1.24 | 2.7 ± 0.73 * |
| 2 | 4.3 ± 1.40 # | 4.8 ± 1.46 | 3.0 ± 0.92 * |
| 3 | 3.8 ± 1.45 *# | 4.8 ± 1.14 | 2.9 ± 0.91 |
| 4 | 3.6 ± 1.32 | 3.9 ± 1.18 | 3.4 ± 0.90 |
| 5 | 3.2 ± 0.99 | 3.4 ± 1.03 | 3.1 ± 0.79 |
| 6 | 2.9 ± 0.88 | 2.6 ± 0.98 | 2.7 ± 0.72 |
| 7 | 2.1 ± 0.62 | 2.1 ± 0.63 | 2.1 ± 0.45 |
| 8 | 1.4 ± 0.38 | 1.4 ± 0.43 | 1.5 ± 0.31 |
| 9 | 0.8 ± 0.16 | 0.7 ± 0.23 | 0.8 ± 0.18 |
| 10 | 0.0 ± 0.00 | 0.0 ± 0.00 | 0.0 ± 0.00 |

* Significantly less than fast-start trial; # Significantly greater than slow-start trial.

**Table 8.** Means ± standard deviations of the summated Hazard Score during self-paced, fast-start, and slow-start time trials.

| Distance (km) | Self-Paced | Fast-Start | Slow-Start |
|---|---|---|---|
| 1 | 3.9 ± 1.24 | 4.8 ± 1.24 * | 2.7 ± 0.73 |
| 2 | 8.1 ± 2.59 * | 9.6 ± 2.65 *# | 5.7 ± 1.61 |
| 3 | 11.9 ± 3.96 * | 14.4 ± 3.76 *# | 8.6 ± 2.50 |
| 4 | 15.5 ± 5.23 * | 18.3 ± 4.73 *# | 12.0 ± 3.27 |
| 5 | 18.7 ± 6.16 * | 21.7 ± 5.64 *# | 15.1 ± 4.02 |
| 6 | 21.6 ± 6.85 * | 24.3 ± 6.49 *# | 17.8 ± 4.69 |
| 7 | 23.7 ± 7.33 * | 26.3 ± 7.08 *# | 19.9 ± 5.11 |
| 8 | 25.1 ± 7.68 * | 27.8 ± 7.45 *# | 21.4 ± 5.40 |
| 9 | 25.9 ± 7.85 * | 28.5 ± 7.66 *# | 22.3 ± 5.65 |
| 10 | 25.9 ± 7.85 * | 28.5 ± 7.66 *# | 22.3 ± 5.65 |

* Significantly greater than slow-start trial; # Significantly greater than self-paced trial.

The relationship between the sRPE and the summated HS is presented in Figure 3. There was a strong correlation (r = 0.88), suggesting that the perceived net effort of a TT was dependent on the pattern of effort within the TT. In particular, the fast-start TT, which was slower for overall performance than the self-selected TT, produced a higher summated HS and a higher sRPE.

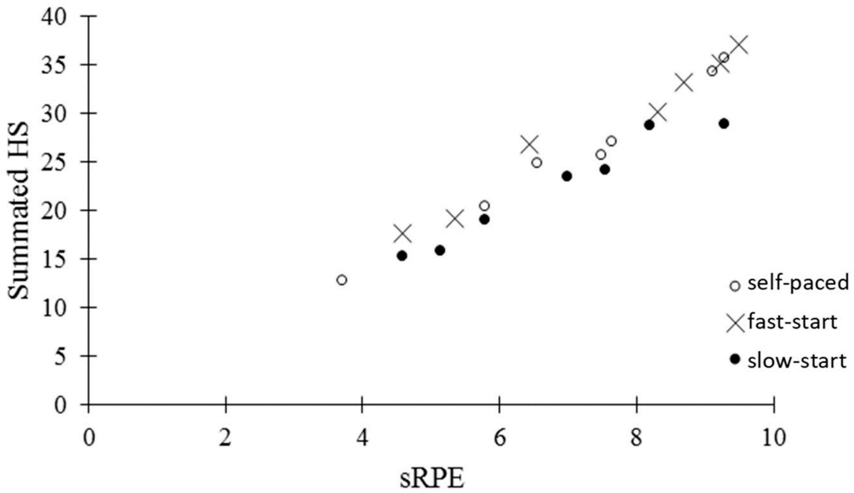



**Figure 3.** Session rating of perceived exertion (sRPE) to summated Hazard Score (HS) relationship during self-paced, fast-start, and slow-start time trials.

## 4. Discussion

The main purpose of this study was to determine whether manipulating starting strategy would affect TT performance, the summated HS, or whether the subject would change their PO so that a common value for summated HS was achieved during a simulated competition. Contrary to the hypothesis, it was found that although there was a reduction in PO following the fast-start, the summated HS remained higher compared to the self-start and slow-start strategy. This occurred despite a meaningfully slower performance time in both the fast-start and slow-start TT. This coincides with Robinson et al. [24] who concluded that it is vital to follow a relatively even pace (e.g., self-selected starting strategy) in order to avoid large homeostatic disturbances early during an event. This was supported in earlier studies performed in our laboratory [2,7,9,28–30,36,39]. The results are consistent with the evolution of pacing strategy to a more even pattern during contemporary 1-mile world records [28], and in events where individuals bettered their own best performance [9].

The importance of these data is reflected in the 2008 Olympic pace data of Thiel et al. [7] who showed that some runners in Olympic finals would run with the leaders for part of the race before suddenly dropping off the leading pace and finding a relatively constant individual pace which allowed them to finish the race, usually with an end-spurt. This mirrors the PO pattern observed in the fast-start TT in the current data and the large reduction in PO after a "break away" effort [28]. In light of the present findings, these data can be interpreted as suggesting that once a critical summated HS is achieved, the PO will require reduction, but that the reduction in PO will not be adequate to force the summated HS toward a common terminal value.

In the present study, the behavior of the summated HS was reflected by the strong correlation between the summated HS and sRPE (r = 0.88). This corresponds with Cohen et al. [36] who showed if RPE is above that usually observed at a specific point during an event, such as after a break away effort, PO will decrease in order to accommodate to, and recover from, large changes in homeostasis. When the RPE comes back into the usually observed scalar pattern of growth, PO returns to the normal profile. Similar results were observed by Schallig et al. [38] in trials where subjects were deceived regarding the duration of the trial. Immediately after being told that a trial was going to be longer than anticipated, subjects reduced PO until the rate of increase of RPE returned to what it normally would have been in the longer trail. Although previous research has shown that athletes tend to follow a predetermined template where the rate of increase of RPE is adjusted to the distance of the race remaining in order to avoid disturbances in homeostasis [30,31], it may be that PO is the variable that is manipulated while RPE continues to increase in a linear fashion. This was also shown in the report of Joseph et al. [30] and Henslin-Harris et al. [44]

where the blinded administration of an inhaled hypoxic gas mixture lead to a reduction in PO without changing the rate of growth of RPE. Other studies have shown that there is a linear relationship between RPE and relative duration of exercise despite exercise conditions [2]. Similar results were shown by Baldassare et al. [40] who found that despite differences in pacing strategies (positive pacing versus even pacing), RPE increased or only slightly decreased similarly with each strategy. Athletes apparently change their pace to match RPE to an anticipated growth pattern, so although HS may be the same between trials at a specific time point, the summated HS would be higher with a faster start.

In the present study, while summated HS was different between TTs, the finish time was not significantly different (although 15 s is a time difference of large practical magnitude) reflecting that since knowledge of the endpoint was present and distance remaining was not relatively large, the athletes were able to generate an end spurt despite the large summated HS. RPE has been shown to increase when athletes are aware of the distance to the endpoint [30,31]. This is also reflected by Foster et al. [6] who showed a significant difference between finishing a race quickly and the ability to maintain a constant, high PO for an extended period of time.

Optimal race performance is not always about who has the highest PO, but who can maintain optimal PO in order to perform a successful end spurt. de Koning et al. [45] compared the effect of various pacing strategies on performance in 1000 and 4000 m track cycling, showing that even small changes in pacing strategy led to changes in performance. This highlighted the importance of pacing strategy in the pursuit of competitive success. While the best time for the 1000 m TT was obtained by the cyclist with the highest peak PO (all-out strategy), the fastest time for the 4000 m was attained with a faster start followed by a constant PO after ~12 s (even pace). Time can also be augmented by the athlete's interaction with the environment. Konings et al. [8] utilized virtual opponents starting either +3% or −1% compared to a familiarization trial. Results showed that even in a lab setting, the use of virtual opponents led to faster performances, showing that the self-selected pacing trial has to be slightly faster than previously attempted in order for the athletes to improve performance. This can be applied to athletes who begin a race too fast leading to an accumulation of fatigue posing potentially, detrimental effects to their performance. More generally, pacing in a way that does not use an unrealistically high PO early within an event can aid in successful athletic competition. It is evident that many high-level athletes may begin a race quickly in order to match the pace of their competitors [7]. This information will also assist in determining the ideal PO for starting in order to optimize performance. However, it must be recognized that to improve performance, an athlete must take a "calculated risk", which often involves a faster start than normal. In many cases, they may develop too much discomfort (e.g., high summated HS) and fail to improve their time. In other cases, this may lead to small improvements in performance which are athletically important.

In this particular study, the specific application was to a maximal effort TT. However, an equivalent argument may be made toward training bouts. Very high early PO can lead to increases in RPE [46] and lead to reduced enjoyment during the training bout [23], which carries the risk that adherence to an exercise program is likely reduced.

One limitation to this study included a limited sample size and task habituated tourist type cyclists rather than experienced TT athletes. Although we have shown that task habituation leads to stable performances [6], more accomplished athletes might deliver somewhat different, and more specifically relevant, results. Future studies should also evaluate the difference of the summated HS in shorter and longer distance events to see how the relationship between RPE and PO differ from a middle-distance event. Further, the effect of PO sequencing within normal training bouts should be considered, relative to adherence to the exercise prescription.

## 5. Conclusions

The results of this study indicate that despite a reduction in PO following a fast-start TT, the summated HS remains higher with a fast-start strategy. This indicates that summated HS is a powerful predictor to better understand accumulated fatigue on pacing pattern during simulated competition. The sum of all HS from the beginning of the race to the present point have a cumulative effect on the outcome of the event, the physiological state, and the sRPE experienced by the exerciser.

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# Plasma Interleukin-10 and Cholesterol Levels May Inform about Interdependences between Fitness and Fatness in Healthy Individuals

**Francesco Sartor [1,2,*], Jonathan P. Moore [2] and Hans-Peter Kubis [2]**

[1] Department of Patient Care and Monitoring, Philips Research, 5656 AE Eindhoven, The Netherlands
[2] College of Human Sciences, Bangor University, Bangor LL57 2EF, UK; j.p.moore@bangor.ac.uk (J.P.M.); h.kubis@bangor.ac.uk (H.-P.K.)
* Correspondence: francesco.sartor@philips.com; Tel.: +31-(0)-615-509-627

**Abstract:** Relationships between demographic, anthropometric, inflammatory, lipid and glucose tolerance markers in connection with the fat but fit paradigm were investigated by supervised and unsupervised learning. Data from 81 apparently healthy participants (87% females) were used to generate four classes of fatness and fitness. Principal Component Analysis (PCA) revealed that the principal component was preponderantly composed of glucose tolerance parameters. IL-10 and high-density lipoprotein, low-density lipoprotein (LDL), and total cholesterol, along with body mass index (BMI), were the most important features according to Random Forest based recursive feature elimination. Decision Tree classification showed that these play a key role into assigning each individual in one of the four classes, with 70% accuracy, and acceptable classification agreement, $\kappa = 0.54$. However, the best classifier with 88% accuracy and $\kappa = 0.79$ was the Naïve Bayes. LDL and BMI partially mediated the relationship between fitness and fatness. Although unsupervised learning showed that the glucose tolerance cluster explains the highest quote of the variance, supervised learning revealed that the importance of IL-10, cholesterol levels and BMI was greater than the glucose tolerance PCA cluster. These results suggest that fitness and fatness may be interconnected by anti-inflammatory responses and cholesterol levels. Randomized controlled trials are needed to confirm these preliminary outcomes.

**Keywords:** $VO_2$max; anti-inflammatory; machine learning; PCA

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## 1. Introduction

In the 1950s, first observational evidence emerged showing that physically active individuals had a lower risk of cardiovascular disease (CVD) [1]. This evidence was later corroborated by the protective effect found for cardiorespiratory fitness (CRF), as shown in the Aerobics Center Longitudinal Study in 1989 [2,3]. Since then, several reviews, systematic reviews, and meta-analysis have confirmed and highlighted the protective role of CRF regardless the level of fatness [4–7]. According to the "fat but fit paradox", people who have a high level of CRF may be better protected from the risk of CVD than leaner people who have low CRF [8]. However, only a small proportion of US citizens can be considered "fat and fit", and obesity is independently associated with low CRF, simply because obese people are generally less active [9].

Lahoz-Garcia et al. [10] showed an interesting partial mediation of CRF between diet and obesity in schoolchildren, meaning that higher CRF contributes, for the same diet, to a lower fat mass (FM). Consistently, others have found that moderate to vigorous physical activity levels, thus higher CRF, were independently associated with a lower atherogenic index of plasma, namely blood fat strongly related with CVD, regardless of diet; and that central adiposity mediated, in other words explains, the relationship between moderate to vigorous physical activity levels and atherogenic index of plasma [11]. This would rule in favor of the protective role of higher CRF against CVD risk. Moreover, poor CRF has been associated with glucose intolerance [12] and a higher risk of insulin resistance in apparently healthy individuals [13]. Furthermore, it has been hypothesized that low CRF could provide an early sign of insulin resistance [14].

Obesity has been shown to be associated with low level systemic inflammation in connection with increased adipose tissue mass [15,16]. In turn there is evidence, in animal studies, of the possible role of inflammation on over-nutrition [17]. However, physical activity may counteract over-nutrition behavior at the hypothalamic level by means of anti-inflammatory signaling mediated interleukin-10 (IL-10) [17]. An anti-inflammatory role of IL-10 has been found also in rat skeletal muscle tissue [18]. In humans it was found consistently that intensive cycling is able to increase, 1 hour after the exercise, gene expression of several interleukins including IL-10, but not IL-6 [19]. High intensity exercise showed an acute, 30 minutes, IL-10 and IL-6 increase in overweight-obese inactive individuals, but this increase was not elicited by moderate intensity exercise [20]. Nevertheless, two weeks of high intensity exercise in overweight-obese unfit individuals did not show a chronic increase in IL-10 nor in IL-6 [21,22]. Rather, a chronic elevation of IL-10 found in obese women was reduced by 12 weeks of lifestyle intervention, including 30 minutes of exercise a day, only in those obese women who did not have metabolic syndrome [23]. Furthermore, higher serum concentration of IL-10 was found in older adults with a higher volume of physical activity [24]. Additionally, animal models show a possible protective role of anti-inflammatory signaling on cardiac function (i.e., left ventricular end-diastolic pressure) [25], a finding supported in human studies involving coronary heart disease patients, obese and diabetic individuals [26,27].

To further investigate the relationship between cardiovascular fitness and body composition characteristics i.e., fatness, we used a database, which combined demographic, blood lipids, insulin resistance, and inflammatory variables in association with CRF and FM% values. Our approach was to create a categorical variable composed of four classes, based on CRF and FM% levels. The four classes or categories are termed High Fatness with High Fitness (HFHF), High Fatness with Low Fitness (HFLF), Low Fatness with High Fitness (LFHF) and finally Low Fatness with Low Fitness (LFLF). The cutoff levels between categories were identified according to the literature [28,29]. We have applied a data driven approach consisting of four steps. First is an unsupervised learning phase, where the variables are clustered using Principal Component Analysis (PCA) [30]. PCA allows clustering of the variables into principal components. Second, a supervised learning phase was deployed to use those clusters in the feature importance selection. We opted for feeding the PCA components as well as the other variables into the feature importance selection algorithm because, although PCA combines uncorrelated variables with one another in such a way that each principal component will maximize variance, this does not mean that the components per se will be the most important classification features. Therefore, as a second step, we have used the same categorical four classes' dependent variable for a random forest based feature importance selection. In detail, we have used the Boruta algorithm, which is an improvement of the Random Forest feature selection model, also known as recursive feature elimination [31,32]. The Boruta algorithm adds randomness to the importance evaluation algorithm, so that the certainty about the importance of a given variable is increased. In short, a randomized copy of the variables is made at each iteration of the random forest importance computation. Thus, if a variable has a higher importance than the maximal importance of all randomized attributes it is retained. If there is some uncertainty, or if a variable has a lower importance it is rejected or discarded [32].

Third, a decision tree was used in order to define the discriminating path to the four classes of fitness and fatness. This classification model was used to visualize which independent variables would best split the data points into the four classes. However, classification was not limited to the decision tree. Another four classification models were used as well with the intent of testing which classification model would maximize the use of the selected independent variables, or features. The four alternative machine learning classification models were Multiple Logistic Regression, Decision Tree, Naïve Bayes, and K-nearest neighbors. This step was necessary to test whether the features selected would effectively classify the data points. Finally, a fourth step, a mediation and moderation analysis [33] was conducted in order to investigate whether attenuation between CRF and FM% would occur when one of the variables extracted was used as covariate. We hypothesized that we would find attenuations, as previously shown in the literature [10,11], by means of variables linked to fat metabolism. The overall aim of this study was to use a data driven approach, employing machine-learning techniques, to generate new insights connecting fitness and fatness with demographic, blood lipids, insulin resistance, and inflammatory variables.

## 2. Materials and Methods

### *2.1. Study Design and Participants*

The data analyzed in this study originated from two separate data collections conducted at Bangor University. Data from 81 apparently healthy participants (10 males and 71 females) were included in the analysis. All participants were informed about the study protocols and objectives, and provided written consent prior to the start of the studies. Study protocols were approved by the Ethics Committee of the School of Sports, Exercise and Health Sciences Department of Bangor University in conformity with the Declaration of Helsinki. The design of this study was purely observational.

### *2.2. Body Composition, Fat Mass Percentage, Blood Markers and Cardiorespiratory Fitness Assessment*

Participants were pre-screened for cardiovascular diseases by means of the American Heart Association/American College of Sports Medicine Pre-Participation Questionnaire [34]. However, participants with elevated fasting levels of glucose, insulin and lipids were not per se excluded from this study. Body composition, fasting blood lipid profile and CRF ($VO_2$max) were determined using standardized protocols described previously [21]. A cardiorespiratory fitness test was executed on a cycle ergometer (Corival 400, Lode, Groningen, The Netherlands), the protocol consisted of an incremental exercise test to exhaustion (1min at 50 + 20 W increments per minute). Oxygen uptake was measured breath by breath by means of a metabolic card (ZAN 600 CPET, Oberthulba, Germany). Fasting blood lipid profile (total Cholesterol, LDL and HDL), plasma insulin, plasma glucose, leptin and cytokines (IL-6, IL-10, and TNF-$\alpha$) collection and analysis is also described in Sartor et al. [21]. Plasma glucose was analyzed by immobilized enzymatic assay (YSI 2300 STAT, Incorporated Life Sciences, Yellow Springs, OH, USA). Lipid profile was analyzed from plasma samples by optic enzymatic assay (Reflotron®, Roche Diagnostics, Mannheim, Germany). Plasma insulin was analyzed by ELISA (ultrasensitive human insulin ELISA kit, Mercodia, Uppsala, Sweden). Cytokines (IL-10, IL-6 and TNF-$\alpha$) and adipokines were also analyzed from fasting plasma samples by ELISA (Bender MedSystems GmbH, Austria and BioVendor, Laboratoní medicína, Czech Republic, respectively). Insulin sensitivity and $\beta$-cell function were estimated using fasting plasma insulin and glucose by means of the Homeostatic model assessment 2 (HOMA2) [35].

### *2.3. Classification Criteria*

Four classes were extracted from the database described above; a Higher-Fatness with Higher-Fitness (HFHF) group, a Higher-Fatness with Lower-Fitness (HFLF) group, a Lower-Fatness with Higher-Fitness (LFHF) group, and finally a Lower-Fatness with Lower-Fitness (LFLF) group. The grouping criteria were taken from Gallagher et al. [28] for fatness, and the American College of Sports Medicine guidelines [29] for fitness. The criteria are represented in Table 1.

**Table 1.** Classification criteria for body fat percentage and relative $VO_2$max (mL/kg/min), age and sex.

| Age | Males | Females |
|---|---|---|
| Young | if AGE < 40 years AND if Sex = 1 AND FatMass% ≥ 26 then Higher-Fatness | Elseif Sex = 0 AND FatMass% ≥ 39 then Higher-Fatness |
| Middle-Age | if 59 ≥ AGE ≥ 40 AND if Sex = 1 AND FatMass% ≥ 29 then Higher-Fatness | Elseif Sex = 0 AND FatMass% ≥ 41 then Higher-Fatness |
| Older | if AGE ≥ 60 AND if Sex = 1 AND FatMass% ≥ 31 then Higher-Fatness | Elseif Sex = 0 AND FatMass% ≥ 43 then Higher-Fatness |
| Young/Middle/Older | Else Lower-Fatness | Else Lower-Fatness |
| Young | If AGE < 29 AND if Sex = 1 AND if rel$VO_2$max > 45.7 then Higher-Fitness | Elseif Sex = 0 AND if rel$VO_2$max > 39.5 then Higher-Fitness |
| Middle-Age | If 39 ≥ AGE > = 30 AND if Sex = 1 AND if rel$VO_2$max > 44.4 then Higher-Fitness | Elseif Sex = 0 AND if rel$VO_2$max > 36.7 then Higher-Fitness |
| | If 49 ≥ AGE ≥ 40 AND if Sex = 1 AND if rel$VO_2$max > 42.4 then Higher-Fitness | Elseif Sex = 0 AND if Orel$VO_2$max > 35.1 then Higher-Fitness |
| Older | If AGE > 50 AND if Sex = 1 AND if rel$VO_2$max > 38.3 then Higher-Fitness | Elseif Sex = 0 AND if Orel$VO_2$max > 31.4 then Higher-Fitness |
| Young/Middle/Older | Else Lower-Fitness | Else Lower-Fitness |

## *2.4. Data Analytics*

### 2.4.1. Preprocessing

The full dataset collected at Bangor University premises was loaded into RStudio (Version 1.2.5033, 2009–2019 RStudio Inc., Boston, MA, USA). This initial dataset included 25 independent variables. A first missing data filter was applied and all variables with more than 70% missing data were discarded. After this step, 19 independent variables were retained. Two variables were converted into factorial variables, the classification variable as explained in Table 1 and the variable Sex. The retained variables were visualized to reveal imbalance. This visualization showed an imbalance towards females, as they represented 87% of our dataset. The imbalance was a consequence of the original research question of one data collection being confined to females. A zero- and near zero-variance predictors analysis was conducted, by means of nearZeroVar function (caret R package), to eliminate any independent variables that would not add anything in explaining variance (Table 2). However, no variables were rejected based on these criteria [36]. The preProcess function (caret R package) was used to center and scale the variables and missing data, were imputed using the bagImpute function which uses the bootstrap aggregating method [37]. Outliers were detected as values outside boxplot notches, using boxplot function (graphics R package). The notches were set as the median, plus or minus the standard error [38]. The detected outliers were excluded from the analysis.

**Table 2.** Zero- and near zero-variance predictors analysis.

| | Frequency Ratio | Percent Unique | Zero Variance | Near Zero Variance |
|---|---|---|---|---|
| Sex | 7.100000 | 2.469136 | FALSE | FALSE |
| Age | 1.555556 | 23.456790 | FALSE | FALSE |
| Height | 1.142857 | 28.395062 | FALSE | FALSE |
| Weight | 1.000000 | 77.777778 | FALSE | FALSE |
| BMI | 1.500000 | 75.308642 | FALSE | FALSE |
| Chol | 1.000000 | 72.839506 | FALSE | FALSE |
| HDL | 1.000000 | 62.962963 | FALSE | FALSE |
| LDL | 1.333333 | 69.135802 | FALSE | FALSE |
| TG | 5.250000 | 49.382716 | FALSE | FALSE |
| Fgluc | 1.500000 | 62.962963 | FALSE | FALSE |
| Leptin | 1.000000 | 76.543210 | FALSE | FALSE |
| Insulin | 1.000000 | 77.777778 | FALSE | FALSE |
| BetacellF | 1.000000 | 77.777778 | FALSE | FALSE |
| InsSens | 1.000000 | 80.246914 | FALSE | FALSE |
| InsRes | 1.000000 | 43.209877 | FALSE | FALSE |
| TNFalpha | 1.333333 | 66.666667 | FALSE | FALSE |
| IL-6 | 1.333333 | 71.604938 | FALSE | FALSE |
| IL-10 | 1.000000 | 50.617284 | FALSE | FALSE |
| RER | 1.200000 | 34.567901 | FALSE | FALSE |

BMI = Body Mass Index, Chol = Fasting Total Cholesterol, HDL = Fasting High Density Lipoprotein, LDL = Fasting Low Density Lipoprotein, TG = Fasting TriGlycerides, Fgluc = Fasting Glucose, BetacellF = β cell Function, InsSens = Insulin Sensitivity, InsRes = Insulin Resistance, TNFalpha = Tumor Necrosis Factor α, IL-6 = Interleukin-6, IL-10 = Interleukin-6, RER = Respiratory Exchange Ratio.

#### 2.4.2. Principal Component Analysis and Feature Selection

Once the data were pre-processed a principal component analysis was conducted to find what combination of variables would explain the variability of the data. The function PCA (FactoMineR R package) as described in [39] was used. Eigenvalues, which represent the amount of the variation explained by each principal component, were extracted by fviz_eig. The number of retained components was set so that 70% of the total variance is explained. Correlation plots of all variables were produced using the corrplot function (corrplot R package). The importance of the twenty variables including five new Principal Components was evaluated by a recursive feature elimination technique based on the Boruta Random Forest method (Boruta R package) [32]. The Boruta function compares original importance attributes against importance achievable by shadow random variables, in iterations until convergence. The principal components were also included in the feature selection step, to test whether the most variation corresponded with the highest importance.

#### 2.4.3. Decision Tree

A decision tree was built using the nine variables selected by the Boruta algorithm, with the exclusion of the PCA dimensions. As first step, the class imbalance was compensated by means of weights for simple random sample (i.e., 1/probability). The decision tree was constructed using the rpart function (rpart R package) and vitalized by rpart.plot (rpart.plot R package). Tree depth was set as the smallest tree within one standard error of the minimum cross validation error [40].

#### 2.4.4. Classification Models

Multiple logistic regression, decision tree, naïve Bayes, and κ-nearest neighbors classification model were trained on our dataset by means of the train function (caret R package) as described in Kuhn [36]. The classes were the four subgroups (HFHF, HFLF, LFHF, LFLF) described above. In order to perform the multinomial logistic regression, the multinom method was selected within the train function. In order to evaluate the performance of each single classifier, accuracy tables and confusion matrices were generated, using the confusionMatrix in caret and visualized thanks to ggplot (ggplot2 R package) [36].

2.4.5. Mediation and Moderation Analysis

Mediation analysis was conducted by means of the mediation R package [41]. Before analyzing, the mediation and moderation raw data for each variable were assessed for normality and linearity by means of quantile-quantile plots (qqnorm function, from the basic stats R package), centered, and scaled when required, as described earlier. Linear regressions models, via the lm function (stats R package), were built between the mediator and the independent variable (relative $VO_2$max), and between the dependent variable (Fat Mass percentage) and the independent variable-mediator combined. The mediate function simulated the comparison between these two linear regressions, showing if the mediation would add a significant contribution in relating the independent and dependent variables. The mediation analysis resulted in the Average Causal Mediation Effects (ACME), the Average Direct Effects (ADE), and the combined effects (Total Effect), and the proportion mediated (Prop. Mediated). Moderation was executed by the gylma and stargazer R packages. A linear model was built between the dependent variable and independent variable plus the moderator, and between the dependent variable and the moderator plus the product.

### *2.5. Statistical Analysis*

The descriptive statistics, means and standard deviations of all participants for the 15 included variables and for each of the four subgroups were analysed using the arsenal R package [42]. Data for the four subgroups were split using the filter function supported by the dplyr R package. One-way ANOVAs were performed to compare the four sub-groups and they were followed-up when appropriate both by the tableby function (arsenal R package). Significance level was set at 0.05.

## 3. Results

### *3.1. Subgrouping and Difference Analysis*

As described in the method section, four subgroups were derived according to participants' CRF, body FM%, age, and sex. The subgroups sizes are not evenly distributed. Two subgroups HFHF and LFHF are rather small ($N = 9$, $N = 6$, respectively). In line with our intention to form four groups of different fatness and fitness levels, the ANOVA and follow-up showed significant differences between the two higher-fitness and lower-fitness levels. Moreover, the HFHF group and the LFHF groups also showed a significant difference in fitness, the lower in fatness being fitter ($40.1 \pm 2.9$ mL/kg/min) than the higher in fatness ($34.3 \pm 4.3$ mL/kg/min). As for the higher fatness/lower fatness split, this was fully achieved, as confirmed by the ANOVA and follow-ups (Table 3). As to be expected, BMI was significantly higher in the HFLF group compared with the LFHF and LFLF subgroups. There was a trend towards a higher BMI for the HFLF group when compared with the HFHF group, and a trend towards a higher BMI in the HFHF group compared with the LFHF group. It is to be noted that BMI does not fully reflect FM% (Table 3). Total fasting plasma Cholesterol levels showed significantly higher levels in the HFLF compared with the HFHF and LFHF groups. There was a strong trend towards a higher cholesterol level in the LFLF group compared with the HFHF group. The LFHF group showed higher HDL than the HFHF group. The LFLF group had a higher HDL level than the HFLF group. Moreover, there were two strong trends for a higher HDL in the LFLF group and the LFHF group versus the HFHF and the HFLF groups, respectively. LDL was higher in the HFLF group compared with the HFHF, LFHF, and LFLF groups. Finally, fasting plasma insulin was higher in the HFLF compared with the HFHF. Interestingly two, LFHF and LFLF, groups showed higher insulin values than the HFHF group (Table 3).

**Table 3.** Descriptive Statistics of Database, difference analysis and follow-up analyses.

| | HFHF ($N$ = 9) | HFLF ($N$ = 47) | LFHF ($N$ = 6) | LFLF ($N$ = 19) | Total ($N$ = 81) | ANOVA $p$ Value | $t$-Test Follow-Up HFHF vs. HFLF $p$ Value | $t$-Test Follow-Up HFHF vs. LFHF $p$ Value | $t$-Test Follow-Up HFHF vs. LFLF $p$ Value | $t$-Test Follow-Up HFLF vs. LFHF $p$ Value | $t$-Test Follow-up HFLF vs. LFLF $p$ Value | $t$-Test Follow-Up LFHF vs. LFLF $p$ Value |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Relative $VO_2$max (mL/kg/min) | | | | | | **<0.001** | **<0.001** | **0.013** | **<0.001** | **<0.001** | 0.346 | **<0.001** |
| Mean(SD) | 34.349 (4.237) | 25.492 (6.432) | 40.123 (2.992) | 26.968 (3.272) | 27.906 (6.932) | | | | | | | |
| Range | 29.560–42.530 | 14.050–41.700 | 35.680–44.400 | 19.300–31.500 | 14.050–44.400 | | | | | | | |
| Fat Mass % | | | | | | **<0.001** | 0.108 | **0.003** | **0.003** | **<0.001** | **<0.001** | 0.065 |
| Mean(SD) | 41.951 (5.686) | 45.842 (6.686) | 31.395 (4.828) | 35.548 (4.510) | 41.925 (7.871) | | | | | | | |
| Range | 32.100–47.500 | 29.800–57.240 | 25.400–37.750 | 26.180–40.500 | 25.400–57.240 | | | | | | | |
| Age, yrs | | | | | | 0.063 | | | | | | |
| Mean (SD) | 42.444 (7.764) | 34.787 (13.454) | 24.500 (8.666) | 33.526 (12.624) | 34.580 (12.866) | | | | | | | |
| Range | 33.000–50.000 | 19.000–57.000 | 19.000–42.000 | 20.000–49.000 | 19.000–57.000 | | | | | | | |
| BMI | | | | | | **0.003** | 0.063 | 0.099 | 0.687 | **0.009** | **0.005** | 0.454 |
| Mean (SD) | 31.174 (1.572) | 33.728 (3.949) | 29.165 (2.828) | 30.577 (4.217) | 32.367 (4.061) | | | | | | | |
| Range | 27.580–33.080 | 26.970–44.990 | 25.000–31.440 | 25.300–39.230 | 25.000–44.990 | | | | | | | |
| Height, m | | | | | | 0.894 | | | | | | |
| Mean (SD) | 1.671 (0.114) | 1.662 (0.092) | 1.657 (0.047) | 1.681 (0.099) | 1.667 (0.093) | | | | | | | |
| Range | 1.570–1.950 | 1.500–1.950 | 1.580–1.710 | 1.540–1.950 | 1.500–1.950 | | | | | | | |
| Weight, kg | | | | | | 0.138 | | | | | | |
| Mean (SD) | 87.458 (13.453) | 93.392 (14.219) | 80.335 (10.806) | 87.141 (18.855) | 90.299 (15.427) | | | | | | | |
| Range | 67.990–119.050 | 63.400–125.690 | 62.500–91.630 | 61.750–125.690 | 61.750–125.690 | | | | | | | |
| Cholesterol, mmol/L | | | | | | **0.006** | **0.003** | 0.995 | 0.055 | **0.013** | 0.447 | 0.113 |
| Mean (SD) | 3.839 (0.623) | 4.756 (0.830) | 3.837 (0.753) | 4.573 (1.003) | 4.543 (0.904) | | | | | | | |
| Range | 3.210–5.020 | 2.590–6.260 | 2.830–4.970 | 3.170–6.320 | 2.590–6.320 | | | | | | | |
| HDL, mmol/L | | | | | | **0.008** | 0.900 | **0.025** | 0.056 | 0.057 | **0.004** | 0.873 |
| Mean (SD) | 1.023 (0.205) | 1.040 (0.395) | 1.368 (0.327) | 1.407 (0.554) | 1.149 (0.445) | | | | | | | |
| Range | 0.610–1.420 | 0.370–2.490 | 1.110–1.790 | 0.700–2.590 | 0.370–2.590 | | | | | | | |
| LDL, mmol/L | | | | | | **<0.001** | **0.002** | 0.367 | 0.388 | **<0.001** | **0.037** | 0.186 |
| N-Miss | 0 | 1 | 0 | 0 | 1 | | | | | | | |
| Mean (SD) | 2.456 (0.509) | 3.221 (0.667) | 2.165 (0.699) | 2.769 (1.006) | 2.949 (0.816) | | | | | | | |
| Range | 1.860–3.240 | 1.910–4.460 | 1.230–2.890 | 0.360–4.560 | 0.360–4.560 | | | | | | | |
| Fglucose, mmol/L | | | | | | 0.237 | | | | | | |
| N-Miss | 0 | 0 | 0 | 1 | 1 | | | | | | | |
| Mean (SD) | 5.416 (0.652) | 5.078 (0.802) | 4.665 (0.565) | 5.030 (0.351) | 5.074 (0.700) | | | | | | | |
| Range | 4.710–6.360 | 3.850–9.050 | 3.800–5.300 | 4.190–5.460 | 3.800–9.050 | | | | | | | |
| Leptin, ng /mL | | | | | | 0.118 | | | | | | |
| N-Miss | 0 | 0 | 1 | 0 | 1 | | | | | | | |
| Mean (SD) | 16.966 (10.307) | 29.711 (15.740) | 22.058 (18.130) | 29.883 (16.539) | 27.840 (15.895) | | | | | | | |

**Table 3.** *Cont.*

| | HFHF ($N$ = 9) | HFLF ($N$ = 47) | LFHF ($N$ = 6) | LFLF ($N$ = 19) | Total ($N$ = 81) | ANOVA $p$ Value | $t$-Test Follow-Up HFHF vs. HFLF $p$ Value | $t$-Test Follow-Up HFHF vs. LFHF $p$ Value | $t$-Test Follow-Up HFHF vs. LFLF $p$ Value | $t$-Test Follow-Up HFLF vs. LFHF $p$ Value | $t$-Test Follow-up HFLF vs. LFLF $p$ Value | $t$-Test Follow-Up LFHF vs. LFLF $p$ Value |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Range | 1.380–26.760 | 2.690–59.970 | 3.070–48.840 | 5.470–57.640 | 1.380–59.970 | | | | | | | |
| Insulin, pmol/L | | | | | | **0.040** | **0.012** | **0.023** | **0.039** | 0.630 | 0.184 | 0.722 |
| N-Miss | 0 | 0 | 1 | 0 | 1 | | | | | | | |
| Mean (SD) | 5.667 (2.978) | 11.053 (6.038) | 9.722 (2.363) | 9.021 (4.129) | 9.881 (5.415) | | | | | | | |
| Range | 1.730–9.640 | 1.210–28.090 | 7.350–12.400 | 2.410–17.470 | 1.210–28.090 | | | | | | | |
| TNFalpha, pg/mL | | | | | | 0.992 | | | | | | |
| Mean (SD) | 1.411 (1.669) | 1.476 (2.253) | 1.188 (1.952) | 1.432 (2.046) | 1.437 (2.093) | | | | | | | |
| Range | 0.280–4.920 | 0.240–10.900 | 0.270–5.170 | 0.240–7.070 | 0.240–10.900 | | | | | | | |
| IL-6, pg/mL | | | | | | **0.045** | 0.087 | 0.418 | 0.183 | **0.028** | 0.394 | 0.061 |
| Mean (SD) | 1.609 (0.525) | 1.118 (0.811) | 1.933 (0.983) | 1.294 (0.589) | 1.274 (0.777) | | | | | | | |
| Range | 0.800–2.200 | 0.000–3.120 | 0.380–3.040 | 0.190–2.250 | 0.000–3.120 | | | | | | | |
| IL-10, pg/mL | | | | | | 0.138 | | | | | | |
| N-Miss | 0 | 0 | 1 | 0 | 1 | | | | | | | |
| Mean (SD) | 0.864 (0.224) | 0.841 (0.332) | 1.130 (0.848) | 1.108 (0.662) | 0.925 (0.470) | | | | | | | |
| Range | 0.430–1.190 | 0.030–1.700 | 0.030–2.370 | 0.040–2.250 | 0.030–2.370 | | | | | | | |

HFHF = Higher-Fatness with Higher-Fitness group, HFLF = Higher-Fatness with Lower-Fitness group, LFHF = Lower-Fatness with Higher-Fitness group, LFLF = Lower-Fatness with Lower-Fitness group, $VO_2max$ = maximal oxygen uptake, BMI = Body Mass Index, HDL = Fasting High Density Lipoprotein, LDL = Fasting Low Density Lipoprotein, TNFalpha = Tumor Necrosis Factor α, IL-6 = Interleukin-6, IL-10 = Interleukin-6. Significant p-levels are highlighted in bold.

### 3.2. Principal Component Analysis

The independent variables, once filtered for missing data, were clustered by means of principal component analysis. Five principal component dimensions were found that explained 70% of the variance (Figure 1). Dimension 1 was dominated by glucose tolerance features, dimension 2 by Leptin and Sex, dimension 3 was constituted by lipid profile, dimension 4 by triglycerides and glucose, and, finally, dimension 5 by BMI and weight. (Figure 1). In Figure 2 the classification and the weight of the single individuals is shown when the first two components are put in relation.

These five dimensions were further included in the feature selection process. Recursive feature elimination based on random forest showed that the stronger features in describing the four groups were IL-10, BMI, total cholesterol, HDL, LDL, dimension 1, beta cell function, dimension 4, IL-6, Age, dimension 3, and weight. In Figure 2 the interrelationship of the first two PCA components is shown and the four groups are clustered. Fitter groups tend to develop along dimension 1 while the less fit along dimension 2.

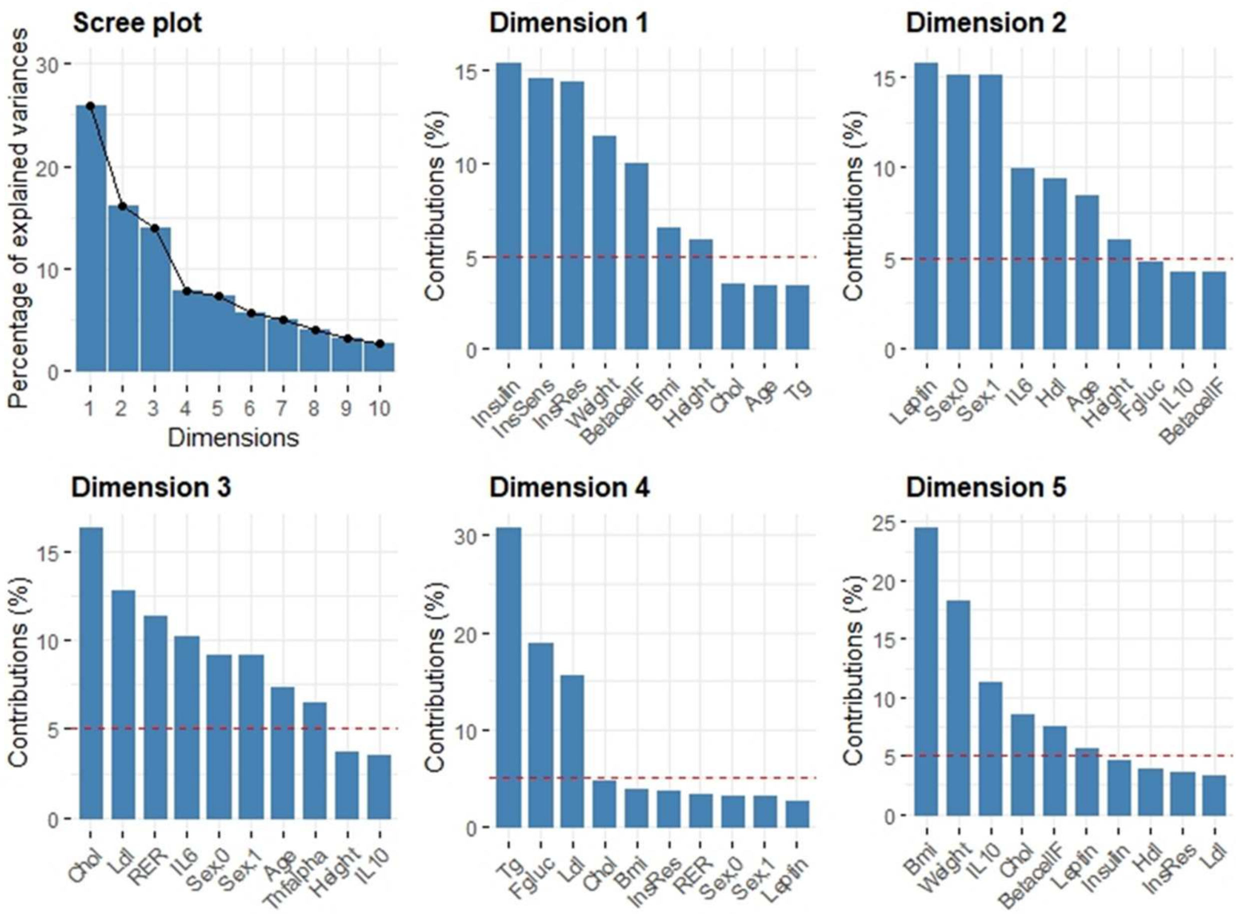


**Figure 1.** Output of the principal component analysis: BMI = Body Mass Index, Chol = Fasting Total Cholesterol, HDL = Fasting High Density Lipoprotein, LDL = Fasting Low Density Lipoprotein, TG = Fasting TriGlycerides, Fgluc = Fasting Glucose, BetacellF = β cell Function, InsSens = Insulin Sensitivity, InsRes = Insulin Resistance, TNFalpha = Tumor Necrosis Factor α, IL-6 = Interleukin-6, IL-10 = Interleukin-6, RER = Respiratory Exchange Ratio, Sex.0 = females, Sex.1 = males.

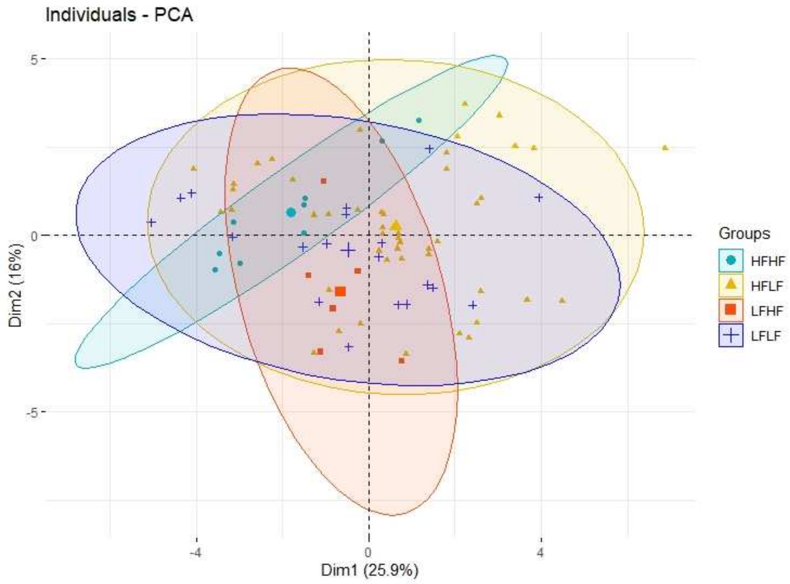


**Figure 2.** Clustering of the categorical variable, including the four fatness and fitness permutations. Relationship between the first principal component and the second principal component computed by PCA. The size of the icons for the single individuals shows their weight in classification. HFHF = Higher-Fatness with Higher-Fitness group, HFLF = Higher-Fatness with Lower-Fitness group, LFHF = Lower-Fatness with Higher-Fitness group, LFLF = Lower-Fatness with Lower -Fitness group.

### 3.3. Classification Models

The Random Forest based recursive feature elimination Boruta algorithm found twelve variables as certainly important in classifying the four fatness and fitness classes (Figure 3). Amongst these twelve are PCA dimensions 1,4 and 3, in order of importance. While the algorithm is uncertain about dimension 5 and discards dimension 2. IL-10, BMI, and cholesterol levels are clearly the most important variables. In Figure S1 the first 10 selected variables are shown as boxplot. Additionally, in Figure S1 linear correlations between variables are displayed, showing how the retained variables still carry most of the correlations.

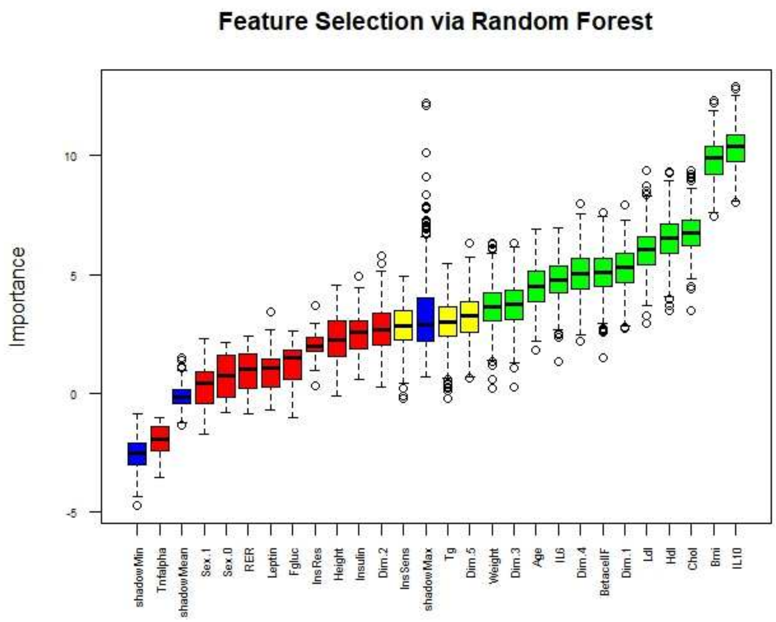


**Figure 3.** Recursive feature elimination; in green are depicted the variables that are certain. IL6. = Interleukin-6, IL-10 = Interleukin-6, RER = Respiratory Exchange Ratio, Sex.0 = females, Sex.1 = males, Dim.1 = Dimension 1 of the PCA, Dim.2 = Dimension 2 of the PCA Dim.3 = Dimension 3 of the PCA, Dim.4 = Dimension 4 of the PCA, Dim.5 = Dimension 5 of the PCA.

When the twelve variables, including the PCA dimensions, selected by the Boruta importance algorithm were used to generate the classification model, we found acceptable classification performances. In fact, the Multiple Logistic Regression model showed a classification accuracy of 0.77 (95% CI: 0.6717, 0.8627), significantly higher than the No Information Rate (0.4691), and a κ-coefficient of 0.65, Figure 4. The Decision Tree model, displayed in Figure 5, although having the lowest accuracy (0.70, 95% CI: 0.5919, 0.8001) amongst the models generated here, still had an accuracy significantly higher than its No Information Rate (0.432), and an acceptable κ-coefficient (0.54) (Figure 4). The Naïve Bayes classifier showed the highest accuracy (0.88, 95% CI: 0.7847, 0.9392), significantly higher than the No Information Rate (0.58), and a moderate κ-coefficient equal to 0.79 (Figure 4). Finally, the K-Nearest Neighbors classifier had an accuracy of 0.73 (95% CI: 0.6181, 0.8213), which was, however, not higher than the No Information Rate (0.76), with a rather weak agreement, a κ-coefficient of 0.47 (Figure 4). Overall, the latter performed worse than the other classification models.

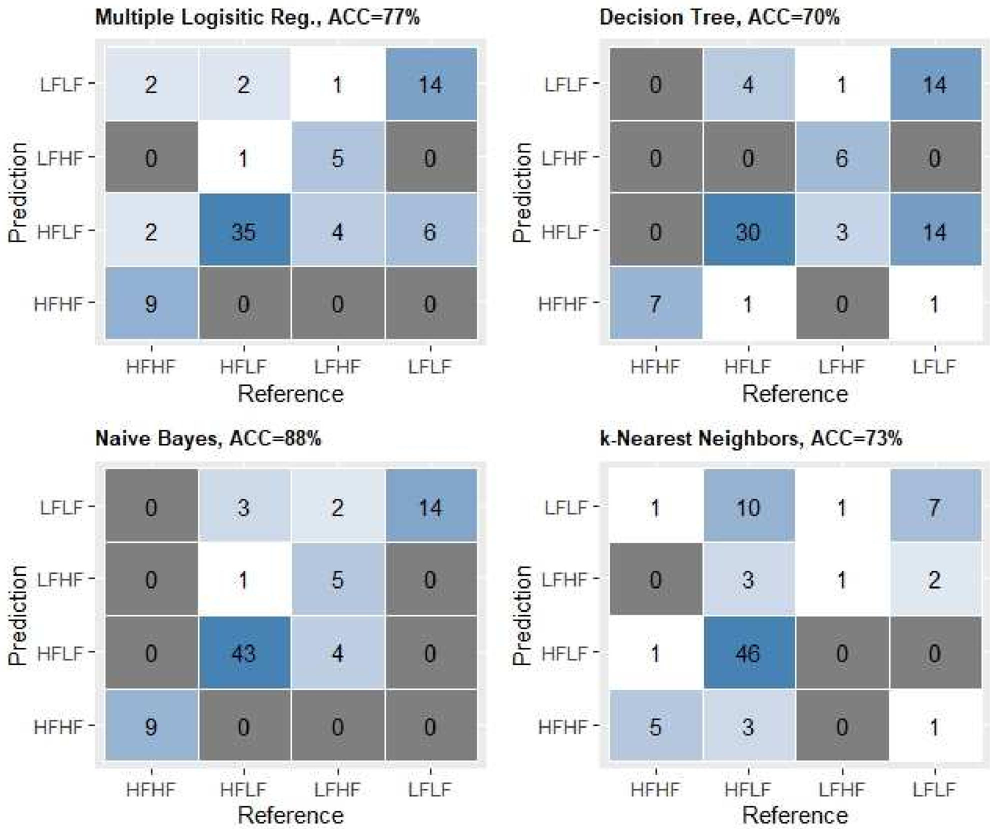


**Figure 4.** Confusion Matrices, and accuracy of the four classification models. ACC = accuracy, HFHF = Higher-Fatness with Higher-Fitness group, HFLF = Higher-Fatness with Lower-Fitness group, LFHF = Lower-Fatness with Higher-Fitness group, LFLF = Lower-Fatness with Lower -Fitness group.

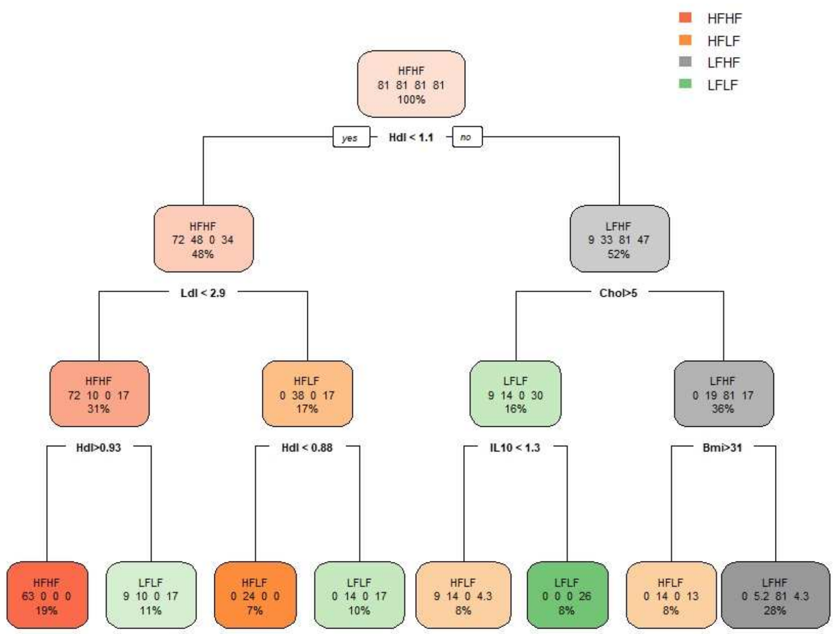


**Figure 5.** Decision tree, where HDL = High Density Lipoprotein, LDL = Low Density Lipoprotein, IL-10 = Interleukin-10 and BMI = Body Mass Index are expressed in their original dimensions (mmol/L, mmol/L, pg/mL, respectively). HFHF = Higher-Fatness with Higher-Fitness group, HFLF = Higher-Fatness with Lower-Fitness group, LFHF = Lower-Fatness with Higher-Fitness group, LFLF = Lower-Fatness with Lower -Fitness group.

### 3.4. Mediation and Moderation Analysis

All selected variables were analyzed for mediation and moderation. As shown by the quantile-quantile plots in Figure 6, LDL and BMI did not require further scaling and/or centering and were the only two variables to show a significant partial mediation effect between CRF and FM% (Figure 7). Details of the causal mediation analysis are captured in Table 4.

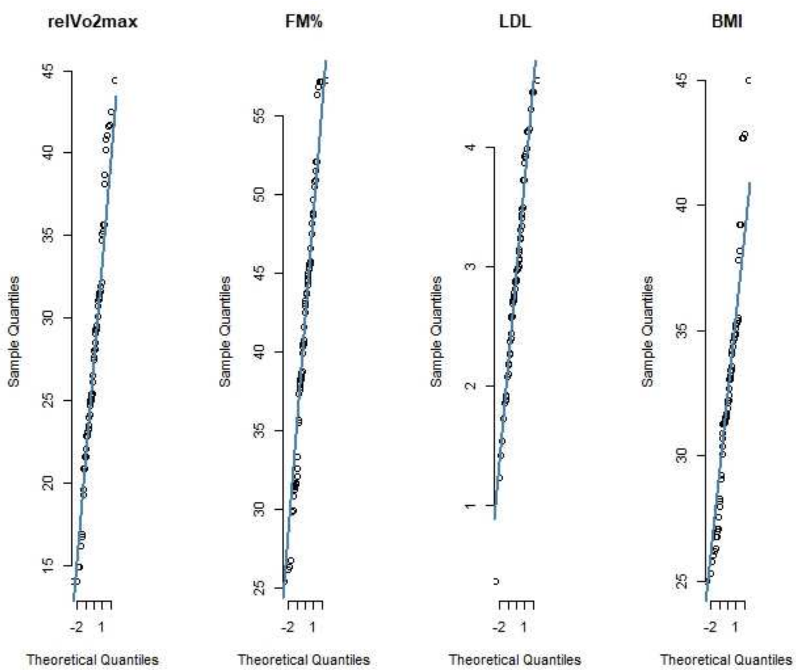


**Figure 6.** Quantile–quantile plots of the variables that showed partial mediation.

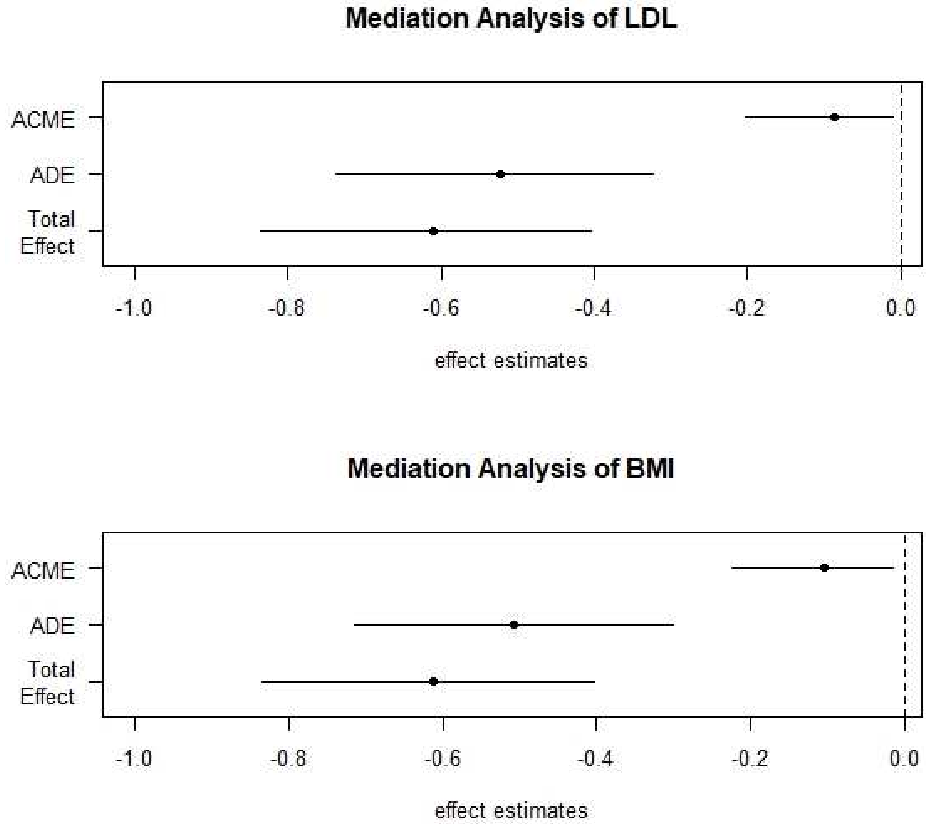


**Figure 7.** Decomposed Mediation Analysis plot: ACME = Average Causal Mediation Effect, ADE = Average Direct Effect, LDL = Low Density Lipoprotein, BMI = Body Mass Index.

**Table 4.** Causal Mediation Analysis, Quasi-Bayesian Confidence Intervals.

| | Estimate | 95% CI Lower | 95% CI Upper | *p*-Value |
|---|---|---|---|---|
| ACME (LDL) | −0.0843 | −0.1813 | −0.01 | 0.024 * |
| ADE (LDL) | −0.5221 | −0.7414 | −0.30 | <0.001 *** |
| Total Effect LDL) | −0.6063 | −0.8271 | −0.40 | <0.001 *** |
| Prop. Mediated (LDL) | 0.1308 | 0.0164 | 0.31 | 0.024 * |
| ACME (BMI) | −0.1078 | −0.2205 | −0.02 | 0.012 * |
| ADE (BMI) | −0.4996 | −0.7034 | −0.30 | <0.001 *** |
| Total Effect (BMI) | −0.6075 | −0.8211 | −0.40 | <0.001 *** |
| Prop. Mediated (BMI) | 0.1728 | 0.0397 | 0.36 | 0.012 * |

LDL = Low Density Lipoprotein, BMI = Body Mass Index, ACME = Average Causal Mediation Effect, ADE = Average Direct Effect, Prop. Mediated = Proportion of the effect Mediated. Significant values: *** <0.001, * <0.05. $N = 81$, Simulations: 1000.

## 4. Discussion

This present study embraces artificial intelligence as a tool to provide new insight into the fat but fit paradox [8]. Using unsupervised and supervised machine learning approaches to interrogate existing physiological data, this work indicates connection between markers of dyslipidemia, inflammation and cardiorespiratory fitness that reveal possible functional interaction of physiological systems underpinning the "fat but fit paradox".

### *4.1. Descriptive Statistics in Relation to Fatness and Fitness*

We have created four classes, or groups, in line with population normative cut-off values [28,29]. Consistently, these groups differed significantly from one another in terms of fitness and fatness (Table 3). Fasting total cholesterol levels and LDL were significantly higher in the HFLF group, while HDL was higher in the groups with lower fatness. The decision tree depicted in Figure 5 shows how well HDL and LDL alone could differentiate the HFHF group from the other groups. Although IL-10 did not show significant differences between the four groups, whereas IL-6 did, IL-10 seemed to be involved in the differentiation of individuals with lower fitness level in function of their fatness (Figure 5). Moreover, the Analysis of Variance amongst the four groups also showed differences in fasting insulin levels. Fasting insulin was the highest in the HFLF group and the lowest in the HFHF group (Table 3). This is of particular interest because it seemed to be associated with fitness rather than with fatness levels. Fitness has been shown to play an important role in protecting against glucose intolerance [43]. This may be related to the well-known effect of muscle contractile activity, hence exercise training, on insulin sensitivity [44].

### 4.2. Machine Learning

Principal component analysis clustered the various markers available in this study so that they could better explain the variance of the fatness and fitness categorical variable. This resulted in PCA Dimension 1, mainly composed of glucose tolerance indicators, such as fasting insulin, insulin sensitivity, and insulin resistance, as well as beta cell function derived from the HOMA2 model (Figure 1). However, supervised learning, namely the random Forest based feature selection algorithm, revealed that the importance of IL-10, cholesterol levels (i.e., HDL, LDL and total Cholesterol) along with BMI in classifying the four classes was greater than that of the above mentioned glucose tolerance PCA cluster. The interesting aspect of our approach is that our analysis clearly points towards dominant features, namely IL-10, LDL, HDL, BMI, for categorizing our four groups, in competition with other features, which are just as well known to be influenced by fatness and fitness. Besides the potential exercise dependent link between IL-10 and insulin/leptin sensitivity in the hypothalamus in animal studies [17], exercise was found to increase IL-10 levels in overweight-obese human subjects [20]. An interlink between fatness and IL-10, however, was found in obese subject after weight loss, revealing higher IL-10 levels [45]. Therefore, distinct features of our data could point towards an important discriminating function of IL-10 and LDL/BMI for fatness and fitness classification and could be linked to these findings. Moreover, exercise has been found to effect LDL as well as HDL levels [46].

### 4.3. Partial Mediation

Fatness and fitness are significantly inversely related [47]. This was confirmed by our data. In addition to this, however, we found that CRF is indirectly related to FM% through the mediation of LDL and BMI. Previous literature found that BMI could mediate CRF and cardio-metabolic risk in schoolchildren [48]. Another investigation in schoolchildren using a large dataset showed that CRF may have a beneficial effect on lipid profile, insulin metabolism and inflammation independent of fatness [49]. Our results seem to lead in the same direction. Specific effects of exercise training, of a high enough intensity, to promote aerobic capacity improvements have been linked to a decrease in concentration of atherogenic ox-LDL [46,50]. In addition, upregulation of fatty acid metabolism and transport through exercise dependent signaling pathways (particularly peroxisome proliferator-activated receptor) [51,52] and concurrent alterations in lipid profiles [53,54] are well described. Interestingly, IL-10 was found to be linked with LDL level as IL-10 was shown to induce uptake of LDL by fluid-phase endocytoses in macrophages leading to lowered LDL plasma levels [55].

### 4.4. Implications

We are aware that our study is retrospective. Thus, it provides a limited level of evidence. It is beyond the purpose of this study to accept or not the hypothesis that fitness plays a protective role in people with higher level of fatness. Yet the discriminating role that anti-inflammatory and cholesterol levels seem to make sense when addressing fatness and fitness may point in the direction of “healthy obesity” when the CRF level is high [4].

### 4.5. Limitations

The current study is based on data from 81 individuals. Several variables, such as systolic and diastolic Blood Pressure and C-Reactive Protein, had to be excluded from the analysis because of missing data. The observations and conclusions drawn from this study would need to be verified in a larger dataset. This study does not provide direct experimental evidence, but is merely observational and retrospective. These considerations need to be taken into account when evaluating our results and conclusions. Our dataset has more females than males, and although sex did not appear to play a key role in determining the classification, we cannot exclude that, with a higher number of males this factorial variable would or could have had a greater weight. Finally, by dividing our dataset into four classes we observed that these were not evenly distributed. This issue was partially mitigated by balancing, using class weights.

## 5. Conclusions

Our data analytics approach has shown a potential key role of IL-10 as well as HDL, LDL, total Cholesterol and BMI in the classification of people according to their fatness and fitness levels. Unsupervised learning showed that a cluster of glucose tolerance related variables explains the highest quote of the variance of the categorical variable. However, supervised learning did not select this PCA cluster. Mediation analysis showed that LDL and BMI partially explain the association between fitness and fatness. These results suggest that CRF and FM% may be interconnected by anti-inflammatory responses and cholesterol blood levels. This may be in line with the protective role of cardiorespiratory fitness suggested in recent years. However, large randomized controlled trials are needed to validate this hypothesis experimentally and conclusively.

**Supplementary Materials:** The following are available online at https://www.mdpi.com/1660-4601/18/4/1800/s1, Figure S1: Boxplot of selected variables, and correlation matrices before and after the selection.

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**Data Availability Statement:** The data presented in this study are available on request from the corresponding author. The data are not publicly available due to restrictions related to the data protection regulations.

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# Effects of a HIIT Protocol on Cardiovascular Risk Factors in a Type 1 Diabetes Mellitus Population

**Jesús Alarcón-Gómez [1], Joaquín Calatayud [2], Iván Chulvi-Medrano [3,*] and Fernando Martín-Rivera [4]**

1. Faculty of Physical Activity and Sports, University of Valencia, 46010 Valencia, Spain; jesusadol18@gmail.com or jeago@alumni.uv.es
2. Exercise Intervention for Health Research Group (EXINH-RG), Department of Physiotherapy, University of Valencia, 46010 Valencia, Spain; joaquin.calatayud@uv.es
3. UIRFIDE (Sport Performance and Physical Fitness Research Group), Department of Physical and Sports Education, University of Valencia, 46010 Valencia, Spain
4. Research Group in Prevention and Health in Exercise and Sport, Department of Physical and Sports Education, University of Valencia, 46010 Valencia, Spain; Fernando.martin-rivera@uv.es

* Correspondence: ivan.chulvi@uv.es

**Abstract:** Cardiovascular complications are important causes of morbidity and mortality of Type 1 Diabetes Mellitus (T1DM) people. Regular exercise is strongly recommended to these patients due to its preventive action against this type of disease. However, a large percentage of patients with T1DM people present a sedentary behavior, mainly, because of the fear of a post-exercise hypoglycemia event and lack of time. High-intensity interval training (HIIT) is an efficient and safe methodology since it prevents hypoglycemia and does not require much time, which are the main barriers for this population to doing exercise and increasing physical conditioning. Nineteen sedentary adults (37 ± 6.5 years) with T1DM were randomly assigned to 6 weeks of either HIIT, 12 bouts first 2 weeks, 16 bouts in weeks 3 and 4, and 20 bouts in the last two weeks x 30-s intervals interspersed with 1-min rest periods, performed thrice weekly or to control group, which did not train. $VO_{2max}$, body composition, heart rate variability (HRV), and fasting glucose were measured as cardiovascular risk factors. We suggest that the 6-week HIIT program used in the present study is safe since no severe hypoglycemia was reported and is an effective strategy in improving $VO_2$max, body composition, HRV, and fasting glucose, which are important cardiovascular risk factors in T1DM people.

**Keywords:** type 1 diabetes; high-intensity interval training; exercise

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## 1. Introduction

Type 1 Diabetes Mellitus (T1DM) is a chronic metabolic disease characterized by the insufficient production of endogen insulin caused by autoimmune β-cell destruction [1]. According to the International Diabetes Federation (IDF) and World Health Organization (WHO), in the world, 25–45 million adults (>20 years old) suffer from T1DM. In reference to children, adolescents, and young adults (0–20 years old), more than a million live with this pathology, with 130.000 new diagnosed cases per year. It was estimated that the number of people with T1DM in the world will increase a 25% by 2030 [2,3].

Microvascular (e.g., retinopathy, neuropathy, and nephropathy) and macrovascular complications (e.g., coronary arterial disease, peripheral artery disease, stroke, and heart failure) are important causes of morbidity and mortality from this disease [4]. In fact, people with T1DM are at a two-fold to eight-fold increased risk of cardiovascular disease, being this, the first cause of premature death in this population [5,6]. Therefore, brush over effective strategies for the prevention of cardiovascular comorbidities must be a primary concern in T1DM patients and health providers.

Regular exercise is strongly recommended for people living with type 1 diabetes to prevent cardiovascular episodes [7]. Nonetheless, the majority (>60%) of this population does not achieve the current guidelines of exercise proposed by the American College of Sports Medicine (ACSM) and the American Diabetes Association (ADA) [8,9], which indicate at least 150 min of moderate to vigorous aerobic exercise per week and resistance training in 2–3 non-consecutive sessions, performing 1–3 sets of 10–15 repetitions, typically 50–75% of 1 repetition maximum (1RM) on 8–10 multijoint exercises [10].

The most recurrent pretexts that T1DM people state for not exercising are the lack of time, the fear of a hypoglycemia event, and loss of glycemic control due to inadequate knowledge about exercise variables management [11]. Those reasons make that few people with T1DM benefit from the improvement of aerobic capacity ($VO_{2max}$), glucose regulation, body composition, endothelial function, blood lipid profile, and cardiac autonomic nervous regulation that physical exercise promotes and which are risk factors to develop cardiovascular disease [1,12–14].

The aforementioned barriers that T1DM people face may be overcome with high-intensity interval training (HIIT), a training method that, despite being used since the early 20th century in sport performance, has been discovered to be an interesting tool for those with cardiometabolic diseases in the recent years [15]. HIIT involves repeated brief bouts of high intensity (>85% $VO_{2max}$) intermitted by passive or active recovery periods, requiring lower exercise duration than moderate-intensity continuous training (MICT), also HIIT prevents the drop of glycemia typical of MICT, due to its anaerobic metabolism predominance [4]. There is also evidence to suggest that HIIT elicits at least the same cardiometabolic effects in healthy and pathologic population that MICT does [16,17]. These safe, effective, and time-efficient results are sufficient to consider HIIT as a beneficial form of training for the T1DM population.

There is little previous literature analyzing the effects of HIIT in T1DM. The trend in previous data shows a long-term benefit on cardiorespiratory fitness and glycemic control. However, the underlying mechanisms are not entirely clear, and positive HRV regulation and improved body composition may be the mechanisms causing this benefit.

Firstly, cardiac autonomic regulation can be monitored by Heart Rate Variability (HRV) which is the fluctuation in the time intervals between adjacent heartbeats [18]. HRV provides indirect insight into cardiovascular autonomic nervous system tone, corresponding to the balance between sympathetic and parasympathetic influences on the sinoatrial node [19]. A reduced HRV, which is related to a sympathetic modulation predominance, is associated with an increased risk of cardiovascular problems including sudden cardiac death [20,21]. The large fluctuations in blood glucose levels associated with T1DM tend to place this population at an autonomic control dysfunction and in a reduced HRV in comparison with their healthy counterparts [22]. Given that physical exercise positively affects cardiac autonomic function in people with type 2 diabetes [23] and HIIT has been shown as a promising strategy to improve HRV in healthy individuals and patients with metabolic syndrome [24], we aimed to examine the effect of a HIIT protocol on HRV of a population with T1DM. Secondly, body composition is a traditional cardiovascular risk factor, and in the same way, obesity and overweight are dramatic increased in T1DM people, in fact, almost 50% of patients with T1DM are either overweight or obese [1]. Insulin therapies and unhealthy lifestyles are the main mechanisms of weight gain in this pathological population [25]. Living with obesity or overweight has been widely linked to an enhanced risk of a cardiovascular accident [26], so preventing this situation is a key point in T1DM patients' healthcare. HIIT has shown interesting effects on body composition in healthy individuals [27] and disappointing results in obese and overweight people with T1DM [28,29], so it is important to expand the analysis of this topic.

Aerobic fitness and glucose regulation are the most studied cardiovascular risk factors in T1DM people after a period of HIIT [4,30–32] since this population shows reduced levels of $VO_{2máx}$ and irregular glucose control, but given there are only a few studies with these objectives, more researches are needed.

Therefore, the aim of this study was to investigate the long-term effects of 6-week high-intensity interval training on HRV, body composition, fasting glucose, and aerobic fitness in a T1DM population since these variables are closely related to cardiovascular health and HIIT could be proposed as the solution to the problems that prevent this population from exercising.

## 2. Materials and Methods

### 2.1. Participants

We recruited 19 inactive adults (10 males and 9 females), clinically diagnosed as T1DM by one of the following criteria: HbA1c $\geq$ 6.5 % ($\geq$48 mmol/mol), random plasma glucose $\geq$ 200 mg/dL ($\geq$11.1 mmol/L), fasting plasma glucose $\geq$ 126 mg/dL ($\geq$7.0 mmol/dL) or oral glucose tolerance test OGTT), 2-h glucose in venous plasma $\geq$ 200 mg/dL ($\geq$11.1 mmol/L) [33]. The Valencian Diabetes Association (VDA) and social media announcement were the main recruitment methods. The following inclusion criteria were adopted: (1) aged 18–45 years, (2) duration of T1DM > 4 years, (3) HbA1C < 10% (4) no structured exercise training programs in the previous 6 months, (5) no diagnosed cardiovascular diseases. Subjects excluded from the study include those who smoke regularly, take any medication that affects heart rate, and those who had major surgery planned. Testing took place in the laboratory of the research group in prevention and health in exercise and sport at the University of Valencia. Participants were informed of the purposes, procedures, and risks involved in the study before giving their informed written consent to participate. The study procedures were in accordance with the principles of the Declaration of Helsinki and were approved by the local Institutional Review Board from the local university (H1421157445503).

### 2.2. Experimental Design

This is a randomized experimental, parallel design, open-label trial. The eligible subjects were randomly allocated by the researchers (www.randomizer.org) to the experimental (N = 11, 38 $\pm$ 5.5 years, 5 men and 6 women, height 1.68 $\pm$ 0.09 m, body mass 70.5 $\pm$ 7.4 kg and 20.5 $\pm$ 8.4 years diagnosed) or control group (N = 8, 35 $\pm$ 8.2 years, 4 men and 4 women, height 1.69 $\pm$ 0.07 m, body mass 72.05 $\pm$ 5.0 kg and 21.1 $\pm$ 6.5 years diagnosed), and stratified/classified by gender to ensure a balanced number of men and women in each group. They all were instructed not to modify their nutritional habits and not to perform any regular exercise program outside of the study, which was not supervised.

### 2.3. Procedures

Initially, participants attended the lab (7.00–9.00 am) after an overnight fast (>10 h) for the first assessment session. Subjects were instructed not to drink any caffeine or alcohol-contained products in the 24–48 h prior to the measurement to avoid any influence on HRV and body composition outcomes. The hour of the day that each subject completed each test was recorded, as well as the menstrual phase of each female participant with the aim of repeating the same conditions in the second measurement to block their influence in the results [34]. The same test protocols were performed exactly in the same way after the experimental period by both control and HIIT groups.

#### 2.3.1. Body Composition

An 8-electrodes bioelectrical impedance analysis scale (Tanita MC780MA, Tanita Corporation of America, Inc., Illionis, United States) with software GMON version 3.1.6. was conducted to measure body composition, specifically, fat mass (FM) and free fat mass (FFM). The participants wore light clothing and assumed a standing posture on their bare feet, then wait for the results printed from the device in accordance with the manufactures' instructions.

2.3.2. Heart Rate Variability

Analysis of resting HRV measurement was conducted in a quiet dimly lit room with a controlled temperature (22 ± 1 °C). Emptying the urinary bladder was asked to the subjects before the beginning of the test. A Polar H10 heart rate (HR) sensor with the Polar Pro strap (Polar Electro, Kempele, Finland), previously moistened to increase the adherence to the skin, was worn around the participant's chest. HR monitor and a tablet with the validated Elite HRV App (Elite HRV LLC®, Asheville, North Caroline, USA) were connected via Bluetooth® [35].

In a supine position and following a 5-min rest, which was used to stabilize the signal without registering it, the HRV readiness began. During 5 min, the participant was instructed to relax and breathe at a natural rate while heart R-R intervals were recorded. Linear parameters in the time domain such SDNN (standard deviation of NN intervals), RMSSD (root mean square of successive RR interval differences and pNN50 (percentage of successive RR intervals that differ by more than 50 ms) and in the frequency domain: HF power and LF power, absolute power of the high and low-frequency band (0.15–0.4 Hz) and LF/HF power ratio (ratio of LF to HF power) were registered, but in order to analyze parasympathetic modulation changes and given the measurement characteristics, RMSSD and HF/LF ratio were the variables examined statistically [20]. HRV short-term recording characteristics were based in the Task Force of the European Society of Cardiology [36,37] used in previous researches with similar objectives [38,39].

2.3.3. $VO_{2max}$ and Peak Power Output

Seven days later to the initial assessment, all the participants performed an incremental test on a cycle ergometer (Excite Unity 3.0, Technogym S.p.A, Cesena, Italia) to determine peak power output (PPO) and peak oxygen consumption ($VO_2$peak) using a gas collection system (PNOE, Athens, Greece) that was calibrated in each test by means of ambient air [40]. Before starting the test, capillary blood glucose concentrations were checked by their own blood glucose monitoring devices. They were told to arrive at the institutional gym with a glycemic level > 100 mg/dL and less than 250 mg/dL in absence of ketones. If the glycemia was correct, the participant began the test normally. If glycemic values were low (<100 mg/dL), intake of 15–30g of fast-acting carbohydrates (CHO) was medically compulsory. Whenever patients presented hyperglycemic status (>250 mg/dL) without ketonuria (determined with test strip), a medically prescribed small corrective insulin dose was self-administered. In the presence of ketones, the exercise would be delayed. Glycemia was checked again until the level of blood glucose was optimum to start the test. In the same way, it was recommended that patients not exercise at the peak of insulin action [30].

The test consisted of a warm-up of 5 min at 40 Watts (W). After that, the workload was increased by 20 W every minute until volitional exhaustion. All the participants were verbally encouraged to give their maximum effort during the exercise. The test ends with a cooldown of 5 min at 40 W. Heart rate was continuously monitored by a Polar H10 (Polar Electro, Kempele, Finland). $VO_2$peak was taken as the highest mean achieved within the last 15 s prior to exhaustion. Peak power output was registered to individualize the workloads in the experimental period training.

2.3.4. Fasting Glucose

Before the intervention period, every morning during 28 days, the participants registered their fasting glycemia level by means of a blood sample obtained by a finger-stick. Subjects were asked to eat their normal diet the evening before each test. They were also instructed to conduct the blood glucose measurement at the same time, in the same position and with the same device, which must be one of the following: FreeStyle (FreeStyle Libre system; Abbott Diabetes Care, Alameda, CA) or Accu-Chek (Accu-chek glucometer, Roche, USA). These glucose monitors are approved by the Diabetes Technology Society and were accessible to the volunteers [41]. An online shared Excel (Microsoft Excel 2013®, Microsoft Corporation, Redmond, United States) file was used to facilitate data recording.

The post-intervention analysis was conducted exactly in the same way and lasted exactly the same time as in the pre-intervention measurement (28 days).

*2.4. Training Protocol*

Training started the following week after the completion of the pre-experimental procedures. Participants of the experimental group trained three times per week for 6 weeks under the supervision of a researcher on a cycle ergometer (Excite Unity 3.0, Technogym S.p.A, Cesena, Italy). Heart rate while exercising was monitored with a Polar H10 (Polar Electro, Kempele, Finland) that was preconfigured with their heart rate zones. The HIIT protocol performed was a type 1:2, which means that the high-intensity intervals lasted half the time that the rest intervals did. The saddle height was always adjusted to the height of the subject's iliac crest. The training began with a 5-min warm-up at 50 W. Then, they performed repeated 30-s bouts of high-intensity cycling at a workload selected to elicit 85% of their individual PPO interspersed with 1 min of recovery at 40% PPO. The number of high-intensity intervals increased from twelve reps in weeks 1 and 2, to sixteen reps in weeks 3 and 4, to twenty reps in weeks 5 and 6. Training ended with a 5-min cooldown performed at 50 W. After the session, participants were told to check their glycemia level frequently and notify the investigators if a glycemia drop below 70 mg/dL occurred during the 24 h following the exercise [1].

All sessions were supervised by the investigators and in order to reflect real-world conditions, researchers did not advise about decreasing fast-acting insulin dosage or increasing carbohydrate consumption prior to each exercise session. Glycemic values were checked ten minutes before starting the training, and when values were out of range, researchers warned the patients and then they corrected the situation following their medically prescribed guidelines as such has been explained in pre-test procedures. Subjects assigned to the control group were asked to maintain their current lifestyle and dietary intakes during the study period.

*2.5. Statistical Analysis*

All variables were expressed as a mean and standard deviation (M $\pm$ SD) and were analyzed using a statistical package (SPSS Inc., Chicago, Illinois, USA). Normality assumption by Shapiro–Wilks was identified for each variable. A mixed factorial ANOVA ($2 \times 2$) was performed to assess the influence of "*condition*" (i.e., control group vs. experimental group) and "*time moment*" variable (i.e., pre-intervention, post-intervention) over $VO_{2max}$, HRV, body composition (FM and FFM), and fasting glucose. In the event that Sphericity assumption was not met, freedom degrees were corrected using Greenhouse-Geisser estimation. Post hoc analysis was corrected using Bonferroni adjustment. D Cohen and the associated CI were used to assess the magnitude of mean differences between control vs. experimental conditions. Significant differences were established at $p < 0.05$.

## 3. Results

The study randomized 21 patients with T1DM. At the end of the study, 2 participants from the control group had dropped out due to personal reasons not determined and pregnancy, respectively. Only completers were analyzed (Figure 1).

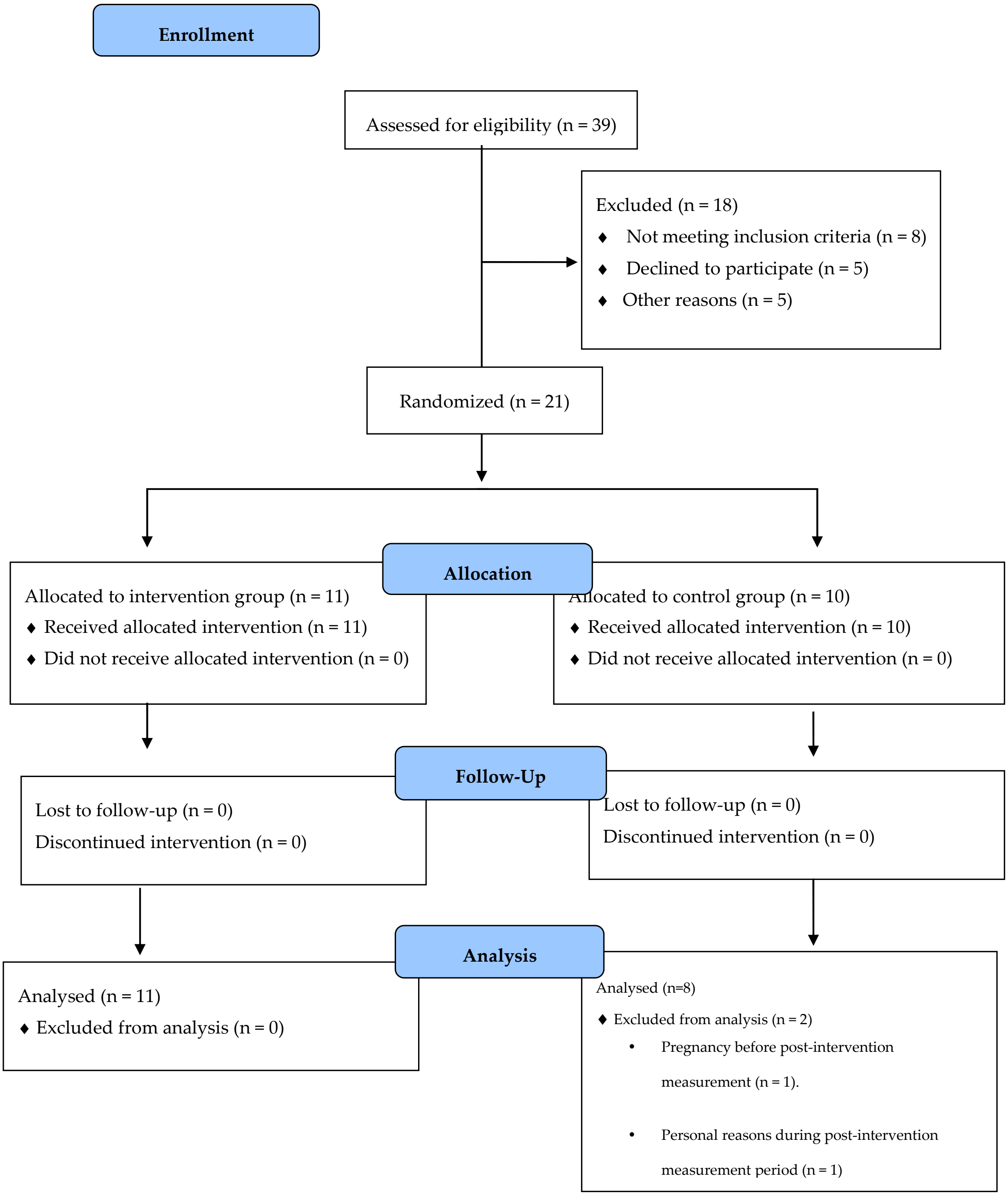


**Figure 1.** Flow diagram of inclusion of patients in the study.

### 3.1. Adverse Events

There were three mild hypoglycemia cases (67.9 ± 2.6 mg/dL) of 198 total trainings (1.5%), occurring immediately after exercise which only required a few minutes of rest and carbohydrate ingestion to be solved. No adverse cardiac events, respiratory events, or musculoskeletal injuries were reported in the experimental period. There were no episodes of hyperglycemia, nocturnal hypoglycemia, or episodes of diabetic ketoacidosis.

### 3.2. Cardiovascular Risk Factor Outcomes

#### 3.2.1. $VO_{2max}$

A significant main effect of the interaction condition*time moment was found (F = 72.18, $p < 0.01$, $\eta_p^2 = 0.81$). The post hoc analysis showed significant changes between pre- and post-conditions in the experimental group (37.1 ± 4.1 vs. 40.4 ± 3.8 mL/min/kg); however, there were no significant changes in the control group (37.0 ± 5.5 vs. 37.2 ± 5.1), results are presented in Table 1.

#### 3.2.2. Body Composition

Body composition was improved in the intervention group after 6 weeks, through positive changes in FFM (F = 43.4, $p < 0.01$, $\eta_p^2 = 0.72$) and FM (F = 60.0, $p < 0.01$, $\eta_p^2 = 0.78$). In contrast, the post hoc analysis showed no significant changes in FFM (57.6 ± 9.8 vs. 57.9 ± 10.0 kg) and FM (15.4 ± 4.5 vs. 15.3 ± 4.6 kg) in the control group, as shown in Table 1.

#### 3.2.3. Heart Rate Variability

LF/HF ratio and rMSSD data obtained by means of short-term *Elite HRV* analysis are listed in Table 1. A significant main effect of the interaction condition*time moment was found in the LF/HF ratio (F = 6.5, $p < 0.05$, $\eta_p^2 = 0.28$). The post hoc analysis showed significant changes between pre- and post-conditions in the experimental group (37.8 ± 27.9 vs. 44.3 ± 27.7 ms). In contrast, the control group did not suffer any important change between test periods (40.0 ± 15.9 vs. 39.3 ± 16.5 ms). Similarly, LF/HF ratio (F = 10.5, $p < 0.05$, $\eta_p^2 = 0.38$) improved significantly. The post hoc analysis showed significant changes between pre- and post-conditions in the experimental group (2.6 ± 1.6 vs. 1.5 ± 0.9 $ms^2$), with no remarkable changes in the control group (2.1 ± 2.0 vs. 1.9 ± 2.2 $ms^2$).

#### 3.2.4. Fasting Glucose

A significant main effect of the interaction condition*time moment was reported in the fasting glucose (F = 0.77, $p < 0.05$, $\eta_p^2 = 0.28$). The post hoc analysis showed significant variations between pre- and post-conditions in the experimental group (135.8 ± 95.0 vs. 124.5 ± 15.6 mg/dL); nonetheless, there were no significant changes in the control group (131.8 ± 21.1 vs. 135.9 ± 25.0 mg/dL), results are presented in Table 1.

**Table 1.** Variables analysis before high-intensity interval training (HIIT) intervention and following training period in both groups.

| | HIIT Group | | Control Group | | |
|---|---|---|---|---|---|
| | **Pre** | **Post** | **Pre** | **Post** | **ES** |
| $VO_{2max}$ (mL/min/kg). | 37.1 ± 4.1 | 40.4 ± 3.8 * | 37.0 ± 5.5 | 37.2 ± 5.1 | 0.71 |
| Fat Mass (Kg)/% Fat mass | 17.1 ± 4.4/24.2% ± 7.6 | 16.0 ± 4.2/22.4% ± 7.4 * | 15.4 ± 4.5/21.4% ± 9.6 | 15.3 ± 4.6/21.1% ± 9.8 | 0.16 |
| Lean Mass (Kg)/%Lean Mass | 53.5 ± 8.7/75.9% ± 7.7 | 55.3 ± 8.8/77.6% ± 7.4 * | 57.6 ± 9.8/79.9% ± 7.8 | 57.9 ± 10.0/80.2% ± 7.4 | 0.28 |
| rMSSD (ms). | 37.8 ± 27.9 | 44.3 ± 27.7 * | 40.0 ± 15.9 | 39.3 ± 16.5 | 0.22 |
| LF/HF ratio ($ms^2$). | 2.6 ± 1.6 | 1.5 ± 0.9 * | 2.1 ± 2.0 | 1.9 ± 2.2 | 0.23 |
| Fasting Glucose (mg/dL). | 135 ± 24.9 | 124.5 ± 15.6 * | 131.8 ± 21.1 | 135.9 ± 25.0 | 0.54 |

Data are presented by mean ± standard deviation, ES: effect size (Cohen's d), * $p < 0.05$ vs. baseline.

## 4. Discussion

The main results of our study indicate that a 6-week HIIT protocol is sufficient to improve HRV and body composition in a previous inactive T1DM population without clinical impairments. Furthermore, our data revealed an increase in $VO_{2max}$ and the long-term reduction in fasting blood glucose.

Noteworthy, only 3 of 198 total trainings resulted in hypoglycemia, and they were mild cases (69.7 ± 2.6 mg/dL), suggesting that HIIT prevents the blood glucose level drop, which is associated with catecholamine releasing and subsequent increase in hepatic glucose production, which offsets the effect of hyperinsulinemia [4,30–32].

### 4.1. $VO_{2max}$

Previous studies have shown the ability of HIIT to improve overall cardiovascular fitness in T1DM individuals [30–32], in line with our results. Nevertheless, there is also a previous study that reports no changes in VO2max in T1DM people after a 12-week HIIT protocol. The methodological differences with those investigations must be taken into account when results are analyzed.

Six weeks of a 1:2 HIIT protocol have increased the $VO_{2max}$ by 8.9% in the present study, which is in line with a previous study reporting a 7% increase [42] after conduction a protocol with a similar time at high intensity. Other studies found a greater improvement in $VO_{2max}$ in T1DM people using HIIT conducted on a cycle ergometer, likely due to the use of higher intensity or volume. For instance, a previous investigation [30] with T1DM (HIIT group: N = 7), using the same 1:1 protocol (e.g., six weeks of three sessions per week increasing from 6 intervals to 10) at 100% $VO_{2max}$ intervals and at 50 W at rest intervals reported a 14% improvement in $VO_{2max}$. Another study with nine sedentary T1DM volunteers [31] found a 19% improvement in VO2max after a 10-week HIIT protocol (3 sessions per week) performing ten 1-min bouts at 90% maximal heart rate (HRmax) interspersed with 1-min active recovery. Another example of greater improvements (18%) due to greater loading is a study [32] where sedentary T1DM people performed an 8-week HIIT protocol. This training method consisted of 20 min at 50% $HR_{peak}$ in weeks 1–2, four 1-min intervals at 80% HRmax interspersed with 5-min active recovery at 50% $HR_{peak}$ in weeks 3–4, and six 1-min intervals at 85% $HR_{peak}$ with the same rest intervals in the last four weeks. In contrast, Lee and her research group showed no improvements in $VO_{2max}$ after a 12-week HIIT protocol, which consisted of 4 bouts of 4 min at 85–95% $HR_{peak}$ interspersed with 3-min recovery intervals at 50–70% $HR_{peak}$ applied in T1DM and overweight people [28], but caution is needed with those results since authors reported inaccuracies that affected to the methodological quality associated with the gas analyzer reliability.

These results have clinical importance given that low $VO_{2max}$ is a strong prognostic marker of cardiovascular disease in healthy [43] and T1DM people [44,45], which is especially important since they are at increased cardiovascular disease risk compared to non-diabetic counterparts [46].

### 4.2. Body Composition

Currently, a paucity of literature remains about the effects of HIIT on body composition of T1DM people. Farinha and coworkers reported a 3.3% increase in FFM, which concur with our results (3.4%). However, in this study, FM did not change, unlike the 6.4% obtained in the present study. Moreover, no changes in FM or lean mass were reported when HIIT was analyzed in obese or overweight T1DM people. These differences between studies may be due to different nutritional habits and baseline body composition levels of the participants. The rest of the investigations, previously mentioned, that analyze the long-term effects of HIIT on T1DM people [30,32,47], did not examine body composition changes. Instead, weight and the body mass index were evaluated, which from our point of view, are not valid variables to ensure the correct body composition measurement [48]. The improvement in body composition in T1DM participants after a HIIT protocol is a relevant finding since overweight and obesity are increasing alarmingly between T1DM patients and their prevention is crucial to reduce the cardiovascular risk in the population with this pathology [49]. However, more studies assessing HIIT on body composition measures are warranted before we can confidently prescribe HIIT as an effective training strategy for the prevention of overweight and obesity.

### 4.3. Heart Rate Variability

To the best of our knowledge, this is the first study to investigate the impact of HIIT on HRV in T1DM people. We found that participants who trained modified their nervous modulation of cardiac tissue by increasing parasympathetic activation through RMSSD (17.2%) and LF/HF ratio (42.3%), which may reduce cardiovascular risk [20,50], while the non-exercise control group remained unchanged. Previous studies have inquired about HIIT effects on HRV, but in people with different pathologies or even healthy individuals and with different methodologies, so comparisons must be taken with caution. Evidence from those studies also suggests tendencies of higher HRV median values of RMSSD (9.6–22%) and lower LF/HF (7.05–30%) [24], in line with our results. It is important to stand out that HIIT protocols used in those investigations ranged from 2 to 24 weeks and were performed in cycle ergometer and treadmill. High-intensity intervals lasted from 8 s to 4 min and rest intervals from 12 s to 4 min, being active and passive. Training intensity was measured by different methods such as % of PPO, $VO_{2max,}$ and $HR_{max}$ and HRV measurement were short- and long-term. Other investigations among sedentary healthy individuals [38] also found a reduction in LF/HF ratio of 8.7%, consistent with our findings, albeit rMSSD did not change, in contrast with our results.

These findings suggest that HIIT, regardless of the protocol type, has beneficial effects on HRV in healthy people and individuals with certain pathologies. Given the congruence with our results in T1DM and the lack of investigations in this cohort, more research is needed to confirm whether HIIT is an effective training strategy to improve HRV in T1DM people to reduce their cardiovascular risk.

### *4.4. Fasting Glucose*

Our results revealed that fasting glucose was reduced by 7.8% in line with previous research with similar characteristics that reported a 7.5% reduction [31]. In the same way, a 11.2% mean glucose reduction was reported by Lee and coworkers, using continuous glucose monitoring during 14 days in overweight and obese volunteers [28]. Investigations that examined glucose behavior after a period of HIIT training, but in Type 2 Diabetes people and subjects with metabolic syndrome, also showed a median reduction in fasting glucose of 16 mg/dL (similar to 11mg/dL reported in the present study) [51]. In those investigations, different HIIT protocols were used, with 2–48 weeks and 3–5 sessions per week of total volume and high-intensity intervals and rest intervals (active and passive) ranging from 8 s to 5 min. Training intensity was always established above 80% of PPO, $HR_{max,}$ or $VO_{2max.}$ Fasting glucose analysis was conducted predominantly by blood biochemistry.

Taking the aforementioned data, we may interpret that our results are consistent with previous investigations that applied an exercise intervention on T1DM people and other related pathologies that courses with impairment of the glycemia regulation (e.g., Type 2 Diabetes and metabolic syndrome). Thus, HIIT could be postulated as an effective training strategy to long-term reduce fasting blood glucose in T1DM people and consequently, reduce the cardiovascular risk in this population [52]. Nevertheless, more investigations are warranted to corroborate this hypothesis.

### *4.5. Limitations*

The results of this study demonstrate cardiovascular risk factors benefits of 6-week HIIT in T1DM subjects. Nevertheless, caution is needed because this study has limitations that must be addressed: the absence of a healthy control group, the relatively small sample size, and the method used for fasting glucose measurement, which was done by the participants in their own home using their own personal glucose analyzer and it was not measured by the researchers or a certified clinical chemistry laboratory under controlled laboratory conditions using a single calibrated glucose analyzer. Moreover, we did not record insulin doses before and after the training period. This would be useful to determine whether insulin sensitivity is modified as reduced insulin exogenous administration is related to a decreased risk of cardiovascular complications in people with T1DM [30,53]. Body composition assessment method (bioimpedance) is a debatable procedure since there is evidence that suggests a decrease in skeletal muscle membrane potential in T1DM people that could disturb the bioimpedance results [54] and other investigations that support its use with this population [55]. Such limitations do not prevent this study from providing novel aspects for the research field and exercise prescription to T1DM.

## 5. Conclusions

In conclusion, a 6-week HIIT protocol 1:2 type, performing high-intensity intervals at 85% PPO and active rest intervals at 40% PPO in a cycle ergometer during 3 sessions per week, apart from being accessible and safe since participants were able to complete all the sessions with the intensity required without suffering any severe undesirable episode of hypoglycemia, was sufficient to improve $VO2_{max}$, HRV, body composition and fasting glucose in a previously sedentary T1DM population. HIIT seems an interesting approach for reducing cardiovascular risk in T1DM individuals.

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# Predictors of Athlete's Performance in Ultra-Endurance Mountain Races

**Pedro Belinchón-deMiguel [1], Pablo Ruisoto [2], Beat Knechtle [3,4], Pantelis T. Nikolaidis [5,6], Beliña Herrera-Tapias [7] and Vicente Javier Clemente-Suárez [8,9,*]**

1 Department of Nursing and Nutrition, Faculty of Biomedical and Health Sciences, Universidad Europea de Madrid, 28670 Villaviciosa de Odón, Spain; pedro.belinchon@universidadeuropea.es
2 Department of Health Sciences, Public University of Navarre, 31006 Pamplona, Spain; pablo.ruisoto@unavarra.es
3 Institute of Primary Care, University of Zurich, 8001 Zurich, Switzerland; beat.knechtle@hispeed.ch
4 Gesundheitszentrum St. Gallen, 9001 St. Gallen, Switzerland
5 School of Health and Caring Sciences, University of West Attica, 12243 Egaleo, Greece; pademil@hotmail.com
6 Exercise Physiology Laboratory, 18450 Nikaia, Greece
7 Grupo de Investigación en Derecho, Política y Sociedad, Universidad de la Costa, 080002 Barranquilla, Colombia; bherrera3@cuc.edu.co
8 Faculty of Sports Sciences, Universidad Europea de Madrid, 28670 Villaviciosa de Odón, Spain
9 Grupo de Investigación en Cultura, Educación y Sociedad, Universidad de la Costa, 080002 Barranquilla, Colombia
* Correspondence: vctxente@yahoo.es

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**Abstract:** Background: In previous studies, ultra-endurance performance has been associated with training and psychological variables. However, performance under extreme conditions is understudied, mainly due to difficulties in making field measures. Aim: The aim of this study was to analyze the role of training, hydration, nutrition, oral health status, and stress-related psychological factors in athletes' performance in ultra-endurance mountain events. Methods: We analyzed the variables of race time and training, hydration state, nutrition, oral health status, and stress-related psychological factors in 448 ultra-endurance mountain race finishers divided into three groups according to race length (less than 45 km, 45–90 km, and greater than 90 km), using a questionnaire. Results: Higher performance in ultra-endurance mountain races was associated with better oral health status and higher accumulative altitude covered per week as well as higher positive accumulative change of altitude per week during training. In longer distance races, experience, a larger volume of training, and better hydration/nutrition prior to the competition were associated with better performance. Conclusions: Ultra-endurance mountain athletes competing in longer races (>90 km) have more experience and follow harder training schedules compared with athletes competing in shorter distances. In longer races, a larger fluid intake before the competition was the single best predictor of performance. For races between 45 and 90 km, training intensity and volume were key predictors of performance, and for races below 45 km, oral health status was a key predictor of performance. Psychological factors previously reported as ultra-endurance mountain race performance predictors were inconsistent or failed to predict the performance of athletes in the present research.

**Keywords:** psychology; odontology; nutrition; training; stress; running

## 1. Introduction

Participation in ultra-endurance mountain events has shown an exponential increase in recent years [1]. Specific research in this extreme endurance event has shown an increase in protein catabolism and muscle degradation [2,3], an increased erythropoiesis to compensate exercise-induced hemolysis [4], an accumulation of blood lactate below the anaerobic threshold [5], and an increase in the consumption of fat [6].

Ultra-endurance mountain events are highly stressful, usually performed at 71% of maximum heart rate (HR) [7] and characterized by an intense sympathetic modulation evaluated on the basis of heart rate variability (HRV) [8]. Regarding the training programs, the literature has highlighted the importance of training schedule (speed and volume), the speed in half-marathon and marathon to attain 'top' performance in ultra-endurance races [9].

A higher performance in ultra-endurance events has been associated with two physiological factors, i.e., low body fat index [10,11] and an appropriate hydration and nutritional status [8,11,12]. In this respect, it was found that successful ultra-endurance mountain athletes drank enough to maintain an optimal performance during the race [12]. In addition, an appropriate fuel support is essential for performance, since an extreme negative energy balance was reported in previous ultra-endurance mountain events [8]. However, nutritional and fluid intake during ultra-endurance events presents a risk for oral health. In fact, the absence of oral health care and the presence of caries, dental erosion, and periodontal disease [13–16] are directly related to the extensive use of sports drinks, gels, and energy bars [17,18]. In this line, the negative effect of acid and high-carbohydrate foods aggravated by a decreased saliva flow rate during intense exercise [19,20] can negatively affect health and performance in ultra-endurance mountain athletes.

Previous literature on athletes' performance in these events has also focused on the analysis of ergogenic aids, showing the extensive consumption of nonsteroidal anti-inflammatory drugs (NSAIDs) or central nervous system activators such as caffeine [1,21]. In addition, different psychological factors such as higher pain tolerance [22,23] or better stress management skills [24,25] have also been associated with better performance.

The role of multifactorial parameters in ultra-endurance mountain performance is still poorly known or understood. For this reason, we conducted the present research with the aim to analyze the role of training schedule, hydration, nutrition, oral health status, and stress-related psychological factors in athletes' performance in ultra-endurance mountain events. The initial hypothesis was that successful athletes would present a different training schedule, hydration, nutrition, oral health, and stress-related psychological profile compared with non-successful athletes.

## 2. Materials and Methods

### 2.1. Participants

A total of 448 ultra-endurance mountain race finishers were analyzed. According to the three types of ultra-endurance mountain races, based on race length, that athletes can perform, they were divided into three groups: G1, athletes involved in ultra-endurance mountain races below 45 km ($n$ = 234; 37.97 ± 7.31 years; 1.7315 ± 0.1341 m; 71.40 ± 10.38 kg); G2, athletes involved in ultra-endurance mountain races between 45 and 90 km ($n$ = 79; 39.26 ± 6.92 years; 1.7535 ± 0.0731 m; 73.86 ± 10.61 kg); and G3, athletes involved in ultra-endurance mountain races longer than 90 km ($n$ = 135; 41.09 ± 7.26 years; 1.7557 ± 0.0713 m; 71.45 ± 8.01 kg). The three groups did not differ in age, body mass index, or total years of experience as ultra-endurance athletes. The average rate of successful (finisher) and non-successful (non-finisher) athletes in G1 was 74%, in G2 61%, and in G3 40%. Participants were recruited when they presented the documentation attesting their participation in the races. The inclusion criterion was that they were official participants in the races, and the exclusion criterion was that participants reported a medical condition or were taking medication. We obtained written consent from each participant in accordance with the Declaration of Helsinki, and the study was approved by the University Bioethics Committee (CIPI/002/17).

Athletes participated in the following races: Valls d'Aneu Ultratrail, 92 km-long and with 7344 m of accumulated positive altitude change, Emmona Ultratrail, 130 km-long and with 10,194 m of accumulated positive altitude change, Canfranc-Canfranc Ultra-endurance Mountain Race, 100 km-long and with 8848 m of accumulated positive altitude change, Great Trail of Peñalara, 114 km-long and with 5100 m of positive altitude change, Gruseg Trail, 51 km-long and with 2516 m of accumulated positive altitude change, and Extremadura Mountain Federation Circuit, including races from 6 km to 72 km and positive altitude changes from 910 m to 6133 m.

### 2.2. Design and Procedure

Data in the following self-reported variables were collected for all participants 24 h before the races at the race place. The questionnaire took about 10 min to complete. All participants in the races were invited to answer the questionnaire, and only those who accepted were registered. After the races, the race time was also recorded, as reported in the official classification of each race.

#### 2.2.1. Training, Hydration, and Nutrition Variables

We analyzed variables related to athletes' experience in mountain races (years), total race time in the last marathon (min) and half-marathon (min), training schedule (volume, intensity, and accumulative altitude change), expected race time (min), difference between expected and real time (min), stretching time per week (min), and stretching sessions' duration per week.

Regarding nutrition and hydration habits before the competitions, the following parameters were evaluated: intake of carbohydrate-based meals during the week of competition and fluid intake before the competition day (l). Finally, regarding the oral health status, the frequency of the following occurrences was recorded: grinding or clenching teeth while performing usual tasks, nibbling objects, biting nails, consuming vitamin C pills, having a wet pillow upon awakening, and burping repeatedly.

#### 2.2.2. Psychological Variables

We analyzed perceived stress, measured by the Perceived Stress Scale (PSS-14) [26], and general mental health status, measured by the Acceptance and Action Questionnaire, (AAQ-II) [27].

#### 2.2.3. Performance Race Variables

We analyzed the variables of total time in ultra-endurance mountain races (min), total distance (km), average running speed (km/h), accumulated positive and negative altitude (m), difficulty coefficient (total km × accumulated positive altitude change/1000), and the speed/difficulty coefficient ratio.

### 2.3. Statistical Analysis

Data were analyzed using the Statistical Package for the Social Sciences (SPSS) version 21 (SPSS Inc., Chicago, IL, USA). Kolmogorov–Smirnov tests were performed to test normality and homogeneity of each variable. A MANOVA was conducted to analyze differences between the three groups (G1, G2, G3) regarding the dependent variables previously described. Tukey tests were conducted for post hoc comparisons. In addition, the athletes in each group were divided in higher- and lower-performance subgroups by percentile 50 according to their race time, to analyze differences between performances in the variables analyzed. For this, an independent *t* test was used. The significance level was set at $p < 0.05$ in all analysis.

## 3. Results

No significant differences were found in any variable between G1 and G2 (Table 1). However, ultra-endurance mountain athletes in G3 recorded more experience, training sessions, hours per week, minutes per session, accumulated positive altitude per session and per week, compared with G1 and G2 athletes. No differences were found in psychological variables between the groups.

**Table 1.** Training and psychological variables in G1–G3 athletes.

| Variables | Group 1 (M ± SD) | Group 2 (M ± SD) | Group 3 (M ± SD) | F | *p* | Intergroup Comparisons |
|---|---|---|---|---|---|---|
| | *n* = 234 | *n* = 79 | *n* = 135 | | | |
| Training-related variables | | | | | | |
| Years of mountain race practice | 3.0 ± 2.7 | 3.3 ± 2.7 | 6.7 ± 4.0 | 8.963 | 0.000 | 1 = 2 < 3 |
| Training per week (h) | 6.5 ± 5.0 | 7.3 ± 3.2 | 10.7 ± 4.7 | 3.646 | 0.030 | 1 = 2 < 3 |
| Training per session (min) | 79.7 ± 42.8 | 77.4 ± 28.7 | 102.5 ± 48.7 | 5.337 | 0.006 | 1 = 2 < 3 |
| Training sessions per week | 4.1 ± 1.2 | 4.5 ± 1.2 | 5.0 ± 1. | 7.504 | 0.001 | 1 = 2 < 3 |
| Accumulated positive altitude difference (m) per session | 542.1 ± 598.9 | 713.9 ± 908.7 | 1878.1 ± 1321.1 | 11.191 | 0.000 | 1 < 2 < 3 |
| Accumulated positive altitude difference (m) per week | 1347.7 ± 2286.7 | 1497.7 ± 1845.5 | 3525.9 ± 2747.8 | 7.773 | 0.001 | 1 = 2 < 3 |
| Marathon best mark (min) | 190.7 ± 67.3 | 220.1 ± 57.9 | 232.9 ± 70.9 | 4.830 | 0.010 | 1 < 2; 1 < 3 |
| Half-marathon time (min) | 98.5 ± 18.3 | 101.8 ± 38.5 | 94.2 ± 19.6 | 0.770 | 0.466 | 1 = 2 > 3 |
| Expected time (min) | 158.6 ± 91.2 | 538.0 ± 160.6 | 1399.4 ± 272.9 | 426.335 | 0.000 | 1 < 2; 1 < 3; 2 < 3 |
| Difference between expected and real time (min) | 0.99 ± 33.1 | 45.0 ± 58.5 | 112.2 ± 147.9 | 15.583 | 0.000 | 1 < 3; 2 < 3 |
| Psychological variables | | | | | | |
| Perceived stress (PPS-14) | 17.1 ± 7.0 | 14.7 ± 6.8 | 17.3 ± 6.8 | 0.235 | 0.791 | n.s. |
| General mental health (AAQ-II score) | 14.0 ± 6.4 | 12.8 ± 6.1 | 14.0 ± 6.4 | 0.543 | 0.583 | n.s. |

Note: Group 1, race length < 45 km; Group 2, race length between 45 km and 90 km; Group 3, race length > 90 km.

Table 2 shows differences in performance predictors for athletes competing in the three ultra-endurance mountain race distances. For G1, better performance was associated with higher speed training per week, but not with differences in psychological or nutritional/hydration status. For G2, higher performance was associated with higher training speed per week and more training sessions per week, but no differences were found for the other variables. For G3, higher performance was associated with higher intake of fluids before the competition, with no differences for the training and psychological variables.

**Table 2.** Predictors of performance for athletes competing in ultra-endurance mountain races, based on race distance.

| Variables | Performance Group | Group 1 (M ± SD) | *p* | Group 2 (M ± SD) | *p* | Group 3 (M ± SD) | *p* |
|---|---|---|---|---|---|---|---|
| Training variables | | | | | | | |
| Expected race time (min) | Higher<br>Lower | 121 ± 37.6<br>194.4 ± 98.1 | 0.000 | 439.8 ± 61.0<br>590.3 ± 151.1 | 0.000 | 1219.3 ± 181.9<br>1550.3 ± 203.3 | 0.000 |
| Difference between expected and real time (min) | Higher<br>lower | −0.39 ± 16.9<br>4.7 ± 39.1 | 0.276 | 33.4 ± 52.2<br>56.5 ± 63.1 | 0.142 | 52.6 ± 103.9<br>169.1 ± 161.8 | 0.000 |
| Marathon best mark (min) | Higher<br>lower | 183.2 ± 56.6<br>195.2 ± 76.2 | 0.491 | 194.7 ± 55.6<br>246.2 ± 59.7 | 0.008 | 224.1 ± 64.8<br>232.4 ± 64.2 | 0.604 |
| Half-marathon time (min) | Higher<br>lower | 93.3 ± 10.8<br>102 ± 18 | 0.001 | 91.2 ± 8.2<br>106.3 ± 31.3 | 0.019 | 90.5 ± 9.8<br>94.8 ± 20.2 | 0.268 |
| Training per week (h) | Higher<br>Lower | 7.3 ± 7.6<br>6 ± 2.3 | 0.145 | 8.9 ± 3.7<br>6.2 ± 2.2 | 0.001 | 10.6 ± 5.1<br>10.4 ± 3.9 | 0.853 |
| Training per session (min) | Higher<br>Lower | 84.5 ± 60.9<br>78.2 ± 27.4 | 0.363 | 80.5 ± 35.4<br>76.6 ± 22.9 | 0.615 | 102.8 ± 50.0<br>106.1 ± 49.7 | 0.771 |
| Sessions per week | Higher<br>Lower | 4.1 ± 1.1<br>4.0 ± 1.1 | 0.601 | 5.2 ± 1.5<br>4.1 ± 0.9 | 0.001 | 4.8 ± 1.5<br>4.9 ± 1.2 | 0.658 |
| Average speed training per week | Higher<br>Lower | 10.3 ± 2.8<br>9.3 ± 2.8 | 0.028 | 10.4 ± 3.1<br>8.3 ± 2.9 | 0.011 | 10.2 ± 2.7<br>9.6 ± 2.2 | 0.269 |
| Positive change of altitude accumulated per training session (m) | Higher<br>Lower | 493.7 ± 523.6<br>561 ± 588.5 | 0.500 | 822.3 ± 1345.6<br>543.4 ± 525.5 | 0.364 | 1945.5 ± 1524.8<br>1793.0 ± 1138.0 | 0.627 |

**Table 2.** *Cont.*

| Variables | Performance Group | Group 1 (M ± SD) | *p* | Group 2 (M ± SD) | *p* | Group 3 (M ± SD) | *p* |
|---|---|---|---|---|---|---|---|
| Positive change of altitude accumulated per week (m) | Higher | 1701.8 ± 3644.3 | | 1934.1 ± 2843.5 | | 3595.3 ± 3214.8 | |
| | Lower | 1259.1 ± 1174.8 | 0.351 | 1200.0 ± 1220.6 | 0.274 | 3434.6 ± 2233.9 | 0.805 |
| Stretching per week (min) | Higher | 10.5 ± 5.8 | | 12.7 ± 11.0 | | 11.6 ± 11.0 | |
| | Lower | 11.4 ± 8.4 | 0.411 | 12.0 ± 5.4 | 0.764 | 13.7 ± 11.5 | 0.392 |
| Stretching sessions per week | Higher | 4.1 ± 1.6 | | 4.5 ± 1.8 | | 3.6 ± 2.2 | |
| | Lower | 3.8 ± 1.7 | 0.249 | 3.7 ± 1.8 | 0.081 | 3.4 ± 2.0 | 0.786 |
| Nutrition/hydration-related variables | | | | | | | |
| Carbohydrate meals during the week of competition | Higher | 4.8 ± 2.2 | | 6.2 ± 3.1 | | 6.3 ± 2.9 | |
| | Lower | 5 ± 2.2 | 0.620 | 5.4 ± 2.6 | 0.320 | 6.5 ± 2.8 | 0.789 |
| Fluid intake before competition day (l) | Higher | 2.5 ± 1.5 | | 2.6 ± 1.0 | | 2.8 ± 1.4 | |
| | Lower | 2.5 ± 1.3 | 0.887 | 2.5 ± 1.4 | 0.733 | 2.2 ± 0.9 | 0.033 |
| Psychological variables | | | | | | | |
| Perceived stress (PPS) | Higher | 16.2 ± 6.7 | | 14.2 ± 5.9 | | 16.7 ± 6.6 | |
| | Lower | 17.1 ± 6.9 | 0.345 | 14.5 ± 7.0 | 0.819 | 17.5 ± 5.6 | 0.531 |
| General mental health (AAQII) | Higher | 13 ± 5.9 | | 13.0 ± 7.0 | | 14.9 ± 7.0 | |
| | Lower | 14.9 ± 6.7 | 0.055 | 12.5 ± 5.8 | 0.792 | 14.0 ± 5.3 | 0.498 |
| Oral health status | | | | | | | |
| Grinding or clenching your teeth while performing your usual tasks | Higher | 0.06 ± 0.2 | | 0.1 ± 0.3 | | 0.1 ± 0.3 | |
| | Lower | 0.2 ± 0.4 | 0.004 | 0.06 ± 0.2 | 0.331 | 0.1 ± 0.3 | 0.967 |
| Nibbling objects | Higher | 0.09 ± 0.2 | | 0.1 ± 0.3 | | 0.2 ± 0.4 | |
| | Lower | 0.2 ± 0.4 | 0.036 | 0.06 ± 0.2 | 0.184 | 0.3 ± 0.4 | 0.235 |
| Biting nails | Higher | 0.1 ± 0.3 | | 0.3 ± 0.4 | | 0.3 ± 0.4 | |
| | Lower | 0.3 ± 0.4 | 0.016 | 0.3 ± 0.4 | 0.792 | 0.4 ± 0.5 | 0.214 |
| Vitamin C pills | Higher | 0.01 ± 0.1 | | 0 ± 0 | | 0.1 ± 0.3 | |
| | Lower | 0.08 ± 0.2 | 0.031 | 0.03 ± 0.1 | 0.338 | 0.1 ± 0.3 | 0.967 |
| Wet pillow upon awakening | Higher | 0.09 ± 0.2 | | 0.1 ± 0.3 | | 0.2 ± 0.4 | |
| | Lower | 0.2 ± 0.4 | 0.027 | 0.09 ± 0.3 | 0.933 | 0.1 ± 0.3 | 0.529 |
| Repeated burps | Higher | 0.08 ± 0.2 | | 0.03 ± 0.1 | | 0.1 ± 0.3 | |
| | Lower | 0.1 ± 0.3 | 0.584 | 0.06 ± 0.2 | 0.620 | 0.02 ± 0.1 | 0.045 |

Note: Group 1, race length < 45 km; Group 2, race length between 45 km and 90 km; Group 3, race length > 90 km.

## 4. Discussion

The aim of the present study was to analyze the role of training, hydration, nutrition, oral health status, and stress-related psychological factors in athletes' performance in ultra-endurance mountain events. The initial hypothesis was partially confirmed, since differences in training, hydration, nutrition, and oral heath parameters were found for athletes depending on their performance and competition distance, but no differences appeared in stress-related psychological factors.

Previous research found that half-marathon and marathon race times predicted race performance in ultra-endurance mountain races [9]. In the current research, we found that G1 athletes and G2 athletes with a better performance had significantly faster marathon times. Better performance in mountain races was associated with faster half-marathon times, which is in line with previous research [9,28]. Higher performance in ultra-endurance mountain races for distances below 90 km was directly linked to three training-related variables, i.e., training intensity and higher speed in shorter races, as previously reported in the literature [29,30]; training volume and density (sessions per week), since a large training volume may be necessary to obtain physiological adaptations in aerobic and anaerobic threshold intensities—which are the intensity zones involved in ultra-endurance race performance [31]—in line with previous research in ultra-endurance mountain events [1,29], though recent studies propose that ultra-endurance runners would benefit from incorporating high-intensity interval training in a low-volume training program [32–35]; higher positive change of altitude accumulated per week. Previous studies have suggested that the mechanical work performed on a positive slope may improve musculature, joint resistance, the resistance of ligamentous and tendinous tissues, and the effort tolerance of the locomotor system, which are critical for successful adaptation to the long-term efforts involved in ultra-endurance mountain events [36,37]. Therefore, it would be recommended to introduce more strength training sessions performed with a higher load in future training interventions for ultra-endurance mountain athletes [38].

Higher performance in ultra-endurance mountain races for distances over 90 km was linked to two main variables. Firstly, a higher fluid intake before the race, a result that highlights the importance of hydration in these races, consistent with previous studies that showed that the hydration status has a positive effect on thermoregulation and muscular function, factors crucial in extreme sport competitions [39]. It is important to note that a large fluid ingestion during ultra-endurance races could have a negative effect on performance, since inappropriate hydration can lead to hyper-hydration, and consequently to hyponatremia because of electrolyte imbalance, producing alterations in athletes' cardiovascular response and performance, or to dehydration which also compromises the athletes' health and performance. Secondly, the influence on performance of a larger experience in ultra-endurance mountain races is a factor that has been identified in earlier studies [1]. Interestingly, athletes with higher experience reported a more accurate self-perception of their performance, which indicates that athletes with a lower performance have a poorer knowledge of their own capacities [40].

Regarding the role of psychological variables in predicting athlete's performance, no differences between groups or performance based on perceived stress or general mental health were observed. One possible explanation is that most participants reported very low psychological stress levels and good general mental health, on the basis of the evaluation scale established for the general population (M = 18.51, SD = 7.05) [41]. Therefore, the collected data may have failed to detect effects because of the lack of variability of our sample, which is not representative of the general population. In addition, in the case of ultra-endurance mountain races below 45 km, better oral health parameters were associated with higher performance. This result is in line with previous research conducted in elite athletes [14,16], highlighting the importance of an optimal oral health status for correct physiological functioning, especially in individuals participating in these extreme races.

A limitation of the present study is that we analyzed distances of <45, 45–90, and >90 km; thus, the findings should be generalized with caution to athletes competing in longer distances. Another limitation is the use of a self-reported questionnaire. On the other hand, a strength of this study is that it analyzed a relatively large sample and examined the role of many performance predictors such as training, hydration, nutrition, oral health, and stress-related psychological factors. These findings are expected to have large practical applications for practitioners working with ultra-endurance runners, considering the increased number of annual ultra-endurance races and participants in these races [42].

Finally, we propose that more research should be conducted on the relationship between oral health and performance in athletes competing in ultra-endurance races, as well as on other factors such as type of diet, specific strength and mountain training programs, and mental strategies that could be adopted by high-performance runners, specifically during longer races.

## 5. Conclusions

Ultra-endurance mountain athletes competing in longer races (>90 km) have more experience and follow harder training schedules than shorter-distance athletes. In longer races, a larger fluid intake before the competition was the single best predictor of performance. For races between 45 and 90 km, training intensity and volume were key predictors of performance, and for races below 45 km, oral health status was a key predictor of performance. Psychological factors, previously reported as good predictors of ultra-endurance mountain race performance, had little influence in the present study.

**Author Contributions:** P.B.-d.M. and V.J.C.-S. did the data collection. P.B.-d.M. and V.J.C.-S. analyzed the data. P.B.-d.M., P.R., B.K., P.T.N., B.H.-T., and V.J.C.-S. wrote the paper. All authors have read and agreed to the published version of the manuscript.

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# Acute Effects of Different Postactivation Potentiation Protocols on Traditional Rowing Performance

**Alfonso Penichet-Tomas , Jose M. Jimenez-Olmedo *, Luis Serra Torregrosa and Basilio Pueo**

Department of General and Specific Didactics, University of Alicante, 03690 Alicante, Spain; alfonso.penichet@ua.es (A.P.-T.); lst15@gcloud.ua.es (L.S.T.); basilio@ua.es (B.P.)
* Correspondence: j.olmedo@ua.es

**Abstract:** Postactivation potentiation (PAP) describes an initial muscular activation with a submaximal or maximal load intensity that produces acute improvements in muscle power and performance in subsequent explosive activities. The objective of this study was to compare the effect of different PAP protocols in rowing performance. A crossover design involving seven rowers was used, in which two different PAP protocols were applied: PAP of maximal conditioning contractions (PAP MCC) on a rowing ergometer to provide greater transferability and, thus, enhance the magnitude of PAP stimuli on subsequent rowing performance; and PAP of maximal strength contractions (PAP MSC) in half squat and bench pull exercises, similar to the main exercises in rowing strength training, to perform a 20 s "all-out" test simulating a competition start. Student's *t*-test was used to compare means of the variables ($p < 0.05$). Effect size statistics were calculated using Cohen's *d*. The PAP MCC protocol resulted in significant differences, with an extremely large effect size in average power output ($p = 0.034$, $d = 0.98$) in the first 3 ($p = 0.019$, $d = 1.15$) and first 5 ($p = 0.036$, $d = 0.91$) strokes. This group also reached a greater number of strokes ($p = 0.049$, $d = 2.29$) and strokes per minute ($p = 0.046$, $d = 1.15$). PAP with maximal conditioning contractions in rowing warm-up enhanced subsequent rowing sprint and is an advisable strategy to potentiate performance at the start of rowing competitions and sprint regattas.

**Keywords:** sprint; postactivation potentiation; fixed seat rowing; performance

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## 1. Introduction

Postactivation potentiation (PAP) describes an initial muscular activation with a submaximal or maximal load intensity that produces acute improvements in muscle power and performance in subsequent explosive activities [1]. This procedure involves concentric contractions of submaximal dynamic force close to a high percentage of maximal repetition (1RM) before the execution of an explosive movement with similar movement patterns. However, if the load induced by the PAP is poorly planned in relation to the volume or intensity of work, it can cause fatigue. Therefore, the balance between PAP and fatigue is vital because of its role in the magnitude of improvement in mechanical power [2]. Determination of the characteristics in relation to the components of the load (volume, intensity, density, and type of exercise) are key to the subsequent performance induced by the PAP [3].

The optimal intensity of the conditioning activities for competitive athletes varies between 75% and 90% of 1RM, and recovery time should be individualized because athletes differ in strength level, training experience, and muscle fiber structure, with the optimal recovery time being 6 min [4]. Stronger recreational level athletes would experience greater benefit with shorter breaks (5–10 min) than weaker athletes, who would need more time (15–20 min) [5]. Results of this study suggest that the principle of individualization is key to determining the rest time necessary for optimal activation performance following PAP protocols. Seitz et al. [6] observed increased force production with activation time after PAP in elite athletes. Coaches must consider individual differences in the strength level(s) of athletes to adapt protocols and maximize performance effects. Esformes et al. [7] related the difference in muscle fiber activation according to the type of contraction with rest time after PAP. They concluded that it could positively influence power performance; however, in relation to the level of activation and type of contraction, there were only significant differences in isometric contractions with a long rest period (12 min), producing positive results for peak power output, peak force, maximum distance and rate of force development, and inducing a longer PAP period. On the other hand, the application of a previous PAP methodology involving maximal dynamic force with submaximal loads close to 1RM in half squat exercises can be very useful for improving performance in the ability to repeat high-intensity sprints [8]. Furthermore, PAP would be beneficial in events where the contribution of the aerobic energy system may be of high importance toward successful performance; however, research in this area is quite limited. Silva et al. [9] found that heavy strength exercise bouts improve 20 km cycling time trial performance with no alteration in pacing strategy. In rowing, PAP could improve the efficiency of the working muscles by increasing force production of muscle fibers if a specific pace is to be maintained [10].

Strength training in elite rowers represents 10–20% of the total training time. During the competitive season, rowers perform strength training with a load of between 85% and 95% of 1RM [11]. There is a strong relationship between a high manifestation of strength and greater performance [12]. Doma et al. [2] demonstrated that maximal dynamic contractions on a rowing machine increased power performance during the execution of a short sprint (10 s). In addition, the average power during a 20 s maximal effort test is an effective predictor of 2000 m Olympic rowing performance [13]. Nevertheless, traditional rowing is characterized, and differs from Olympic rowing, in technical execution because the rower is supported by a fixed seat in the coccyx area [14]. This implies that the degree of trunk amplitude both in the attack and final phases is greater than in Olympic rowing. Studies on traditional rowing have evaluated physiological factors as predictors of performance [15] as well as specific protocols for improving sports performance [16]. On the other hand, assessment and analysis strategies derived from Olympic rowing have been developed [17] to be able to adapt to the needs of traditional rowing [18], leading to comparative studies between both disciplines [19]. The scientific literature also includes studies in the area of traditional rowing on specific and conditional physiological requirements, quantifying the workload in official competition [20]. Accordingly, there are studies on the relationship between the characteristics of rowers and their sports performance [21], sports practice habits and quantification of training hours [22], as well as profile analysis of rowers using traditional rowing modalities based on the competitive level [14].

The PAP is considered to be an adequate specific warm-up by coaches in both day-to-day training or competition, and current scientific evidence shows that there is a positive effect on performance when using PAP in short sprint efforts [1]. In addition, the greatest response is manifested in experienced subjects in high-intensity training [23]. However, there is no current scientific evidence supporting intervention studies that have proposed the comparison of the effects of different PAP types on rowing sprint performance, a sport in which physical and physiological factors, such as aerobic and anaerobic power, influence as well as a high level of physical strength [24]. In addition, no study has analyzed the influence of PAP using a traditional rowing modality. Therefore, the objective of this study was to analyze and compare the acute effect of two different postactivation potentiation protocols in traditional rowing performance at the start of competition. The strength contraction with maximum loads in strength exercises of the main muscle groups in the rowing gesture are an effective PAP method for rowing performance. However, maximum effort power conditioning contractions will better prepare the rower as this PAP method increases neuromuscular performance and has a greater dynamic transfer because it involves a biomechanically similar exercise, and rowers perform more effective neural patterns enhancing a more specific gesture.

## 2. Materials and Methods

### *2.1. Experimental Design*

A crossover design was used to compare the effect of both PAP protocols: PAP of maximal conditioning contractions (PAP MCC) and PAP of maximal strength contractions (PAP MSC). In this repeated measurement design, each participant performed the different protocols during different time periods (i.e., the participants crossed over from one protocol to another during the research process). The reason a crossover design was considered was that it could yield a more efficient comparison of treatments than a parallel design (i.e., fewer participants might be required in the crossover design to attain the same level of statistical power or precision as a parallel design). Hence, each participant served as his own matched control and performed both protocols: PAP MCC and PAP MSC [25]. Participants were tested three times in three consecutive weeks on the same day of the week at the same time. The first session was oriented to familiarize the athletes with the techniques and methods, and the next weeks' session addressed the 2 PAP protocols (Figure 1). The protocols were assessed in randomized order with a one-week interval in between.

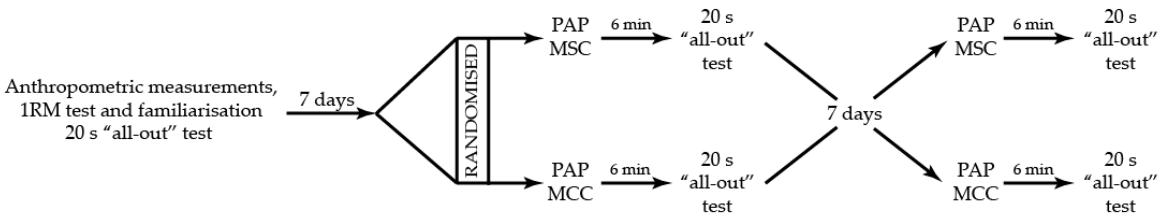



**Figure 1.** Schematic representation of the study design.

### *2.2. Participants*

Seven male rowers, competing at the national level, participated in the study. Inclusion criteria for the present study consisted of a minimum previous experience of 2 consecutive full years in traditional rowing, with a minimum of 10 months per year and an average of 12 h per week [17]. Rowers who did not meet the selection criteria were excluded from the study. Table 1 summarizes the anthropometric characteristics of the sample.

**Table 1.** Anthropometric characteristics.

| | Mean ± SD | 95% CI |
|---|---|---|
| Body height (cm) | 181.6 ± 5.8 | 178.1–185.0 |
| Body mass (kg) | 76.1 ± 4.4 | 73.5–78.7 |
| BMI (kg/m$^2$) | 23.1 ± 1.4 | 22.3–23.9 |
| Fat mass (%) | 10.5 ± 2.0 | 9.3–11.5 |
| Muscle mass (%) | 46.5 ± 2.0 | 45.3–47.7 |

BMI: body mass index; SD: standard deviation; CI: confidence interval.

The Ethics Committee at the University of Alicante gave institutional approval for this study, in accordance with the Declaration of Helsinki (IRB UA-2020-07-21). The subjects were informed about the study and gave their written informed consent. They were notified of the need for their commitment to the following requirements on the day of data collection and the previous day: not to perform high-intensity physical activity in the previous 24 h; not to consume any type of stimulant at least 5 h before testing; and not to eat any solid food at least 3 h before testing.

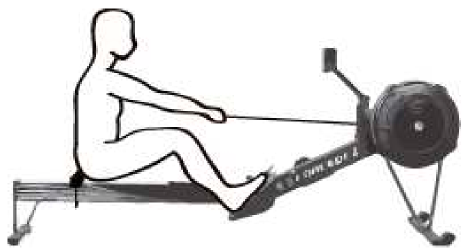
### *2.3. Procedures*

Data collection was performed for 3 weeks on the same day of the week at the same time each week. The first week was used to perform the test of maximal repetition

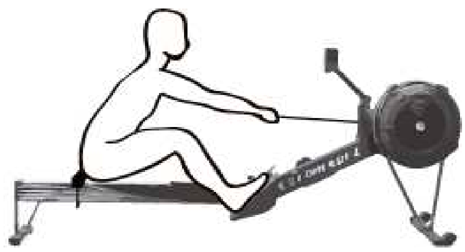
(1RM) in half squat and bench pull [26], to perform anthropometric measurements, and to familiarize the athletes with the 20 s "all-out" test. Anthropometric measurements were performed in basal conditions following standard protocols from the International Society for the Advancement of Kinanthropometry (ISAK) [27] using the following instruments: a TanitaBC-545N balance for body mass (0.1 kg) (Tanita Co., Tokyo, Japan) [28] and an astra stadiometer with a mechanical scale to measure height (0.1 cm). Body mass index (BMI) was computed as body mass (kg) divided by height squared ($m^2$) [29]. Skinfolds (sub-scapular, tricipital, bicipital, iliac crest, supra-spinal, abdominal, anterior thigh, and middle leg) were measured using a caliper calibrated to the nearest 0.2 mm (Holtain Ltd., Crymych, UK). Girth (relaxed arm, flexed arm, thigh, and calf) and breadth (humerus, stylion, and femur) measurements were performed using a flexible anthropometric steel tape to the nearest 0.1 cm (Holtain Ltd., Crymych, UK). Finally, body composition was calculated using the equations described by Withers, Craig, Bourdon, and Norton [30] for fat mass and the equation proposed by Lee et al. [31] for muscle mass.

After warm-up, the 1RM test consisted of two sets of 5 and 3 repetitions at approximately 50% and 70% 1RM, respectively. The subjects then had up to 5 attempts to obtain their 1RM [8]. A 3–5 min rest interval was adopted between trials. Each attempt consisted of 1 series of 1 repetition. If the attempt was successful, between 5% and 10% of the weight was added for the next attempt. When the subject could not perform the execution properly, until the subject was unable to lift the load, his previous attempt was his 1RM.

After performing the 1RM tests, the familiarization test was performed for proper technical execution of the 20 s "all-out" test. The subjects performed three sets of 20 s at maximal with a rest interval of 6 min to simulate the intensity on test days. The test simulated a start; as such, in the first 3 strokes, the shoulders started from a vertical position of the body (Figure 2). After the first 3 strokes, the objective would be to achieve the maximal possible power in 20 s with a correct wide stroke and with a maximal ratio of strokes per minute.



(**a**)



(**b**)

| | **Mean ± SD** | **95% CI** |
|---|---|---|
| Body height (cm) | 181.6 ± 5.8 | 178.1–185.0 |
| Body mass (kg) | 76.1 ± 4.4 | 73.5–78.7 |
| BMI (kg/$m^2$) | 23.1 ± 1.4 | 22.3–23.9 |
| Fat mass (%) | 10.5 ± 2.0 | 9.3–11.5 |
| Muscle mass (%) | 46.5 ± 2.0 | 45.3–47.7 |

**Figure 2.** Differences in technique for (**a**) the first 3 strokes and (**b**) after the first 3 strokes.

During the second week, data were collected according to the crossover design in which the subjects were distributed in two groups: one performed the PAP MCC protocol and the other performed the PAP MSC protocol. In the third week, the groups rotated to perform the protocol they did not perform the week before. First, both groups performed 5 min of warm-up on the rowing machine (Concept 2 Model D, USA, Vermont) [11] with a coupling adapted for the reproduction of the traditional rowing stroke, programmed with a drag factor of 160, a given power (up to a maximal of 140 W or 2:15 / 500 m), and at a heart rate (HR) not exceeding 140 beats/min [17].

After the warm-up, each group performed a different method of PAP in each session before the 20 s "all-out" test, with a 6 min rest before and after the PAP protocol. The PAP MCC protocol consisted of performing a series of 20 s at maximal effort on the rowing machine before performing the 20 s "all-out" test. In Doma et al. [2], a 10 s maximal dynamic conditioning contraction protocol was executed on a rowing ergometer at maximal effort, followed by a 10 s "all-out" test. In the present study, the 20 s "all-out" sprint test was performed because it covered the 10 s time span and could yield additional information. In addition, a 20 s "all-out" test can be an effective predictor of the performance in a 2000 m test [13]. The rest interval between the PAP and the post-test was 6 min [32].

The athletes performed the PAP MSC protocol in the two exercises performed in the 1RM test, with a protocol of 4 series of submaximal approach (1 × 5 with the bar/2 min, 1 × 2 50% RM/4 min, and 1 × 1 85% RM) and 1 set of 3 repetitions at 90% of 1RM [33]. The rest interval prior to the 20 s "all-out" test was also 6 min [32]. The intensity of the exercise that elicits the greatest PAP effect should be individualized (60–100% 1RM) because it is dependent on the level of maximal strength [34]. The 20 s "all-out" test was performed on a rowing machine (Concept 2 Model D, Morrisville, VT, USA) [11] with a coupling adapted for traditional rowing fixing the seat. The measurement of performance variables was achieved using the Erg Data mobile device application in sync with the PM5 performance monitor of the rowing machine via Bluetooth Smart. Heart rate parameters were measured with the Polar M400 (Polar Inc., Kempele, Finland) with H7 Bluetooth® Smart Band [8].

### 2.4. Statistical Analysis

Results were analyzed using Statistical Package for Social Sciences (SPSS v.26 for Windows, SPSS Inc., Chicago, IL, USA), and values of each variable are expressed as mean and standard deviation. With the aim to determine whether the quantitative variables maintained the criterion of normality, a Shapiro–Wilk statistical test was performed. Fulfilling the criteria of normality, Student's *t*-test was used to compare the means of the variables ($p < 0.05$) pairwise between PAP MCC and PAP MSC. Cohen's $d$ was used as a measure of the effect size of differences between protocols and interpreted according to Cohen's thresholds: small ($d < 0.3$), medium ($d = 0.3$–$0.4$), large ($d = 0.5$–$0.6$), very large ($d = 0.7$–$0.9$), and extremely large ($d > 0.9$) [35].

## 3. Results

When comparing performance parameters between PAP MCC and PAP MSC, the power outputs of the PAP MCC group were highest in the 20 s "all out" test. Significant differences with an extremely large effect size were noted in average power output ($p = 0.034$, $d = 0.98$), power output in the first 3 strokes ($p = 0.019$, $d = 1.15$), and in the first 5 strokes ($p = 0.036$, $d = 0.91$) (Table 2). Higher values and very large effect size were reached in maximal power output ($p = 0.080$, $d = 0.74$) and first stroke power output ($p = 0.085$, $d = 0.84$), although no significant differences were found.

**Table 2.** Results of the 20 s sprint test "all-out".

| | PAP MCC | PAP MSC | $p$ | 95% CI | Effect Size | |
|---|---|---|---|---|---|---|
| | Mean ± SD | Mean ± SD | | | $d$ | Size |
| Wmean (W) | 554.3 ± 30.5 | 514.5 ± 48.9 | 0.034 * | 4.6–96.7 | 0.98 | Extremely large |
| Wmax (W) | 621.4 ± 54.9 | 582.8 ± 48.7 | 0.080 | −6.9–106.0 | 0.74 | Very large |
| $W_1$stroke (W) | 251.4 ± 63.0 | 211.0 ± 25.2 | 0.085 | −11.0–133.0 | 0.84 | Very large |
| $W_3$strokes (W) | 470.2 ± 64.3 | 392.5 ± 70.2 | 0.019 * | 18.5–171.0 | 1.15 | Extremely large |
| $W_5$strokes (W) | 600.4 ± 43.7 | 562.0 ± 40.9 | 0.036 * | 4.1–102.8 | 0.91 | Extremely large |
| Strokes (n) | 17.2 ± 1.6 | 15.2 ± 1.5 | 0.049 * | 0.0–3.7 | 1.29 | Extremely large |
| Ratio (stroke/min) | 49.9 ± 4.4 | 44.8 ± 4.5 | 0.046 * | 0.1–11.5 | 1.15 | Extremely large |
| HRmean (bpm) | 118.5 ± 9.1 | 101.2 ± 14.9 | 0.050 | 0.0–34.7 | 1.40 | Extremely large |
| HRmax (bpm) | 129.8 ± 11.9 | 115.3 ± 23.4 | 0.225 | −10.9–38.9 | 0.78 | Very large |

PAP: postactivation potentiation; MCC: maximal conditioning contractions; MSC: maximal strength contractions; SD: standard deviation; CI: confidence interval; W: watt; max: maximum; N: number; min: minute; HR: heart rate; *: statistically significant ($p < 0.05$).

The total number of strokes ($p$ = 0.049, $d$ = 2.29) and the rate of strokes per minute ($p$ = 0.046, $d$ = 1.15) were significantly greater in the PAP MCC group than in the PAP MSC group, with an extremely large effect size.

Both average and maximum heart rates were also higher in the PAP MCC group than in the PAP MSC group, but no significant differences were found in heart rate difference. The effect size for average heart rate was extremely large ($p$ = 0.050, $d$ = 1.40), whereas there was a very large effect size for maximum heart rate ($p$ = 0.225, $d$ = 0.78).

## 4. Discussion

The objective of this study was to analyze and compare the acute effects of two different PAP protocols in traditional rowing performance using a crossover design such that each participant performed different protocols during different time periods. In the current study, we sought to determine the PAP protocol that would be most beneficial for rowing performance. The group with the highest values of power output reached in the 20-s "all-out" test was the group that performed the PAP of maximal conditioning contractions (PAP MCC) in rowing ergometer compared with the group that performed the PAP of maximal strength contractions (PAP MSC) in half squat and bench pull. Doma et al. [2] found higher power values in Wmean, Wmax, and $W_1$stroke with the rowers who performed dynamic conditioning contractions before the test. In the same way, isometric conditioning contractions on a rowing ergometer to the rowing warm-up appears to increase short-term rowing ergometer performance, especially at the start [10]. The effect of the postactivation potentiation of conditioning contractions, with similar movement patterns of rowing gesture, enhances power output. However, the type of conditioning contractions may have different effects on PAP and fatigue. Isometric conditioning contractions may induce central fatigue, while dynamic conditioning contractions may induce the opposite response [36].

Prior heavy load exercise will induce some activation adaptations to the nervous system that will help increase performance in the subsequent test(s) as long as the recovery time is adequate [8]. However, the PAP MSC group reached the lower values in all measured power variables. This may indicate that this type of PAP may not benefit rowing performance. The greatest adaptations will occur in experienced athletes performing high-intensity training [23]; therefore, they would need a longer recovery time after PAP [5]. In a study by Esformes et al. [7], greater manifestation of the PAP MSC was also related to a shorter recovery time after the PAP. In this way, if the recovery time after the PAP is not sufficient, it will cause fatigue conditioning in subsequent efforts. Both the degree of PAP MSC and the recovery time after a PAP will be linked to performance optimization. Therefore, the degree of manifestation of the maximum dynamic strength must be taken into account individually to quantify the recovery time after the PAP correctly [6].

The increase in power achieved with the PAP MCC protocol may have explained the faster average stroke rate and the total number of the strokes, both in the present study performed in a 20 s "all-out" test and in other studies evaluated over 1000 m rowing ergometer time trial [10] and over a 10 s "all-out" test [2].

The mean and maximum heart rate values were higher in the PAP MCC group. When a very explosive test is carried out, HR increases very quickly when it comes from a 6 min recovery where it practically returns to a resting HR range. The PAP MCC group previously performed the PAP protocol, and the heart had already reached a working HR range. The same did not occur with the PAP MSC group because during the PAP protocol, they did not reach such high HR values. Therefore, when the test was performed, the HR did not increase so fast because HR is a component of late physiological response or due to a possible greater activation of the sympathetic system after conditioning contractions versus strength contractions [37].

Regarding limitations, findings from the present study should be interpreted with caution due its to the small sample size, although a crossover design was used. Furthermore, the results should be interpreted considering that the study was performed on a rowing start and not on competitive distance, an event in which contribution(s) of the aerobic energy system may be highly important to successful performance. Future research aimed at confirming our results in a larger population and using a 2000 m rowing performance test, and not only in performance at the rowing start, would be interesting. Additionally, training using a 1RM load is inconsistent with safety rules. A better solution to describe the 1RM movement technique is to work at a specific rate of movement, describing the tempo of phases of movement (e.g., eccentric, transition, and concentric) [38].

## 5. Conclusions

The results suggested that postactivation potentiation with maximal conditioning contractions in rowing warm-up enhanced subsequent rowing sprint performance, simulating the start of a race in traditional rowing. It can be an interesting strategy to potentiate rowing performance if prescribed by coaches before activities that involve explosive starts; as such, rowing coaches should implement this form of training.

Coaches can prescribe maximal conditioning contractions in warm-ups before starting specific rowing training as well as in competitions. However, more research is needed to determine whether this PAP protocol and other methodologies can also improve 2 km rowing performance.

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# Are There Differences in Concentric Isokinetic Strength Perfor-Mance Profiles between International and Non-International Elite Soccer Players?

**Robert Śliwowski [1,*], Jakub Marynowicz [1], Monika Grygorowicz [2,3], Andrzej Wieczorek [1] and Łukasz Jadczak [1]**

1 Department of Team Sports Games, Poznan University of Physical Education, 61-871 Poznan, Poland; marynowicz@awf.poznan.pl (J.M.); wieczorek@awf.poznan.pl (A.W.); lukasz.jadczak@onet.pl (Ł.J.)
2 Department of Physiotherapy, Poznan University of Medical Sciences, 61-701 Poznan, Poland; grygorowicz@ump.edu.pl
3 Rehasport Clinic FIFA Medical Centre of Excellence, 60-201 Poznan, Poland
* Correspondence: sliwowski@awf.poznan.pl

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**Abstract:** The purpose of this study is to evaluate the differences in concentric isokinetic strength characteristics of the knee extensor and knee flexor musculature between international (IL) and non-international level (N-IL) soccer players. The second aim is to establish strength symmetry status in knee muscles for dominant (DL) and non-dominant (NDL) legs for both within and between groups. 100 male top elite soccer players (IL: $n = 36$, age = 27.5 ± 3.4 years and N-IL: $n = 64$, age = 27.7 ± 6.4 years) underwent concentric isokinetic strength tests, using a Biodex System 3 dynamometer. Results indicate that statistically significant differences between groups were noted for peak torque of hamstrings (PT-H), hamstrings/quadriceps (H/Q) ratio, and total work of hamstrings (TW-H), where mean values for the IL were similarly higher than for the N-IL group ($p = 0.006$, $p < 0.001$, and $p = 0.012$, respectively). Our results also showed statistically significant differences for peak torque of quadriceps (PT-Q), PT-H, total work of quadriceps (TW-Q) and TW-H between legs, where mean values noted for the DL were higher than for the NDL for both groups ($p = 0.021$, $p < 0.001$, $p = 0.006$, and $p = 0.004$, respectively). Additional results show that IL players presented more symmetrical strength between legs than N-IL. The results of this study indicate that that the greatest differences in isokinetic strength performance across players at different soccer levels relate to the hamstring muscle. As a result, systematic strength training of these muscle groups is strongly recommended.

**Keywords:** muscular strength profile; quadriceps; hamstring; H/Q ratio; total work

## 1. Introduction

Isokinetic testing is one of the most commonly used methods of assessment for a wide range of strength evaluations. Traditionally, the focus of isokinetic research has been the measurement of concentric and eccentric absolute peak torque (PT) of quadriceps and hamstrings. Away from PT, the most commonly described variables in isokinetic tests for soccer players' knee muscles are: hamstring/quadriceps ratio, total work, average power, and fatigue index. The evaluation of muscular isokinetic strength allows for the determination of soccer players' muscular performance profiles and is therefore relevant for both maximization of physical performance and injury prevention.

Previous research has identified the isokinetic strength of knee extensor and flexor muscles as differentiating factors between soccer players of playing levels [1–7] and positional differences [8–11]. Some prior research indicates that soccer playing leads to a significant increase in strength in the muscles surrounding the knee [12]. Other studies have found hamstring and quadriceps strength increases, albeit to different degrees. For example, Lehance et al. [4] reported that concentric PT of the extensors and flexors increases with the age and sporting level of soccer players. The earlier study of Oberg et al. [5] also indicated that concentric isokinetic PT of the quadriceps and hamstrings increased in line with level of play in Swedish soccer divisions. The same study found that international soccer players were stronger than non-internationals. Conversely, Cotte and Chatard [3], found that international soccer players were no stronger than national players. Another study indicated that the more years of training professional soccer players had, the higher the PT of their knee extensors and flexors [13]. It should be noted that, based on comparisons of PT values between young and adult players, it has been suggested that soccer playing may be conducive to greater development of the hamstrings [14]. This phenomenon is also confirmed by the study of Cometti et al. [1] which indicates that the only parameter that differs between elite and amateur players is concentric knee flexor strength. Moreover, that study also found that hamstrings were stronger in professional players than in amateurs. This, in turn, may indicate that it is the level of hamstring muscle strength that differentiates soccer players at various levels.

The significance of differences in muscle strength between legs continues to be a hotly debated question in the existing research. Soccer players rarely use both legs with equal emphasis, often favouring the use of their dominant limb when performing game-specific activities [15]. This can result a stronger dominant leg (DL) compared to the non-dominant leg (NDL) [16–18]. A number of studies [9,19,20] have indicated no significant difference between the two extremities, while other studies [7,17] have found significant superiority of DL over NDL with regard to concentric strength. In contrast, other studies [16,21,22] have showed that either knee flexors of the dominant side to be significantly stronger than those of the non-dominant side or vice versa (i.e. NDL knee flexors can be significantly stronger than DL knee flexors) [23]. Additionally, there may be many combinations of muscular asymmetries within the type of muscular contraction (concentric vs. eccentric), leg (D vs. NDL) and a given muscle group (flexors vs. extensors). It may be expected that with a constant increase in research on this specific topic (i.e., inter- and between-limb asymmetries) and with the change in approach to preventative training, the differences in muscle strength between legs will gradually decline in the coming years. Thus, as can be expected, explanations for this discrepancy is still a subject of debate.

Despite the growing popularity of between limb asymmetry topic at different levels, there is a lack of specific research regarding the differences in isokinetic strength performance between soccer players at highest competition level. There is a similar knowledge deficit surrounding about differences in the concentric isokinetic strength characteristics of the knee extensor and knee flexor musculature between international and non-international soccer players. The advancement of such knowledge may have important implications for soccer training programs.

Therefore, the aim of the current study is to evaluate the differences in concentric isokinetic strength characteristics of the knee extensor and knee flexor musculature between international and non-international soccer players. The second aim is to establish strength symmetry status in knee muscles for dominant and non-dominant limbs for both within- and between-limb groups. To our knowledge, this information will be first of its kind that uses soccer as the sporting context.

## 2. Material and Methods

### 2.1. Participants and Data Collection

The cohort for this study included 100 male soccer players, 36 who played at an international level (IL) and 64 at a professional (non-international) elite level (N-IL). The IL group (age: 27.5 ± 3.4 years; height: 181.8 ± 5.1 cm; body mass: 77.3 ± 5.5 kg; training experience: 17.1 years) included international players from the Polish Ekstraklasa (the top competition level in Poland), who had played a minimum of 10 games for national teams of their respective countries (mainly Poland and countries of Southern, Eastern and Northern Europe). The N-IL group (age: 27.7 ± 6.4 years; height: 182.3 ± 2.7 cm; body mass:

79.4 ± 8.9 kg; training experience: 16.8 years) consisted of Polish Ekstraklasa players, without experience playing for a national team.

All participants from the IL and N-IL groups had at least three years of professional soccer playing experience, with regular training (as expounded in their contracts). The study was carried out from 2010 to 2019. Every measurement was performed twice per year: at the beginning of the pre-season period (from January to February), and from June to July. The official start of the season was in August every year. During every season, each participant completed two functional movement screen tests, as well as isokinetic strength tests for hamstring quadriceps, and knee, proprioception tests, and ground reaction force analysis, which were part of their routine biomechanical evaluation. As an annex to their professional contracts, players were given information about the experimental risks and provided written consent for their data to be collected and used. In cases where players below the age of 18, parents or guardians were informed about the risks and their written, informed consent was obtained before commencement of the study. The study was conducted in accordance with the Declaration of Helsinki and the research protocol was approved by the local research ethics committee (the Bioethical Committee at the Poznań University of Medical Sciences).

### 2.2. Test Procedures

The tests in this study were carried out at the Rehasport Clinic, a FIFA Medical Centre of Excellence in Poznań, Poland. All measurements were performed by the same team of examiners, who had completed additional specialized biomechanical evaluation courses. In addition, each examiner had at least 3 years of isokinetic joint testing experience, including knee joints. The Biodex System 3 (Biodex Corp, Shirley, NY, USA) dynamometer was used to measure isokinetic knee muscle strength (ascertained by PT and muscle endurance (as measured by total work [TW])).

With regard to the participants' alignment axis of dynamometer rotation, position, gravity correction, and stabilization, all procedures followed guidelines previously described in existing literature [19,24,25]. Before the isokinetic assessment, each player performed a 10–15 min warm-up, which entailed pedaling on a Monark 828E Ergomedic stationary cycle ergometer (Monark, Vansbro, Sweden) at a moderate pace (50–100 watt) and dynamic stretches for the major lower-limb muscle groups [19,23]. To assess the concentric isokinetic torque of the quadriceps and hamstrings, continuous, bidirectional knee extension-flexion movements were completed at an angular velocity of $60^\circ \cdot s^{-1}$ and $240^\circ \cdot s^{-1}$ through a knee range of motion of 0° (flexed) to 90° (full extension). The above testing speeds of $60^\circ \cdot s^{-1}$ and $240^\circ \cdot s^{-1}$ have been extensively implemented in other studies looking at muscle strength in soccer players [4,12,20]. The participants performed three trials at submaximal efforts, with a load gradually increasing to 50%, 75%, and approximately 100% of maximum capability, followed by one set of three repetitions at the maximal concentric contraction at angular velocities of $60^\circ \cdot s^{-1}$, and 30 repetitions at angular velocities of $240^\circ \cdot s^{-1}$. The same procedure was then repeated for the remaining leg. After the third submaximal trial, the participants were given a 30-s rest, and a further, one-minute break between two angular velocities, followed by a three-minute break. During this break, machine settings was altered for the opposite leg). Participants were also asked to complete the movement in full range of motion. The order of testing was randomized for the dominant (DL) and non-dominant (NDL) legs [16,19,25]. dominance player's dominant limb was determined on the basis of their preference when kicking a ball [18,19]. Only windowed data was used in order to limit the analysis to constant velocity periods. In the statistical analysis, the following data were analyzed: relative PTs (normalized by the body weight and expressed in $Nm \cdot kg^{-1}$) for flexors (PT-Q) and extensors (PT-H) in both legs, the unilateral ratio of muscle torque for both the dominant and non-dominant extremities (HDL/QDL and HNDL/QNDL, respectively) at an angular velocity of $60^o \cdot s^{-1}$ and, similarly, the relative TWs ($J \cdot kg^{-1}$) for extensors (TW-Q) and flexors (TW-H) for both legs at an angular velocity of $240^\circ \cdot s^{-1}$.

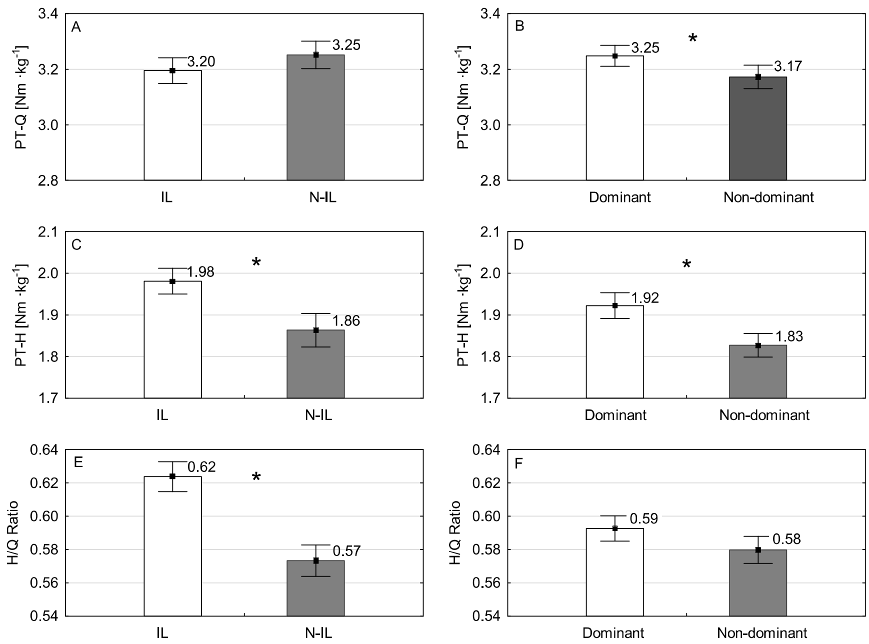
All tests were performed before 1 pm to exclude inter-day variability and were performed in the same order for each participant. Players undergoing the evaluation were exempted from intensive training for 48 h prior to testing. Before commencement of the testing, participants were asked to complete a questionnaire to determine whether they had any musculoskeletal pain, discomfort, or known injury in a lower extremity. Participants reporting either a major or moderate lower leg injury or any injury to the knee or thigh were excluded from further analysis. None of the participants had prior significant knee injuries, none had a history of anterior cruciate ligament (ACL) repairs or rehabilitation, and none had a history of a leg fracture or surgery during the year preceding each evaluation.

### *2.3. Statistical Analysis*

All statistical analyses were performed using Statistica Version 13.0 (StatSoft Polska Sp. z o.o. 2020, Krakow, Poland). Descriptive data are presented as means and standard-deviation, whereas percentage difference in the variables between dominant and non-dominant leg is expressed as an absolute value of mean with 95% confidence limits. The normality of each variable was initially tested with the Kolmogorov-Smirnov test, the coefficients of asymmetry and kurtosis were also ascertained. All the variables presented a normal distribution. Five separate two-way mixed analyses of variance (ANOVA) were used to evaluate the effects of groups (between subject factor, levels: international vs. non-international level) and legs (within subject factor levels: dominant vs. non-dominant), and their interactions on dependent neuromuscular variables (PT-Q, PT-H, H/Q ratio, TW-Q and TW-H). F-ratios (F), degrees of freedom subscripted, *P* value (*P*), and effects sizes (partial $\eta^2$) were reported for each ANOVA. A paired *t*-test was also applied to examine differences between the scores of the dominant and non-dominant legs for the all neuromuscular variables in both cohorts independently. T statistics (*t*), degrees of freedom subscripted, *P* value (*P*), and Cohen's *d* (*d*) effect sizes were reported for each *t*-test. Cohen's *d* was determined as a measure of effect size for between leg comparisons. Cohen's *d* lower than 0.2 was considered irrelevant, between 0.2 and 0.49 was small, between 0.50 and 0.8 was considered medium, and greater more than 0.8 was considered high [26]. The level of statistical significance was at 0.05 for all statistical procedures.

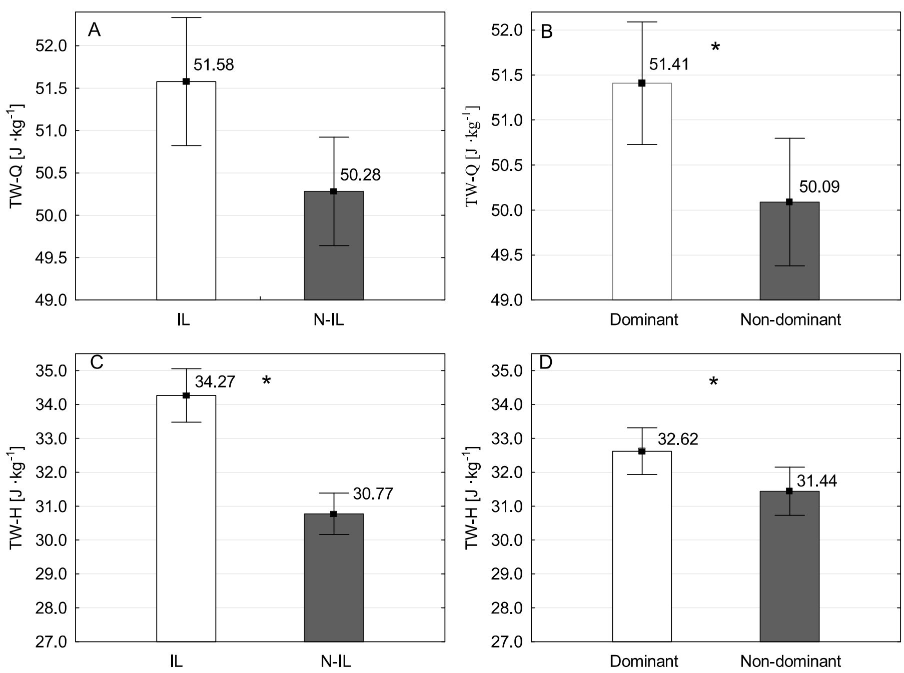
## 3. Results

There were no significant differences in height or weight across the studied participants. Figures 1 and 2 presents the mean values of PT-Q, PT-H, H/Q, TW-Q and TW-H for groups and legs. For PT-Q there was no interaction ($F_{1,98}$ = 0.210, *P* = 0.648, partial $\eta^2$ = 0.002) and no main effect for groups ($F_{1,98}$ = 0.004, *P* = 0.949, partial $\eta^2$ < 0.001; Figure 1A). However, there was a main effect for legs ($F_{1,98}$ = 5.516, *P* = 0.021, partial $\eta^2$ = 0.053; Figure 1B), where the mean values for DL values were greater than NDL. For PT-H there was no interaction ($F_{1,98}$ = 0.036, *P* = 0.850, partial $\eta^2$ < 0.001). However, there was a main effect for groups ($F_{1,98}$ = 7.903, *P* = 0.006, partial $\eta^2$ = 0.075; Figure 1C), where the mean values for IL were greater than N-IL, and for legs ($F_{1,98}$ = 23.503, *P* < 0.001, partial $\eta^2$ = 0.193; Figure 1D), where the mean values for DL were greater than NDL. For H/Q ratio there was no interaction ($F_{1,98}$ = 0.095, *P* = 0.758, partial $\eta^2$ < 0.001) and no main effect for legs ($F_{1,98}$ = 3.871, *P* = 0.052, partial $\eta^2$ = 0.038; Figure 1F). However, there was a main effect for groups ($F_{1,98}$ = 13.574, *P* < 0.001, partial $\eta^2$ = 0.122; Figure 1E), where the mean values for IL were greater than N-IL. For TW-Q there was no interaction ($F_{1,98}$ = 0.830, *P* = 0.364, partial $\eta^2$ = 0.008) and no main effect for groups ($F_{1,98}$ = 0.878, *P* = 0.351, partial $\eta^2$ = 0.009; Figure 2A). However, there was a main effect for legs ($F_{1,98}$ = 7.871, *P* = 0.006, partial $\eta^2$ = 0.074; Figure 2B), where the mean values for DL were greater than NDL. For TW-H there was no interaction ($F_{1,98}$ < 0.001, *P* = 0.992, partial $\eta^2$ < 0.001; Figure 2C). However, there was a main effect for groups ($F_{1,98}$ = 6.522, *P* = 0.012, partial $\eta^2$ = 0.062; Figure 2C), where the mean values for IL were greater than N-IL, and for legs ($F_{1,98}$ = 8.520, *P* = 0.004, partial $\eta^2$ = 0.079; Figure 2D), where the mean values for DL were greater than NDL.




Notes: * Significant differences between groups and legs ($P < 0.05$), PT-Q—peak torque of quadriceps, PT-H—peak torque of hamstrings, H/Q—hamstrings/quadriceps ratio.

**Figure 1.** Mean values and standard error for PT of quadriceps and hamstrings by: (**A**,**C**) soccer player groups (international, non-international); (**B**,**D**) legs (dominant, non-dominant), and H/Q ratios by: (**E**) soccer player groups (international, non-international); (**F**) legs (dominant, non-dominant).




Notes: * Significant differences between groups and legs ($P < 0.05$), TW-Q—total work of quadriceps and TW-H—total work of hamstrings.

**Figure 2.** Mean values and standard error for TW of quadriceps and hamstrings (**A**,**C**) across soccer player groups (international, non-international); (**B**,**D**) legs (dominant, non-dominant).

Table 1 presents the mean values of neuromuscular characteristics for both groups. Statistically significant differences were only reported in the international group for PT-H and TW-H ($t_{35}$ = 3.756, $P < 0.001$, $d = 0.42$, and $t_{35}$ = 2.321, $P = 0.026$, $d = 0.18$, respectively), where the mean DL values were greater than NDL. In the case of the non-international group, statistical significance was noted for PT-Q, PT-H, TW-Q and TW-H ($t_{63}$ = 2.362, $P = 0.021$, $d = 0.19$; $t_{63}$ = 3.597, $P < 0.001$, $d = 0.29$; $t_{63}$ = 3.154, $P = 0.003$, $d = 0.22$ and $t_{63}$ = 2.204, $P = 0.031$, $d = 0.17$, respectively), where mean values for DL were higher than for NDL.

**Table 1.** Characteristics of the PT of quadriceps and hamstrings, H/Q ratios at 60°·s$^{-1}$ and TW of quadriceps and hamstrings at 240°·s$^{-1}$ angular velocity across soccer player groups.

| Variables | International Level (n = 36) | | | Non-International Level (n = 64) | | |
|---|---|---|---|---|---|---|
| | DL | NDL | Δ% 95% CL | DL | NDL | Δ% 95% CL |
| | Mean ± SD | | | Mean ± SD | | |
| PT-Q [Nm·kg$^{-1}$] | 3.24 ± 0.35 | 3.18 ± 0.41 | 7.95 (6.0 − 9.9) | 3.25 ± 0.39 * | 3.17 ± 0.44 | 6.95 (5.4 − 8.5) |
| PT-H [Nm·kg$^{-1}$] | 2.03 ± 0.26 * | 1.93 ± 0.22 | 6.67 (4.9 − 8.5) | 1.86 ± 0.32 * | 1.77 ± 0.30 | 9.82 (8.1 − 11.6) |
| H/Q Ratio | 0.63 ± 0.06 | 0.61 ± 0.08 | 8.55 (6.5 − 10.6) | 0.57 ± 0.08 | 0.56 ± 0.08 | 9.13 (7.4 − 10.9) |
| TW-Q [J·kg$^{-1}$] | 51.99 ± 6.46 | 51.17 ± 6.42 | 7.11 (5.4 − 8.8) | 51.08 ± 7.03 * | 49.48 ± 7.41 | 6.75 (5.2 − 8.3) |
| TW-H [J·kg$^{-1}$] | 34.86 ± 6.31* | 33.67 ± 7.09 | 7.37 (5.3 − 9.4) | 31.36 ± 6.94 * | 30.18 ± 6.89 | 11.87 (9.9 − 13.9) |

Notes: * Significant differences between legs ($P < 0.05$), PT-Q—peak torque of quadriceps, PT-H—peak torque of hamstrings, H/Q—hamstrings/quadriceps ratio, TW-Q—total work of quadriceps and TW-H—total work of hamstrings.

## 4. Discussion

The primary findings of the present study reveal that isokinetic flexors characteristics (i.e. PT-H and TW-H), and H/Q ratio were significantly greater for international soccer players compared to non-internationals. Notably, no statistically significant differences were noted for PT-Q and TW-Q between the compared groups. These findings suggest that specific strength adaptations in muscular architecture among knee joints in international players are mainly manifested in the flexor muscle group, which could directly translate into higher values of H/Q ratio in this group.

These results are in accordance with the findings of Cometti et al. [1], who found that experienced professional soccer players had stronger knee flexors and higher conventional H/Q ratios than amateur players, thus highlighting the effect of level of play. Similar to our findings, above, they found a comparable level of quadriceps strength across the groups. A comparable phenomenon was described in a recent study by Herdy et al. [27], where professional adult soccer players demonstrated significant differences in hamstring PT in both legs, compared to U-17 players. As in our study, statistically significant differences were also noted among the same groups in the case of a conventional H/Q ratio; however, these differences related only to DL. A number of cohort studies [5,28] have suggested that players from higher leagues produce higher PT values during concentric extension and flexion actions, compared to players in lower divisions or leagues [28]. They attributed the greater strength of high-level soccer players to longer off-season periods and also to a greater number of specific strength training sessions. These relations, however, were not confirmed in another study, which found no significant differences in the PT of the quadriceps and hamstrings, nor the H/Q ratio, across four divisions of soccer players [6], nor between international and national soccer players [3]. In relation to the total work variable, the only study in this area known to us [2] found statistically significant differences with regard to both quadriceps and hamstrings—between professional and

U-17 soccer players for all the studied angular velocities. Unfortunately, wider comparisons of TW with other elite players is not available in the current literature.

These observations indicate that many years of changes in knee muscular strength and endurance in soccer players can have various results. Soccer training is likely to have significant potential for both quadriceps and hamstring muscle group strengthening, but a clear effect in our study seems relatively higher for the hamstring muscle in international players. It seems that experienced professional players, performing at a high level exhibit a better strength balance around the knee joint and stronger knee flexors than lower level players. It is generally accepted that the quadriceps muscle group plays an important role in kicking, passing and jumping—primarily in the concentric mode [8,10–12]. By contrast, hamstrings are largely used eccentrically to control, decelerate, and stabilize the knee, although it should be noted that they are also used concentrically in actions such as tackling, high velocity running, and turning [8,10,11,24]. Many studies indicate that a player's high-intensity activity during a match is influenced by training level [29] and the level of competition [30]. More precisely, Thorpe and Sunderland [31] revealed that semi-professional players have been found to cover lower total distances and distances at high velocities. At the same time, modern soccer is becoming faster and more dynamic and as such, high-intensity running distances and high-intensity actions during a game have increased exponentially in recent years [32]. Altogether, these differences can generate different musculature adaptations between players representing various sports levels, especially with regard to flexor muscles. As a result, the significantly higher PT-H and TW-H values observed in the international soccer players in our study are likely a result of increased game exposure. Compared to non-international players, the higher number of matches played per season (more than 70 matches played per season) among international players increased the number of high-intensity efforts performed, such as high-speed running or sprints [33]. There is a substantial body of evidence showing correlatory relationships between, on the one hand, the eccentric [34–36] and concentric [4,35] strength of the hamstring, with, on the other hand, speed performance. Morin et al., [37] highlighted the crucial role of hamstring muscles in producing propulsive force during acceleration performance. Furthermore, hamstrings play an important role in producing the required joint moments when running at high velocities. Moreover, Exell et al. [38] found that hamstrings are instrumental in accelerating the center of mass when performing fast consecutive hips-extensions and are also important for increasing step frequency and speed when performing fast knee-flexions. Such findings indicate the need for further research in this area, especially with regard to concentric contractions for flexor muscles, as has been done in the present study.

Compared to the non-international group soccer players, the higher H/Q ratios shown in the international group in our study can thus be explained by their stronger hamstrings. It should be noted though that PT-Q strength did not show statistically significant differences between the compared groups of soccer players (Table 1). It should also be born in mind that the H/Q ratio is not only a significant indicator in the prevention of injuries [12,19,24], but also reflects the relatively important relationship between the strength generated between knee flexors and extensors during specific functional efforts and the type of movement activities performed on the pitch. The higher values of H/Q ratio in the international group may indicate better strength balance around the knee joint than in the non-international group. Indeed, research suggests that strength balance around the knee joint is better in experienced professionals playing at a high level than it is in lower level players (see also [1,13]). Moreover, it is widely accepted that high hamstring strength can be used as a preventative neuromuscular strategy against over-fatiguing and subsequent injury [39].

Although modern training programs focus on the two-legged preparation of players, some research [13,18] has suggested that soccer players seldom use both legs with equal emphasis. In general, more experienced players may show a greater tendency for asymmetry due to a natural preference for their left or right foot when performing particular movement patterns [13]. These findings are consistent with our own results, but only if we take into consideration the non-international group, which found statistically significant differences in PT-Q, PT-H, TW-Q and TW-H between players' legs (Table 1), where mean values noted for the DL were higher than for the NDL. Greater symmetry between legs was reported in the international group, and, interestingly the symmetry related mainly to the quadriceps, and was not apparent for hamstrings. We hypothesize that this pattern is a result of a greater manifestation of two-leggedness in the play of the international group, however it can also be a compensatory effect of other musculature such as hip flexors/extensors or ankle. An analysis of patterns of shooting on goal during top-level competition revealed that most successful players shot for goal using both left and right lower legs [40]. More recent research has emphasized the importance of using both feet equally in soccer [15]. It is worth mentioning that larger lower limb strength asymmetries may negatively affect jumping ability and power output and hence limit athletes' potential [41]. In addition, we assume that magnitude of symmetry can be associated with playing position, and therefore further research should focus on position-specific asymmetry.

Differences between DL and the NDL for soccer players are a controversial subject, as some studies demonstrate various ranges of musculoskeletal asymmetries in the knee extensor and flexor strength. The latest meta-analysis by DeLang et al. [42] indicates that soccer players across all ages and levels demonstrate between-limb symmetry in knee extensor and flexor peak torque, as well as H/Q ratio, regardless of concentric or eccentric measurements. These findings are confirmed by a number of other studies which have found no statistically significant differences in the level of PT-Q, PT-H or conventional H/Q ratios between extremities [7,10,15,20,25]. The study by Fousekis et al. [17] provides additional data indicating that fluctuating asymmetries between DL and NDL among semi-professional soccer players from the Greek third division relate mainly to eccentric work and no significant tendency toward asymmetry was noted when concentric measurements were applied. Unlike our findings, in Fousekis et al.'s view [17], this phenomenon demonstrates that asymmetric strength adaptations taking place in the lower extremities of professional soccer players are mainly eccentric in nature. Elsewhere, similar to our study, the superiority of the concentric isokinetic strength in DL was observed in at $60^\circ\ s^{-1}$ angular velocity [7] and number of other studies have found that knee flexors [16,21,22] and extensors [18] of the dominant leg were significantly stronger than those of the non-dominant one. Such data, together with the results of our study, strongly support the theory that various degrees and modes of functional asymmetry develop as a result of long-term participation in soccer [17].

As with all such research, this study has some limitations, which should be elucidated. The main limitation of the current study is that measurement procedures were based exclusively on the concentric contractions mode. Additionally establishing eccentric PT-H could not only reveal some interesting relationships between concentric and eccentric PT-H, but also enable the calculation of dynamic H/Q ratios and would thus contribute to a complete report of the muscle profile.

## 5. Conclusions

The principal finding of this study is that the greatest differences in isokinetic strength performance across players at different soccer levels relate to the hamstring muscle. It is noteworthy that this phenomenon relates to isokinetic indicators of both strength and strength endurance. However, no significant differences in these areas was observed in the quadriceps muscle group. It appears that the intergroup heterogeneity in terms of hamstring muscle strength may result from the difference in training adaptations and the level of competition of the analysed players. It thus seems logical to infer that knee flexor strength is extremely important in soccer players for repeated high-intensity bouts of activity and for joint stabilisation during various tasks; systematic strength training of these muscle groups is therefore highly recommended. We also found statistically significant intergroup differences in H/Q ratios. A higher level of this indicator, along with a greater reciprocal ratio, and greater hamstring muscle strength may indicate better performance and strength balance around the knee joint in the international players than non-international, as well as a greater potential for muscular joint stabilisation. Other results show that international players presented more between-leg symmetrical strength than non-international players. These findings indicate that specific kinetic patterns found in international soccer could be of more balanced and symmetrical nature. Finally, we believe that further research of this type should be complemented with measurement of the eccentric contractions mode, particularly with reference to hamstring muscles.

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**Institutional Review Board Statement:** The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Ethics Committee of the Poznan University of Medical Sciences (629/13).

**Informed Consent Statement:** Informed consent was obtained from all subjects involved in the study.

**Data Availability Statement:** The data are not publicly available due to Rehasport restrictions. Requests for the data and information for the Rehasport Clinic Institutional Data Access can be sent to Joanna Wiese, joanna.wiese@rehasport.pl.

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# Considerations for the Design of a Physical Fitness Battery to Assess Adults with Intellectual Disabilities: Preliminary Reference Values for the SAMU DIS-FIT Study

**Ruth Cabeza-Ruiz**

Department of Human Movement and Sport Performance, University of Seville, 41013 Seville, Spain; ruthcr@us.es

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**Abstract:** For the assessment of the health-related physical fitness (PF) of individuals with intellectual disabilities (ID), tools designed for people without disabilities have generally been used. Also, the results of these assessments have routinely been compared with the scores obtained by people without ID. The objectives of the present study are to present the rationale for the design of an assessment battery for PF, the so-called SAMU DIS-FIT battery, and to present the results obtained by the participants classified according to age, sex, and level of PF (physical fitness). The selection criteria for the tests that would make up the battery were: (i) utility, (ii) psychometric properties, (iii) easiness and diversity, (iv) simplicity of execution, (v) familiarity and motivation, and (vi) economy of resources. A cross-sectional study was designed to assess the PF of 261 individuals with ID. To interpret the results obtained by the participants, each of the quantitative variables of PF was categorized into three levels: lower-fit, mid-fit, and higher-fit. The findings of this study serve as a first step in establishing PF baseline values for individuals with ID.

**Keywords:** disability; tool; health; life span; physical fitness; reference values

## 1. Introduction

Individuals with intellectual disabilities (ID) generally show lower levels of physical fitness (PF) than those without disabilities of the same sex and age [1–4]. However, making comparisons between values obtained by individuals without disabilities and individuals with disabilities could imply a comparative disadvantage for the latter because the personal and social development as well as the characteristics of adults with and without ID are not similar. In general, studies describing the PF of individuals with ID are scarce or use small samples. Only studies carried out with people who participate in the Special Olympics World Games have many participants [5–8], but they do not provide the psychometric properties of the tests used, so the suitability of the tools used for the assessment of PF in individuals with ID is unknown. Hilgenkamp et al. have conducted studies with large samples of older people with severe or profound ID [9]. The results of their research show good to excellent values for the psychometric properties of the tests used. However, it was necessary to have a battery of tests with good reliability and feasibility for younger adults with mild or moderate ID as they constitute the largest group of individuals with ID.

In many cases, tests designed for people without ID, which have passed validity tests, have been used to assess PF in individuals with ID [10–14]. In some cases, these tests have been evaluated for their reliability in the ID population but only with small samples [15] or older people [16]. The reliability of some isolated tests has also been evaluated [17], and, to a lesser extent, original tests have been adapted to be performed by individuals with ID, providing feasibility values [9,18,19].

In September 2017, the SAMU Foundation (Seville, Spain), an organization that assists people with disabilities, and the Department of Human Movement and Sport Performance of the University of Seville (Seville, Spain) were interested in carrying out a joint study (University of Seville 3054/0780) on constructing PF tests for adults with ID. The study came up with a battery of tests to assess PF in individuals with ID, adapted to their characteristics and with appropriate psychometric criteria. To this end, it was necessary to review the scientific literature to find previous studies and select PF assessment tests that could form a feasible, reliable, and valid battery for individuals with ID. The results of these meetings and literature studies led the research team to formulate the following long-term objectives: (i) to design a PF assessment tool for persons with ID that would provide reliable data on their fitness status; (ii) to design a PF assessment tool for individuals with ID that would take into account the characteristics of this population; and (iii) to provide a description of the PF status of individuals with ID according to age, sex, and fitness level that would serve as a guide for other researchers and clinicians and that would be based on the results of a large sample of persons with ID.

Two years later, the battery, called the SAMU DIS-FIT, was designed and tested. Although the results on the suitability of the battery have previously been published [20,21], the criteria that were taken into account by the research team to select the different tests based on the characteristics of the population with ID have not yet been shared with the scientific community. Neither were the results obtained by the participants of the SAMU DIS-FIT study available to date. Therefore, the objectives of the present study are: (i) to describe the qualitative aspects that led the research team to select the tests that would make up the battery for the assessment of PF in individuals with ID and (ii) to show the results obtained by the participants according to sex, age, and level of physical condition.

## 2. Materials and Methods

### 2.1. Rationale for the Test Battery Used

The research team, consisting of four sports science and physical activity professionals, two psychologists, and one social worker with more than 5 years of experience working with individuals with ID, met to design a battery for the assessment of PF in adults with ID. To do so, it was necessary to hold a brainstorming session to gather all the aspects that the team believed were important when working with individuals with ID. In addition, a review of the literature was conducted to identify studies related to the objective of the project that could be used to select and analyze those tests that meet the psychometric criteria. Once the ideas were compiled, they were grouped into categories related to motor aspects; psychobehavioral aspects; group-specific needs; consistency of the tool; and aspects related to material, human, and economic resources.

The project was divided over two years by the SAMU Foundation and the University of Seville. During the first 3 months, the literature review was carried out, and the inclusion criteria for the tests that would form part of the battery were established. Subsequently, working meetings of the multidisciplinary team were held to design the final tool. Simultaneously, a group of last-year Sport Science students was selected to participate in the study as research fellows. The chosen students were given a training course to learn how to handle and apply the PF assessment battery and were called to participate as evaluators in the pilot study.

To achieve the research objectives, a large sample of individuals with ID was needed. After pre-selecting and recruiting the sample, the next step was to design the final PF assessment instrument that was appropriate for the research requirements and respectful of the characteristics of individuals with ID. Assessing individuals with disabilities is often challenging because of the particularities of the disabilities. The different ways of receiving, processing, and interpreting information or aspects related to motivation, attention, and communication are a major challenge for data collection and the certainty that the data are consistent with reality when working with persons with disabilities [22,23].

As a result of these meetings, the following criteria were established for the inclusion of a test in the fitness test battery:

(1) Utility criteria

The first element that was considered when designing the battery was that it should comply with the recommendations of the American College of Sports Medicine [24]. To this end, the assessment of the PF components directly related to health, and not merely to fitness-related skills, was studied, and a combination of six tests was proposed to evaluate the four fundamental components of PF [16]: body composition, flexibility, muscle strength, and cardiorespiratory fitness. Although body balance is regarded as a fitness-related skill and not a health-related fitness component [25], without the ability to maintain body balance it is impossible to perform any other motor action, so a test to assess dynamic balance was included in the battery.

(2) Psychometric criteria: validity, reliability, and feasibility

Once the most relevant fitness components had been selected, psychometric criteria were taken into account for the selection of the tests. In order to design a solid, useful test battery based on objective criteria of repeatability, the instrument had to be built on the basis of validity, reliability, and feasibility to be included in the battery [23]. In this way, a tool would be obtained that provides accurate information about the PF levels of individuals with mild or moderate ID. Validity is the adequacy and appropriateness of a test to accurately measure what it is trying to measure (to learn more read Yun & Ulrich, 2002) [26]. In the battery, one test was included if there were previous studies on the validity of the instrument. The reliability of a tool refers to its ability to obtain the same results when measuring the same phenomenon again. To know whether an instrument measures the same thing at different times, the intraclass correlation coefficient could be used, among other measures. Finally, feasibility is the rate of successful cases—that is, the percentage of individuals who perform the test properly, which entails not only understanding the test but also executing it correctly [27].

The following steps were taken to meet these objectives:

(a). The selected tests were those previously supported by validity studies.
(b). If the previous criterion was met, reliability and feasibility criteria were also applied, either by reviewing previous studies undertaken with individuals with ID or by carrying out pilot studies by the research team.

(3) Criteria of simplicity and diversity of instructions

Individuals with ID are characterized by a different memory and attention capacity and by a different way of processing, retrieving, or integrating information. The way in which the instructions are presented conditions the way in which the subjects will understand the dynamics of a test and, subsequently, the way they perform it [18,23]. In tests for which it is necessary to provide extensive and detailed information because of the technical complexity of the movement, individuals with ID will encounter barriers to understanding and memorization. That is why it is necessary to offer simplified information—that is, to give a participant only the necessary information to perform the test properly. For example, to correctly execute a maximum vertical jump, it is sufficient to ask a participant to jump as high as possible, without including information on specific technical aspects, such as the degree of knee flexion or arm coordination. In addition to verbal information, it is essential that evaluators give demonstrations of every test to each of the participants—sometimes more than once. It is possible that, in some cases, it is necessary to use pictograms and other forms of communication, such as sign language.

(4) Criterion of easiness of motor response

Even if the information received is simple and the individuals with ID can understand the procedure of the tests following the techniques required, it is also necessary that these tests do not involve a complex motor act—that is, that the test is also simple in relation to its execution [23]. It is well known that people with disabilities lead sedentary lives [28–31] as they encounter numerous barriers to participating in regular physical activities [8], so their level of motor skills is often limited. Although some tests may seem simple in their description, sometimes the execution of these tests involves taking into account numerous elements that could invalidate the results. An example of this is the Sit and Reach Test, in which the assessed persons must maintain trunk flexion while extending both arms without bending their knees.

(5) Familiarity and motivation criteria

This aspect refers to the requirement that the places, the instruments, and the assessment staff are, as far as possible, familiar to the participants [23]. Taking into account the psychological and behavioral characteristics of individuals with ID, the research team recommended that the assessments should ideally be carried out in the participants' care centers, since it could improve the outcome of the assessments when the participants feel more comfortable and confident [32,33]. The researchers also advised that the assessments be done in a group, since this way the participants feel accompanied and motivated by their peers, which generates familiarity and confidence, creating a more favorable work environment, in which the assessments do not seem like an examination but rather a game.

(6) Cost criterion

Some tests for assessing PF are considered to be more objective than others. In general, these are tests that are carried out under strictly controlled conditions, with highly sophisticated instruments, and in laboratories dedicated to the assessment of the physical and physiological capacities of humans. However, these types of instruments represent a high-cost investment that is not available to most organizations that attend to individuals with disabilities. Moreover, the use of these instruments requires specific training of the assessment staff, and these professionals must often be health care personnel [22]. For these reasons, PF assessment tests with less complex instruments are more affordable to professionals who work with individuals with disabilities outside of universities or research centers. These instruments are less complex and expensive than laboratory equipment and therefore can be operated by anyone with minimal training.

In addition to material and human resources, time management was another important aspect that the researchers considered when designing the battery. As a main objective, it was proposed that the complete assessment of a person should not exceed 45 min. However, in the present study, strategies are proposed for assessing groups of five people in approximately 1 h. These time management principles aim not only at facilitating the measurements for the evaluators but also at avoiding the physical and psychological fatigue of the participants.

### 2.2. Design

A cross-sectional design was employed. This study is part of a larger project with a test-retest design in which the reliability and feasibility of the final battery were tested.

### 2.3. Participants

To recruit as many participants as possible, the heads of the SAMU Foundation contacted the directors of 15 local associations in Seville (Spain) that attend to individuals with ID to invite them to participate. In these contacts, the procedures and objectives of the study were explained to the directors of the interested centers. Subsequently, each center director contacted their clients and their families to invite them to participate. An information sheet was used. Those individuals with ID who showed interest in participating were given a consent form to be signed by each participant and co-signed by their legal guardians if necessary. Of the 15 organizations consulted, 12 agreed to collaborate. In addition to the participation consent, all participants were required to submit a medical authorization, signed by their referring physician, that confirmed their ability to carry out physical activity without risk to their health. Of the 753 individuals with ID contacted, 300 were selected. Finally, the study included 261 people between 18 and 65 years old with mild or moderate ID (82 women and 179 men), of whom 37 had Down syndrome (11 women and 26 men).

The biomedical committee of the competent government was asked to evaluate the research project (Biomedical Research Committee of the Junta de Andalucía, Andalucía, Spain), which was approved with internal code 0316-N-15. The study was conducted in accordance with the Declaration of Helsinki.

### 2.4. Materials

The SAMU DIS-FIT battery

After the application of the criteria described above all those tests that did not meet these criteria were discarded. Finally, the battery was composed of the following tests: body composition (body mass index and waist circumference), muscular strength (upper, middle, and low body strength), flexibility, motor fitness (dynamic balance), and cardiorespiratory fitness. The procedures for performing the tests can be read elsewhere [20,21].

(1) Body composition

The body mass index (BMI) was selected for the assessment of body composition for its reliability and feasibility in the ID population [19]. The BMI has shown a good correlation with other instruments for measuring body composition [34], is simple to carry out, does not require complex equipment, and is cost-effective.

Besides the use of a general body fat index, the waist circumference (WC) was measured as an index of the visceral adipose tissue, located in the middle of the body. The WC has shown strong correlations with other body composition measures that provide good validity results [34]. The results of feasibility and reliability tests have shown good values in individuals with severe intellectual and sensory disabilities [19], and its use is simple and affordable, so the research team decided to include it in the battery. Body composition tests do not require the active participation of the participants, so they do not involve demands on cognitive or motor functions.

(2) Muscular strength

To assess muscle strength, three different tests were selected: (i) Grip Strength (GS), (ii) 30 s Sit Up (SUP), and (iii) the Timed Stand Test (TST). The use of three tests was justified by the need to assess different manifestations of strength and different muscle groups as a basis for determining a person's PF [2,15].

The GS test measures the muscle tension that can be generated by the muscles of the hand and forearm and is related to the ability to perform daily tasks and to the nutritional status of a person. This test has previously been tested for its psychometric properties of reliability and feasibility in older individuals with severe ID, obtaining good results [16]. The validity of the test has shown positive results in older adults [10].

The SUP estimates the endurance strength of the abdominal muscles and the hip flexors. For this purpose, the test proposed by Skowroński et al. was adapted [35] so that it records a repetition if the subjects manage to touch their knees with their hands. This test has obtained good indices of validity [36] and reliability [32] in individuals with ID, but previous feasibility studies are lacking, so it was decided to include it in the battery in order to find out its suitability in individuals with ID.

For the assessment of lower limb strength, the 10-repetition TST was used because it was thought that individuals with ID would have better results in brief, targeted tests in which they can manage their effort (10 repetitions as quickly as possible) more easily than in longer tests. The validity and reliability of this test have previously been tested in people with different diseases [37]. No previous feasibility studies were found in adults with moderate ID. However, Hilgenkamp, Van Wijck, and Evenhuis [16] found moderate values of feasibility and good reliability in the 30 s TST in elderly adults with severe ID.

All three tests require cost-effective instruments, as well as low cognitive and motor involvement of the participants in performing the tests, so the research team selected them to be included in the final battery.

(3) Dynamic balance

No static tests were used to assess body balance. In previous studies conducted with populations with similar ID characteristics, the reliability results of the One-Leg Stand test were low [38], so tests on one foot were discarded and replaced by more natural dynamic tests. The selected test was a modification of the Timed Up and Go (TUAG) test [39]. The reliability of the test has previously been studied in individuals with ID [40], but in the test, the subjects moved at "a comfortable speed." In our opinion, it is easier and more reliable to move "as fast as possible" than to prescribe a comfortable speed. Validity tests in previous studies have obtained excellent results for people with chronic stroke [41]. No previous feasibility data were found, but the test was included with the aim of assessing its suitability in the population with ID, as well as for its simplicity and reduced cost.

(4) Flexibility

Flexibility would be assessed with the Deep Trunk Flexibility (DTF) test, which measures the range of motion in the spine and hip during deep trunk flexion. Although no previous studies of validity, feasibility, or reliability of the test were found, its choice was based on the fact that its execution is similar to the execution of everyday tasks, such as picking up objects from the ground, making it a simple and cost-effective test.

(5) Cardiorespiratory fitness

Cardiorespiratory fitness is one of the main components of PF. The 6-Minute Walk Test (6MWT) has previously been tested in different studies to determine its reliability and validity in populations with ID, showing excellent values both in adults [17,32] and in adolescents [42]. However, these studies have been carried out with small samples and without differentiating participants according to sex. Regarding the feasibility of the test, Wouters et al. [18] found positive results in children with ID. The equipment needed to perform the test is inexpensive, and the test requires participants to perform a regular activity of daily life, so the test was included in the final battery.

### *2.5. Duration and Order of Test Administration*

The research team went in groups of five people with the testing material to each of the care centers to assess the residents who had given their consent to participate. The assessments were always carried out between 10 a.m. and 2 p.m. The tests were conducted between January 2018 and December 2018. This was one of the great challenges of the research group, since all the staff had to organize themselves in order not to miss the weekly evaluations. In the first half of the year, 160 people were assessed, and in the second half, after the summer months, 101 people. On average, about 10 subjects were assessed per week.

The duration of the tests depended on the characteristics of each participant. It was recommended that there were several evaluators in order to make a wheel of measurements that allowed the evaluation of an average of five people in 1 h. Owing to the attentional and memory characteristics of people with ID, it was not possible to give the information about how to perform the tests collectively, so it was necessary to explain the protocol to each participant individually. Therefore, the total battery duration was 30–45 min per person. Explanations, demonstrations, and attempts are included in that period of time.

Regarding the order of the application of the tests, the recommendation is to perform the body composition test at the beginning and the cardiorespiratory fitness test at the end. The remaining tests can be applied in any order or counterbalancing, as none of them involve such a significant effort that they can influence the performance of the subsequent tests. As a guideline, this could be the order of a complete assessment:

(1) Body composition (5–8 min)
(2) Timed Up and Go (2–3 min)
(3) Deep Trunk Flexibility (2–3 min)
(4) Grip Strength (3 min)
(5) Sit Up (5 min)
(6) Timed Stand Test (5–10 min)
(7) 6-Minute Walk Test (10 min)

### *2.6. Data Analysis*

To categorize each of the quantitative variables of PF into three levels, we used 95% of the mean confidence interval (mean 95%CI) for each group (men, women) and for each age range (young [< 30 years old], middle-aged [30–50 years old], and old [>50 years old]). Based on the mean 95%CI, the values above and below this interval were established, following Bohannon's indications [43]. In this way, the results were grouped into three categories: lower-fit (results under mean 95%CI), mid-fit (mean 95%CI), and higher-fit (over mean 95%CI). The values obtained were rounded to the nearest whole number. Finally, to calculate the percentages and number of subjects in each PF category, custom tables were designed for each variable, sex, and age range. All these analyses were performed in SPSS, PASW Statistics 18 (IBM, Inc., Armonk, NY, USA).

## **3. Results**

Figure 1 shows the flow chart with the whole sample participating in the project. Concerning the achievement of the first objective of this study, all the criteria that were established for the design of the battery have been explained. The results of reliability and feasibility have been published previously [20,21]. The results on PF obtained by the participants according to sex, age, and level of PF can be found in Tables 1–6.

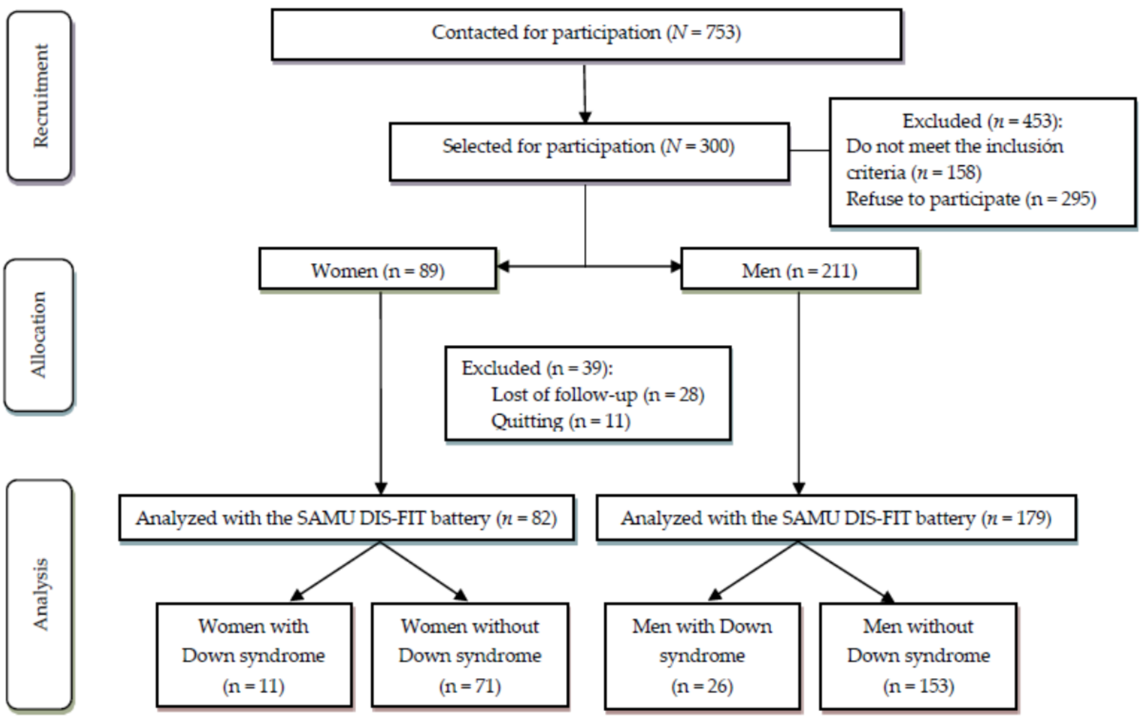


**Figure 1.** Study flowchart.

**Table 1.** Younger men (<30 years old) results for each variable categorized in 3 physical fitness levels.

| N = 179; n = 46 (N% = 25.7) | | Higher-Fit | Mid-Fit | Lower-Fit |
|---|---|---|---|---|
| **BMI (kg/m$^2$)** | Cutoff point | <27 | 27–30 | >30 |
| | Mean | 23.1 | 28.6 | 34 |
| | Nº of people (n%) | 18 (39.1%) | 11 (23.9%) | 17 (37%) |
| **WC (cm)** | Cutoff point | <91 | 91–99 | >99 |
| | Mean | 81.9 | 96.4 | 108.9 |
| | Nº of people (n%) | 20 (43.5%) | 8 (17.4%) | 18 (39.1%) |
| **GS (kg)** | Cutoff point | >34 | 28–34 | <28 |
| | Mean | 41.7 | 30.1 | 21.8 |
| | Nº of people (n%) | 19 (41.3%) | 11 (23.9%) | 16 (34.8%) |
| **SUP (rep)** | Cutoff point | >20 | 16–20 | <16 |
| | Mean | 23.9 | 17.4 | 11.1 |
| | Nº of people (n%) | 19 (41.3%) | 11 (23.9%) | 16 (34.8%) |
| **TST (s)** | Cutoff point | <16 | 16–20 | >20 |
| | Mean | 12.57 | 17.45 | 25.29 |
| | Nº of people (n%) | 22 (47.8%) | 8 (17.4%) | 16 (34.8%) |
| **TUAG (s)** | Cutoff point | <4 | 4–5 | >5 |
| | Mean | 3.4 | 4.6 | 5.9 |
| | Nº of people (n%) | 23 (50%) | 13 (28.3%) | 10 (21.7%) |
| **DTF (cm)** | Cutoff point | >40 | 35–40 | <35 |
| | Mean | 45.1 | 36.8 | 27.8 |
| | Nº of people (n%) | 22 (47.8%) | 8 (17.4%) | 16 (34.8%) |
| **6MWT (m)** | Cutoff point | >595 | 532–595 | <532 |
| | Mean | 673.4 | 571.5 | 466.4 |
| | Nº of people (n%) | 17 (37.0%) | 9 (19.6%) | 20 (43.5%) |

BMI, body mass index; WC, waist circumference; GS, grip strength; SUP, 30 s Sit Up; TST, timed stand test; TUAG, timed up and go; DTF, Deep trunk flexibility; 6MWT, 6 min walk test.

**Table 2.** Middle-aged men (30–50 years old) results for each variable categorized in 3 physical fitness levels.

| N = 179; n = 111 (N% = 62) | | Higher-Fit PF | Mid-Fit | Lower-Fit |
|---|---|---|---|---|
| **BMI (kg/m$^2$)** | Cutoff point | <27 | 27–30 | >30 |
| | MeanNº of people (n%) | 23.6<br>46 (41.4%) | 28.6<br>28 (25.2%) | 34.5<br>37 (33.3%) |
| **WC (cm)** | Cutoff point | <96 | 96–101 | >101 |
| | Mean | 86.7 | 98.7 | 110.6 |
| | Nº of people (n%) | 50 (45%) | 13 (11.7%) | 48 (43.2%) |
| **GS (kg)** | Cutoff point | >32 | 29–32 | <29 |
| | MeanNº of people (n%) | 38.5<br>51 (45.9%) | 30.0<br>8 (7.2%) | 23.3<br>52 (46.8%) |
| **SUP (rep)** | Cutoff point | >19 | 16–19 | <16 |
| | Mean | 22.2 | 17.2 | 11.3 |
| | Nº of people (n%) | 56 (50.4%) | 14 (12.6%) | 41 (37%) |
| **TST (s)** | Cutoff point | >20 | 18–20 | <18 |
| | Mean | 24.9 | 18.9 | 14.8 |
| | Nº of people (n%) | 43 (38.7%) | 14 (12.6%) | 54 (48.6%) |
| **TUAG (s)** | Cutoff point | <4 | 4–5 | >5 |
| | Mean | 3.5 | 4.5 | 6.2 |
| | Nº of people (n%) | 47 (42.4%) | 40 (36%) | 24 (21.6%) |
| **DTF (cm)** | Cutoff point | >36 | 33–36 | <33 |
| | Mean | 41.4 | 34 | 26.8 |
| | Nº of people (n%) | 51 (45.9%) | 18 (16.2%) | 42 (37.9%) |
| **6MWT (m)** | Cutoff point | >538 | 503–538 | <503 |
| | Mean | 607.5 | 519.3 | 430.8 |
| | Nº of people (n%) | 48 (43.2%) | 18 (16.2%) | 45 (40.6%) |

BMI, body mass index; WC, waist circumference; GS, grip strength; SUP, 30 s Sit Up; TST, timed stand test; TUAG, timed up and go; DTF, Deep trunk flexibility; 6MWT, 6 min walk test.

**Table 3.** Older men (>50 years old) results for each variable categorized in 3 physical fitness levels.

| N = 179; n = 22 (N% = 12.3) | | Higher-Fit | Mid-Fit | Lower-Fit |
|---|---|---|---|---|
| **BMI (kg/m²)** | Cutoff point | <25 | 25–30 | >30 |
| | Mean | 20.9 | 27 | 32.9 |
| | Nº of people (n%) | 6 (27.3%) | 7 (31.8%) | 9 (40.9%) |
| **WC (cm)** | Cutoff point | <89 | 89–101 | >101 |
| | Mean | 77.2 | 95.6 | 107.4 |
| | Nº of people (n%) | 6 (27.3%) | 7 (31.8%) | 9 (40.9%) |
| **GS (kg)** | Cutoff point | >28 | 23–28 | <23 |
| | Mean | 31.2 | 24.9 | 19.5 |
| | Nº of people (n%) | 8 (36.4%) | 6 (27.3%) | 8 (36.4%) |
| **SUP (rep)** | Cutoff point | >17 | 13–17 | <13 |
| | MeanNº of people (n%) | 20.3<br>9 (40.9%) | 15.3<br>5 (22.7%) | 10<br>8 (36.4%) |
| **TST (s)** | Cutoff point | <18 | 18–24 | >24 |
| | Mean | 15.7 | 19.9 | 29.1 |
| | Nº of people (n%) | 8 (36.4%) | 7 (31.8%) | 7 (31.8%) |
| **TUAG (s)** | Cutoff point | <4 | 4–5 | >5 |
| | Mean | 3.7 | 4.6 | 5.9 |
| | Nº of people (n%) | 3 (13.6%) | 11 (50%) | 8 (36.4%) |
| **DTF (cm)** | Cutoff point | >35 | 26–35 | <26 |
| | Mean | 40.1 | 29.8 | 17.6 |
| | Nº of people (n%) | 8 (36.4%) | 8 (36.4%) | 6 (27.2%) |
| **6MWT (m)** | Cutoff point | >575 | 457–575 | <457 |
| | MeanNº of people (n%) | 620.3<br>2 (9.1%) | 508.9<br>11 (50%) | 428.3<br>9 (40.9%) |

BMI, body mass index; WC, waist circumference; GS, grip strength; SUP, 30 s Sit Up; TST, timed stand test; TUAG, timed up and go; DTF, Deep trunk flexibility; 6MWT, 6 min walk test.

**Table 4.** Younger women (<30 years old) results for each variable categorized in 3 PF levels.

| N = 82; n = 23 (N% = 28) | | Higher-Fit | Mid-Fit | Lower-Fit |
|---|---|---|---|---|
| **BMI (kg/m²)** | Cutoff point | <25 | 25–31 | >31 |
| | Mean | 22.3 | 27.7 | 37 |
| | Nº of people (n%) | 8 (34.8%) | 9 (39.1%) | 6 (26.1%) |
| **WC (cm)** | Cutoff point | <83 | 83–96 | >96 |
| | Mean | 72.8 | 90.5 | 105.8 |
| | Nº of people (n%) | 8 (34.8%) | 7 (30.4%) | 8 (34.8%) |
| **GS (kg)** | Cutoff point | >26 | 20–26 | <20 |
| | Mean | 30.7 | 23 | 17 |
| | Nº of people (n%) | 8 (34.8%) | 5 (21.7%) | 10 (43.5%) |
| **SUP (rep)** | Cutoff point | >18 | 14–18 | <14 |
| | Mean | 21.7 | 15.7 | 11 |
| | Nº of people (n%) | 7 (30.4%) | 11 (47.9%) | 5 (21.7%) |
| **TST (s)** | Cutoff point | <18 | 18–23<br>20.36 (26.1%) | >23 |
| | Mean | 15.2 | | 27.8 |
| | Nº of people (n%) | 10 (43.5%) | | 7 (30.4%) |
| **TUAG (s)** | Cutoff point | <4 | 4–5 | >5 |
| | MeanNº of people (n%) | 3.5<br>4 (17.4%) | 4.4<br>14 (60.9%) | 6.4<br>5 (21.7%) |
| **DTF (cm)** | Cutoff point | >38 | 31–38 | <31 |
| | Mean | 43.2 | 35.1 | 21.9 |
| | Nº of people (n%) | 7 (30.4%) | 10 (43.4%) | 6 (26.1%) |
| **6MWT (m)** | Cutoff point | >551 | 457–551 | <457 |
| | Mean | 624.7 | 502.2 | 400.4 |
| | Nº of people (n%) | 6 (26.1%) | 12 (52.2%) | 5 (21.7%) |

BMI, body mass index; WC, waist circumference; GS, grip strength; SUP, 30 s Sit Up; TST, timed stand test; TUAG, timed up and go; DTF, Deep trunk flexibility; 6MWT, 6 min walk test.

**Table 5.** Middle-aged women (30–50 years old) results for each variable categorized in 3 PF levels.

| N = 82; n = 47 (N% = 57.3) | | Higher-Fit | Mid-Fit | Lower-Fit |
|---|---|---|---|---|
| **BMI (kg/m²)** | Cutoff point | <30 | 30–34 | >34 |
| | Mean | 25.2 | 32.2 | 39.5 |
| | Nº of people (n%) | 17 (36.2%) | 13 (27.6%) | 17 (36.2%) |
| **WC (cm)** | Cutoff point | <96 | 96–105 | >105 |
| | Mean | 85.7 | 101.3 | 115.3 |
| | Nº of people (n%) | 20 (42.5%) | 7 (15%) | 20 (42.5%) |
| **GS (kg)** | Cutoff point | >23 | 19–23 | <19 |
| | Mean | 28.4 | 20.6 | 15.5 |
| | Nº of people (n%) | 14 (29.8%) | 16 (30%) | 18 (38.2%) |
| **SUP (rep)** | Cutoff point | >16 | 13–16 | <13 |
| | Mean | 21.1 | 14.5 | 8.4 |
| | Nº of people (n%) | 17 (36.2%) | 14 (29.8%) | 16 (34%) |
| **TST (s)** | Range | <20 | 20–23 | >23 |
| | Mean | 15.4 | 21.6 | 28.1 |
| | Nº of people (n%) | 17 (36.2%) | 15 (31.9%) | 15 (31.9%) |
| **TUAG (s)** | Cutoff point | <4 | 4–5 | >5 |
| | Mean | 3.7 | 4.5 | 6.6 |
| | Nº of people (n%) | 11 (23.4%) | 22 (46.8%) | 14 (29.8%) |
| **DTF (cm)** | Cutoff point | >35 | 31–35 | <31 |
| | Mean | 40.4 | 32.5 | 26.8 |
| | Nº of people (n%) | 16 (34%) | 15 (32%) | 16 (34%) |
| **6MWT (m)** | Cutoff point | | | |
| | Mean | >489 | 444–489 | <444 |
| | Nº of people (n%) | 18 (38.2%) | 12 (25.6%) | 17 (36.2%) |

BMI, body mass index; WC, waist circumference; GS, grip strength; SUP, 30 s Sit Up; TST, timed stand test; TUAG, timed up and go; DTF, Deep trunk flexibility; 6MWT, 6 min walk test.

**Table 6.** Older women (>50 years old) results for each variable categorized in 3 PF levels.

| N = 82; n = 12 (N% = 14.6) | | Higher-Fit | Mid-Fit | Lower-Fit |
|---|---|---|---|---|
| **BMI (kg/m²)** | Cutoff point | <24 | 24–31 | <31 |
| | Mean | 20.8 | 26.3 | 35.6 |
| | Nº of people (n%) | 2 (16.7%) | 7 (58.3%) | 3 (25%) |
| **WC (cm)** | Cutoff point | <83 | 83–96 | >96 |
| | Mean | 77.9 | 86.8 | 103.8 |
| | Nº of people (n%) | 2 (16.7%) | 7 (58.3%) | 3 (25%) |
| **GS (kg)** | Cutoff point | >23 | 17–23 | <17 |
| | Mean | 30.7 | 20.5 | 15.1 |
| | Nº of people (n%) | 1 (8.3%) | 8 (66.7%) | 3 (25%) |
| **SUP (rep)** | Cutoff point | >21 | 10–21 | <10 |
| | Mean | 29 | 16.8 | 7 |
| | Nº of people (n%) | 2 (16.7%) | 7 (58.3%) | 3 (25%) |
| **TST (s)** | Cutoff point | <18 | 18–23 | >23 |
| | Mean | 16.8 | 20.1 | 29.2 |
| | Nº of people (n%) | 3 (25%) | 7 (58.3%) | 2 (16.7%) |
| **TUAG (s)** | Cutoff point | <4 | 4–6 | >6 |
| | Mean | 3.2 | 4.7 | 7 |
| | Nº of people (n%) | 1 (8.3%) | 7 (58.3%) | 4 (33.4%) |
| **DTF (cm)** | Cutoff point | >39 | 29–39 | <29 |
| | Mean | 42.9 | 36.2 | 22.8 |
| | Nº of people (n%) | 4 (33.4%) | 5 (41.7%) | 3 (25%) |
| **6MWT (m)** | Cutoff point | >519 | 430–519 | <430 |
| | MeanNº of people | 546.6 | 501.6 | 387.24 |
| | (n%) | 3 (25%) | 5 (41.7%) | (33.3%) |

BMI, body mass index; WC, waist circumference; GS, grip strength; SUP, 30 s Sit Up; TST, timed stand test; TUAG, timed up and go; DTF, Deep trunk flexibility; 6MWT, 6 min walk test.

The custom tables resulted in three categories for the male participants: younger (n = 46), middle-aged (n = 111), and older (n = 22). For women, the sample sizes for each category were as follows: younger (n = 23), middle-aged (n = 47), and older (n = 12).

In the male group, more than half of the young and middle-aged (18–50 years) participants had a BMI > 27 kg/m$^2$. More than 72% of those over 50 years old had a BMI > 25 kg/m$^2$. All the male participants had WC results > 89 cm. In the group of young women, more than 50% presented a BMI above 25 kg/m$^2$ and a WC > 83 cm. Almost 70% of the women between 30 and 50 years presented a BMI > 30 kg/m$^2$, and more than 50% a WC > 96 cm. Approximately 85% of the old women had a BMI above 24 kg/m$^2$ and a WC of more than 83 cm.

As for the variables related to muscle strength, dynamic balance, and flexibility, approximately 50% of the young and middle-aged men were in the higher-fit range. However, only 17 out of 46 young men were in that category for the cardiorespiratory fitness test. Between 36.4% and 40.9% of men over the age of 50 were in the higher-fit category for the GS, SUP, TST, and DTF tests. Only 3 (13.6%) and 2 (9.1%) people had the highest values in the TUAG and 6MWT tests, respectively.

Between 30.4% and 43.5% of the younger women obtained higher-fit values in the GS, SUP, TST, and DTF tests. However, these percentages were lower in the TUAG and 6MWT tests (17.4% and 26.1%, respectively). The tests in which more middle-aged women fell in the higher-fit category were the SUP and TST (36.2%) and 6MWT (38.2%) tests. In the older women group, all the PF variables were in the mid-fit and lower-fit categories.

## 4. Discussion

This is the first study to present PF values of adults with ID categorized into lower-fit, mid-fit, and higher-fit groups. It is necessary to point out that in this study, no attempt was made to relate belonging to one of these categories to a better health status. The author has just established three levels of PF according to the results of the participants themselves, thus avoiding a comparison with individuals without disabilities. The results of PF tests in any type of population need an interpretation of the data to give meaning to the values achieved by a particular person. In this type of studies, the results obtained by individuals with disabilities are usually compared with those obtained by individuals without disabilities [8,44]. This can be interesting if the reference values that establish relationships between the levels of fitness and health are included. However, because the personal and social development as well as the characteristics of individuals with and without ID are not similar, it seems inappropriate to make comparisons between both groups. If this is done, a person with ID who has good values within his or her group will present a low fitness level when compared with individuals with typical development, just as an older person will have lower PF results than a younger person of the same sex.

Since there are no previous studies conducted on individuals with ID that present their results categorized by PF level, it is necessary to discuss our findings by making comparisons with the results of other studies in which central tendency data, such as the mean, are presented and in which the same assessment instruments have been used as in the present work.

In a study conducted by Boer and Moss [32], in which PF was assessed in 43 adults with Down syndrome aged 18–45 years, average BMI values of 30.3 kg/m$^2$ were found. In the same work, the values obtained by the participants in the 6MWT ranged from 513 to 578 m. Both results are similar to those of the present study. However, the participants of the SAMU DIS-FIT study present average values of 30 kg in the GS tests. This difference may be due to the fact that men and women were included in the same group in Boer and Moss's study, so their results are lower. Hilgenkamp, van Wijck, and Evenhuis [4] obtained values close to 30 kg in GS tests performed on a large sample of older men with severe ID and values between 20.08 and 21.34 kg in a group of women with the same characteristics.

Guerra et al. [17] performed cardiorespiratory fitness tests on 46 individuals with mild, moderate, and severe ID. The results from participants with mild and moderate ID showed means between 449.6

and 531.7 m in the 6MWT. Although their results are not presented for men and women separately, they are similar to those obtained in the present work.

In the 10-repetition TST, Cuesta-Vargas, Paz-Lourido, and Rodriguez [8] assessed 266 individuals with ID with a mean age of 31.1 years (187 males and 79 females) recruited from the Spanish Special Olympics Games. The men obtained mean values of 19.9 ± 9.5 s, while the women completed the test with mean values of 22.8 ± 9.7 s. Their results are similar to those obtained in the present study, both in the men's and women's groups.

Although no similar studies that used DTF, TUAG, and SUP tests have been found the present results cannot be compared with those in the literature, it is necessary to emphasize that the findings achieved by other researchers in assessment tests of GS, 6MWT, TST, and BMI are similar to those of the SAMU DIS-FIT study, which could indicate that the reference values presented here are not different from those obtained by individuals with ID who participated in other studies.

In light of the results of this study, it should be noted that a high percentage of people with mild or moderate ID of both sexes present medium and low PF values. This low PF impairs the quality of life and lowers the life expectancy of people with ID more than being obese [45] and leads to high costs of families and health systems. However, other authors state that despite having low fitness, individuals with ID who minimally improve their PF gain significant health benefits [44]. In this sense, this paper may be useful in guiding clinicians to design and run physical exercise programs to improve the PF level of individuals with ID, so that minimally improving the score of a given PF component could significantly improve a person's level of health. For example, an old man who scores 20 kg in the GS test would be in the lower-fit level, but if he managed to improve his performance by 3 kg and be in the mid-fit level, he could be significantly improving his health. To this end, some authors have suggested different types of physical exercise programs that can generate benefits in PF of individuals with intellectual disabilities [46].

One of the most relevant aspects of knowing the PF of adults with ID is to make predictions regarding their functional performance based on their own results. In this respect, Terblanche and Boer [36] studied the functional fitness capacity of 371 adults with Down syndrome. The researchers found that the capacity most closely related to functional independence for activities of daily living was leg strength, both for men and women, but also grip strength. In the same vein, other studies analyzed the relationship between different PF components and gait parameters in 31 adults with ID. They found that body composition was related to gait performance at comfortable speed but that muscular endurance and body balance were related to gait performance at fast speed [47]. This is important because a decrease in walking speed has been associated with a lack of autonomy, disability, risk of falls, and mortality. In a longitudinal study conducted with 601 older adults with ID [48], different PF components (manual dexterity, balance, gait speed, muscular endurance, and cardiorespiratory fitness) were related to PF decline after 3 years, so PF turns out to be a fundamental aspect in maintaining activities of daily living and autonomy in adults with ID. In this sense, using the SAMU DIS-FIT, and making comparisons with the values presented here, can help individuals with ID, their families and clinicians to know their fitness level and make predictions based on those results in order to carry out physical activity programmes that improve their level of autonomy in the future.

The present study's limitations are related mainly to the size of the sample. On the one hand, although a total sample of 261 individuals with ID is substantial, it is not large enough to establish reference values for the whole population with ID. It is therefore necessary to stepwise increase the number of individuals with ID who are assessed with the same instruments so that the database can be expanded and bigger sample sizes can be reached in order to establish PF reference values for the ID population. On the other hand, because of the categorization of the results into age groups, the sample sizes of the groups, especially those with older participants, became too small to be representative of people with ID.

Finally, the scientific field must establish PF reference values for the population with ID in order to know their capacities without falling into the error of demanding the same levels of PF as those established for adults without disabilities. Knowing the limitations and potential of individuals with ID will make it possible to set up respectful health improvement programs that are suited to their particularities and characteristics.

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MDPI

*Brief Report*

# Descriptive Kinematic Analysis of the Potentially Tragic Accident at the 2020 Austrian MotoGP Grand Prix Using Low-Cost Instruments: A Brief Report

**Marco Gervasi *, Erica Gobbi, Valentina Natalucci, Stefano Amatori and Fabrizio Perroni**

Department of Biomolecular Sciences, University of Urbino, 61029 Urbino, Italy; erica.gobbi@uniurb.it (E.G.); valentina.natalucci@uniurb.it (V.N.); s.amatori1@campus.uniurb.it (S.A.); fabrizio.perroni@uniurb.it (F.P.)

* Correspondence: marco.gervasi@uniurb.it; Tel.: +39-07-2230-3413

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**Abstract:** Background: During the first Austrian MotoGP Grand Prix of 2020, following a serious accident involving the riders J. Zarco and F. Morbidelli, Morbidelli's riderless bike cartwheeled across turn 3, narrowly missing V. Rossi and M. Viñales by just a few centimeters. As is the case with ordinary traffic accidents, analyzing the dynamics of motorcycle racing accidents can help improve safety; however, to date, the literature lacks studies that analyze the causes and severity of such accidents. Hence, the purpose of this study was to analyze the main causes that led to the accident at the 2020 Austrian MotoGp Grand Prix, to quantify the speeds and distances of the bikes and riders involved, and to hypothesize several alternative scenarios using a low-cost method. Method: Kinovea and Google Earth Pro software were used to identify markers along the racetrack and to measure the distances and calculate the time it took the motorcycles to cover those distances. The analyses were carried out on three 30-fps (frames per second) videos. Results: Zarco's average speed as he was overtaking Morbidelli on the straightaway before turn 2 was 302 ± 1.8 km/h, higher than that of Rins and Rossi (299.7 ± 1.7 and 296 ± 1.7 km/h, respectively). The speed of Zarco and Rossi's bikes 44.5 m before the crash was the same (267 ± 7.9 km/h). Immediately after overtaking Morbidelli, Zarco moved 2.92 m towards the center of the racetrack from point A to B, crossing Morbidelli's trajectory and triggering the accident. Morbidelli's riderless bike flew across turn 3 at a speed of about 76 km/h, missing V. Rossi by just 20 cm. The consequences could have been catastrophic if Rossi had not braked just 0.42 s before encountering Morbidelli's bike in turn 3. Conclusion: Through a low-cost quali-quantitative analysis, the present study helps us to gain a deeper understanding of the dynamics of the accident and its main causes. Furthermore, in light of our findings regarding the dynamics and severity of the accident and the particular layout of the Red Bull Ring circuit, racers should be aware that overtaking at the end of turn 2, following the same trajectory as the riders involved in the crash, could be very risky.

**Keywords:** MotoGP; video analysis; collision; accident; safety

## 1. Introduction

Motorcycle racing in the elite MotoGP class attracts millions of spectators worldwide, with riders competing in 18 races across the globe each year. Crashes are a rare but regular feature of elite motorcycle racing [1–3], with a prevalence of 9.7 per hundred rider hours, while injuries are uncommon, occurring in only 9% of crashes [4]. In a recent study, Bedolla et al. identified four basic crash types in elite motorcycle racing: lowside, highside, topside, and collision crashes [4]. The causes and dynamics of such accidents are multiple and, without reliable data, difficult to understand. However, as is often done in the case of ordinary traffic accidents, a reliable analysis of motorcycle crash dynamics can be made using video footage, providing us with insights into the causes of the accident and, in some cases, leading to improvements in safety conditions [5–8].

In particular, in the case of ordinary traffic accidents, the video footage that is analyzed comes from safety cameras installed in vehicles, from smartphones [5,8], or from surveillance cameras found in the area of the accident [7]. This footage is then analyzed using software that allows us to precisely measure distances, speed, and angles and hence, reconstruct specific trajectories. Nevertheless, in these cases, there are limitations stemming from the difficulty of obtaining video footage from different angles, as well as limitations related to the frequency of the frames per second of the images, which can vary according to the type of camera being used. On the contrary, elite MotoGp motorcycle races are filmed with cameras providing top quality images from multiple angles, making video analyses based on such footage more precise. Unfortunately, in the literature, there are few studies investigating the dynamics of accidents in motorcycle racing [6]. This lack of research is probably due to the inherent difficulty of obtaining data even though such sporting events are monitored by high definition cameras and multiple high precision sensors. In the absence of this sort of high-quality data, the analysis of television footage using low-cost instruments can provide insights into the dynamics and seriousness of accidents, as well as other key factors contributing to accidents, to improve race safety conditions. In this brief report, we analyzed the potentially catastrophic accident that occurred at the MotoGP Grand Prix in Austria on 16 August 2020. Veteran rider Valentino Rossi and his teammate Maverik Viñales miraculously emerged from the crash unscathed, narrowly avoiding being struck by not just one, but two airborne motorbikes. The circuit at the Austrian Grand Prix, namely the "Red Bull Ring" (see Figure 1), is among the fastest in the world [9], featuring numerous stretches where riders reach speeds of over 300 km/h, followed by sections that require them to slow down to 50–60 km/h. The total length of the track is 4318 m and it features 10 turns with a vertical drop of 65 m. In the specific case of the 2020 Austrian Grand Prix, the contact that occurred between the two bikes could easily have resulted in an unprecedented tragedy.

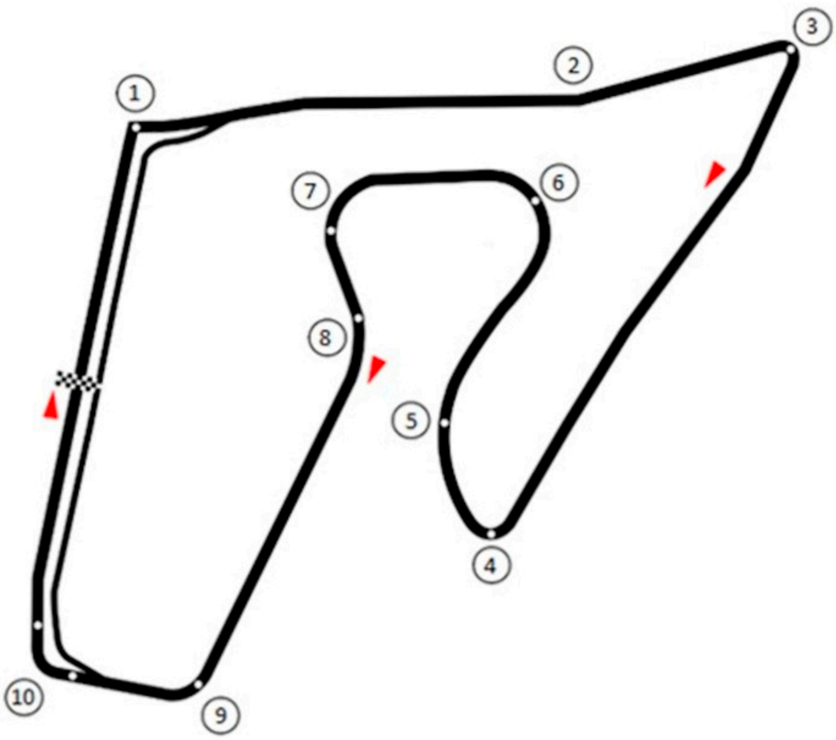


**Figure 1.** An overview of the Red Bull Ring circuit, Austria: points from 1 to 10 represent the turns in the track.

*Accident Description*

It all unfolded on the eighth lap of the race, as the riders raced down the straightaway between turns 2 and 3 (see Video S1). Until the moment of the crash, the riders were in the following order, from first to tenth: P. Espargaró, A. Dovizioso, J. Miller, J Mir, M. Oliveira, M. Viñales, V. Rossi, F. Morbidelli, J. Zarco, and A. Rins. The accident occurred after turn 2. Zarco had just overtaken Morbidelli and was preparing to enter turn 3, but moments after overtaking the other rider, Zarco's rear wheel came into contact with the front wheel of Morbidelli's bike, setting off a terrible chain of events. Following the contact, the two riders were thrown from their bikes, which continued careening down the track at high speed along different trajectories. Morbidelli's bike proceeded along the outer edge of the track in proximity to the curb, crossing over turn 3 and maintaining the same trajectory that it had been on in the straightaway leading into the curve. Zarco's bike followed a different trajectory, crashing into barriers, which, nonetheless, did not prevent it from careening across turn 3 an instant before Morbidelli's bike. Viñales and Rossi were rounding turn 3 just as the two bikes cartwheeled across their paths. Miraculously, Morbidelli and Zarco's bikes missed the riders by only a few centimeters. Zarco's bike, after striking the barriers, flew across the curve just a few centimeters over Vinales' helmet, while Morbidelli's bike sliced between Viñales (in front) and Rossi, crossing the latter rider's path. This accident has been the focus of a great deal of media attention, and in its wake, there have been numerous unconfirmed reports regarding the factors that may have led to the crash. Hence, the aim of the present study was to perform an analysis of the available race footage to answer the following questions: What were the main factors and dynamics that led to the accident? How fast was Morbidelli's bike travelling as it careened across Rossi's path? How close did Morbidelli's bike come to striking Rossi and why did it miss him? Can we quantify the hypothetical impact of Morbidelli's bike with Valentino Rossi?

## 2. Materials and Methods

The analysis of the available race footage was developed according the procedure showed in Figure 2.

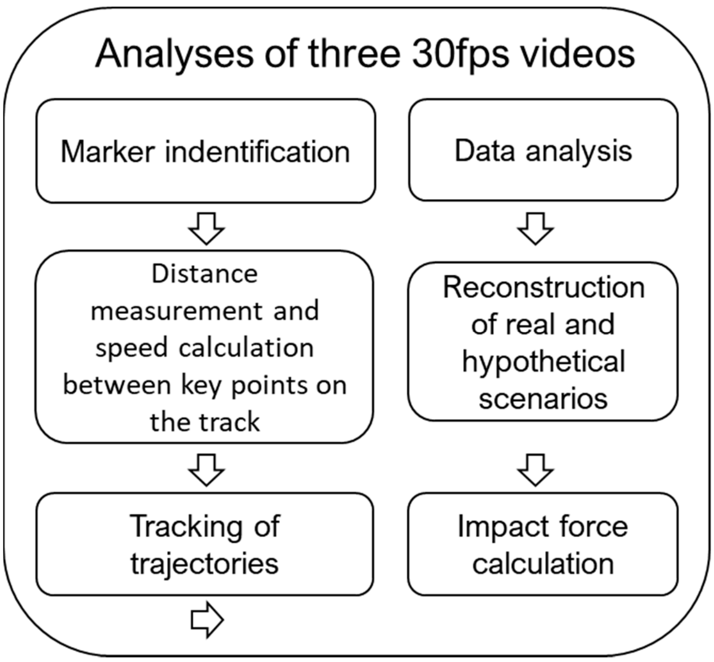


**Figure 2.** Chart showing the analytical procedures applied in the study.

The analysis was performed using Kinovea software (Kinovea ver. 0.8.15, open source project) [10] applied to three 30 fps (frames per second) videos (30 fps means that the camera captured 30 frames in a single second of video). Due to the video frame rate that limits precision to 0.03 s, we incorporated this error into the calculated speeds, showing the upper and lower average error estimates. Google Earth Pro software (Google LLC, Mountain View CA, USA) was used to measure the distance between the key points on the racetrack (see Figures 3–5). This software is scientifically validated for measurements of this kind [11]. Finally, Microsoft Excel (Microsoft Corporation, Redmond, WA, USA) was used to perform data analysis and to create the figures.


**Figure 3.** Satellite image showing the section of the straightaway from point A0 (corresponding to the point where the asphalt ends and the grass begins on the outer edge of the track) to point A (line between points G and H, where a shadow was cast directly under the "myWorld" billboard). The distance from A0 to A measures 288 m.

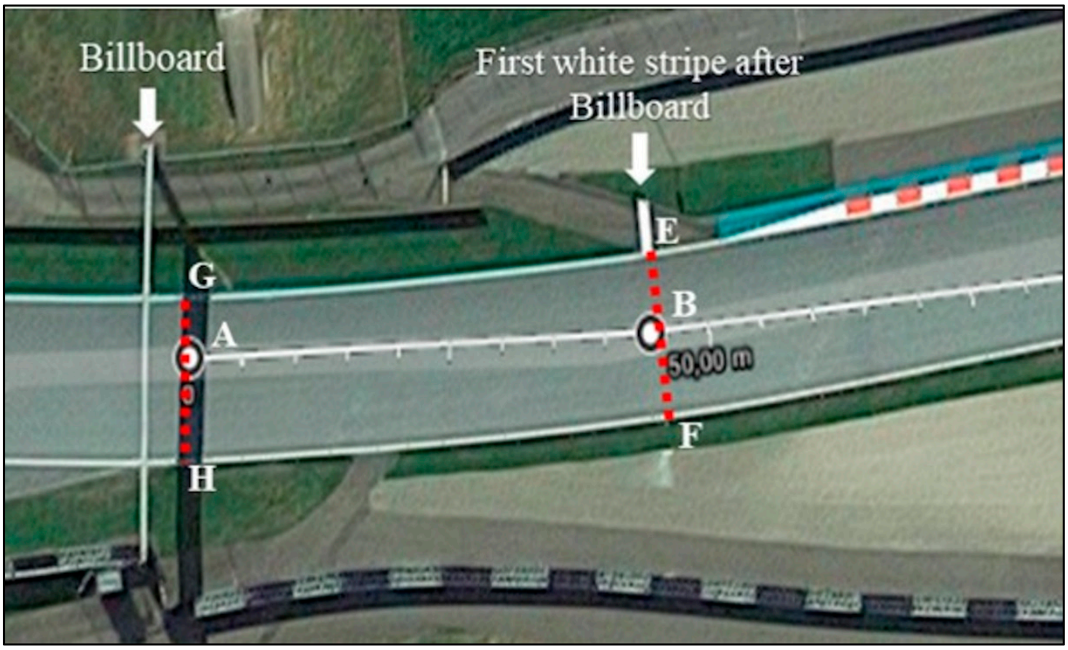


**Figure 4.** Satellite image showing the section of the straightaway before turn 3. The white arrows indicate a billboard and the first white stripe on the left side of the track (race direction). The red dashed lines were traced from point G to point H and from point E to point F. Points A and B indicate the crossing of the front wheel of Zarco's bike, as well as the front wheels of the other riders under consideration. The distance from point A to point B measures 44.5 m.

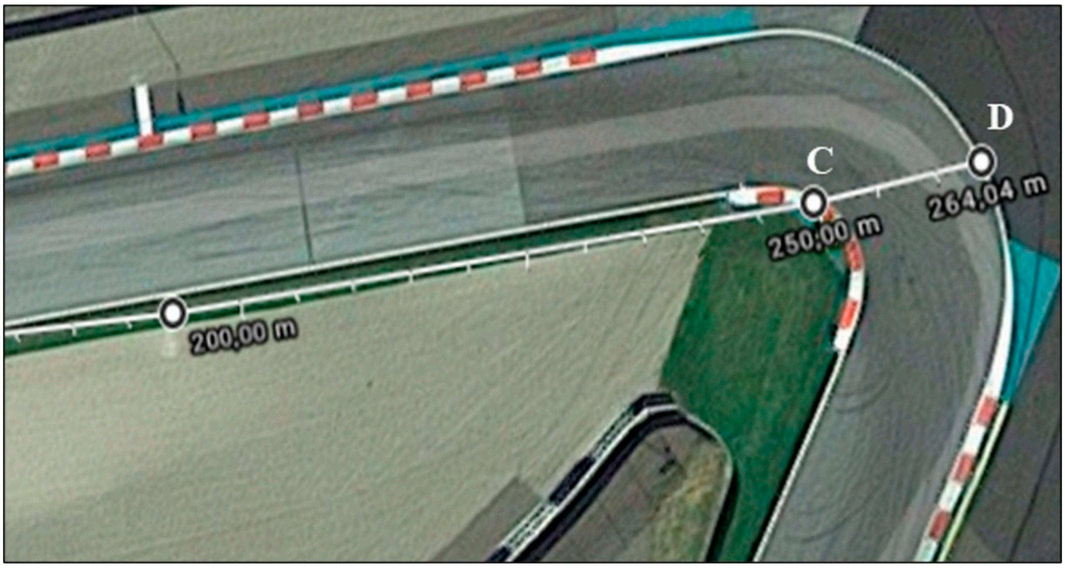


**Figure 5.** Satellite image showing the section of the straightaway leading into turn 3. Point C corresponds to a marker on the internal curb of turn 3, the point where Morbidelli's bike began cartwheeling across the track. Point D is shown by a marker on the outer edge of turn 3 with a trajectory that follows the line of the straightaway, the same trajectory that Morbidelli's bike followed as it cartwheeled across the curve. The line from C to D measures 14 m.

The first video was provided by a fixed camera near the track, while the other two videos were from the onboard cameras of Rins (second video) and Rossi (third video). In all three videos, but from different angles, we identified point A as the exact instant when the front wheel of Zarco's bike crossed the line between points G and H (Figure 4), where a shadow was cast directly under the 'myWorld' billboard, while point B indicates the exact instant when the front wheel of Zarco's bike crossed the line formed between the first white stripe, clearly visible on the left side of the track (point E) and the point on the opposite side of the racetrack (point F, Figure 4), just before Zarco and Morbidelli's bikes first made contact. Point C indicates the moment just before Morbidelli's bike began crossing turn 3, while point D indicates the moment when it had completed its trajectory across turn 3 (Figure 5). In the first video, provided by the fixed camera positioned near turn 3, we can see the straightaway where the accident took place and turn 3 as Rossi and Viñales encountered the careening bikes. In order to measure the movement of each rider towards the middle of the track immediately after turn 2, we used the first video to calculate the distance that the first nine riders maintained between their Front Wheel and the inner edge of the track at point G (FWG) and point E (FWE) (Figure 6); hence, we calculated the delta between the two distances ($\Delta$ = FWE − FWG). In addition, we traced the trajectories of the first nine riders and reported the movement of Morbidelli and Zarco immediately before, during, and after Zarco's overtaking of Morbidelli. In order to calculate the average speed of the bikes at various stages of the accident, we measured how long it took Zarco's bike to travel from point A to point B and Morbidelli's bike to travel from point B to point C and from point C to point D. Furthermore, examining the first video, we identified and analyzed the frame that captures the exact moment when Rossi encountered Morbidelli's bike in turn 3. Considering the measurement of the diameter of Morbidelli's rear wheel, we were able to measure how close the bike came to striking Rossi.

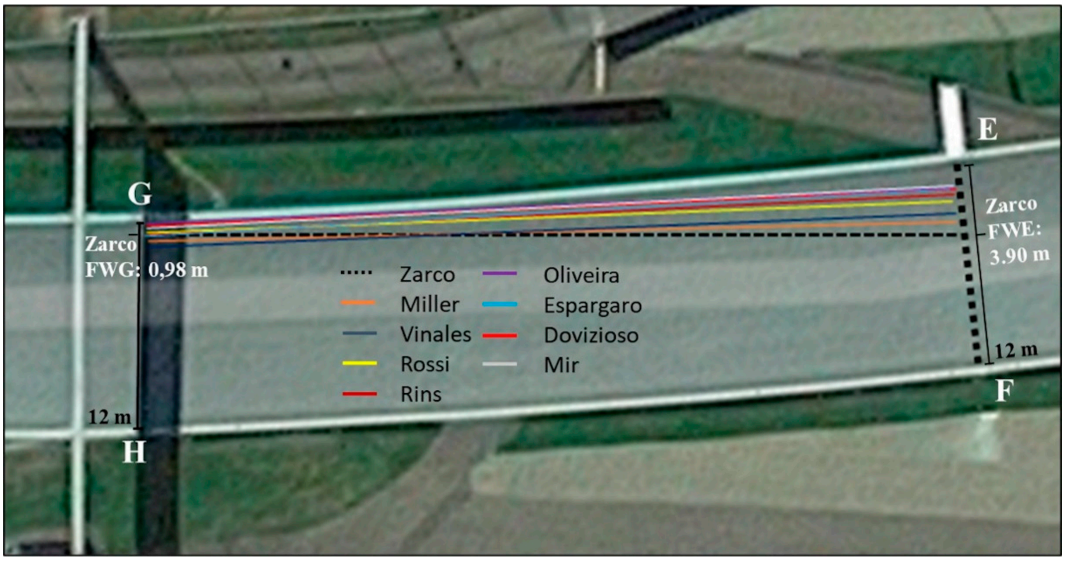


**Figure 6.** Distance between point G and point H: 12 m; distance between point E and point F: 12 m. The colored lines represent the trajectories of the first nine riders traced from point A, where the front wheels of the bikes cross the line between G and H, and point B, where they cross the line between E and F. We also reported the distance between Zarco's Front Wheel and point G (FWG) and between his Front Wheel and point E (FWE): FWG: 0.98 m; FWE: 3.90 m.

We also analyzed the second video from the onboard camera of Rins, who, at that moment in the race, was right behind Zarco and Morbidelli. The analysis of this footage allowed us to measure the average speed of Zarco and Rins before they headed into turn 2 and to identify the moment when the riders passed point A0 (corresponding to the point where the asphalt ends and the grass begins on the outer edge of the track; see Figure 3). Using Google Earth Pro, we then measured the distance between points A0 and A, and, using Kinovea, we measured the time it took Zarco and Rins to travel between those points. Moreover, in order to confirm the previous measurements made using the first video, the same calculations for Zarco and Morbidelli's bikes were performed from points A to B and from points C to D. Using the third video provided by the onboard camera of Rossi, which shows the speed of the rider in real time, we tested the reliability of the indirect measurements. Specifically, we compared Rossi's average speed from points A0 to A and from points A to B, calculated using both the average speed from all the collected frames and the time it took Rossi to travel the distances measured. To understand why Morbidelli's bike did not strike Rossi, we analyzed Rossi's actual speed and the lean angles from point A to the exact moment when Rossi encountered Morbidelli's bike. Finally, we hypothesized two alternative scenarios and calculated the potential impact force of a collision between Rossi and Morbidelli's bike.

## 3. Results

The distances between the key points, which were identified on the track and measured using Google Earth Pro, are reported in Table 1 (see Figures 3–5), whereas the FWG and FWE distances of the first nine riders and their delta are reported in Table 2.

From a qualitative standpoint, the analysis of the trajectory showed that Zarco, as he moved past Morbidelli, crossed the latter rider's trajectory, moving 2.92 m towards the center of the track (see Table 2 and Figures 6 and 7).

**Table 1.** Distances between key points on the racetrack.

| From Point | To point | Distance (m) |
|---|---|---|
| A0 | A | 288 |
| A | B | 44.5 |
| B | C | 205.3 |
| C | D | 14 |
| G | H | 12 |
| E | F | 12 |

A0 = point where the asphalt ends and the grass begins on the outer edge of the track; A = point where the front wheels of the riders cross the line between points G and H; B = point where the front wheels of the riders cross the line between points E and F; C = point where Morbidelli's bike began to cross the track of turn 3; D = point where Morbidelli's bike ended to cross turn 3; G and H = the two ends of the line cast directly under the "myWorld" billboard; E and F = the two ends of the segment crossing the racetrack starting from the first white stripe on the left side of the track.

**Table 2.** Distances between the front wheels of the first nine riders and points G (FWG) and E (FWE) and their Delta. Zarco's values are in bold.

| Pilots | FWG (m) | FWE (m) | Δ (FEW − FWG) (m) |
|---|---|---|---|
| Espargaró | 0.84 | 1.68 | 0.84 |
| Dovizioso | 0.3 | 1.65 | 1.35 |
| Miller | 1.35 | 3.6 | 2.25 |
| Mir | 0.39 | 1.5 | 1.11 |
| Oliveira | 0.28 | 1.81 | 1.53 |
| Viñales | 1.92 | 3.3 | 1.38 |
| Rossi | 0.83 | 2.5 | 1.67 |
| Zarco | **0.98** | **3.9** | **2.92** |
| Rins | 0.89 | 1.96 | 1.07 |

FWG = distance that the first nine riders maintained between their front wheel and the inner edge of the track at point G; FWE = distance that the first nine riders maintained between their front wheel and the inner edge of the track at point E.

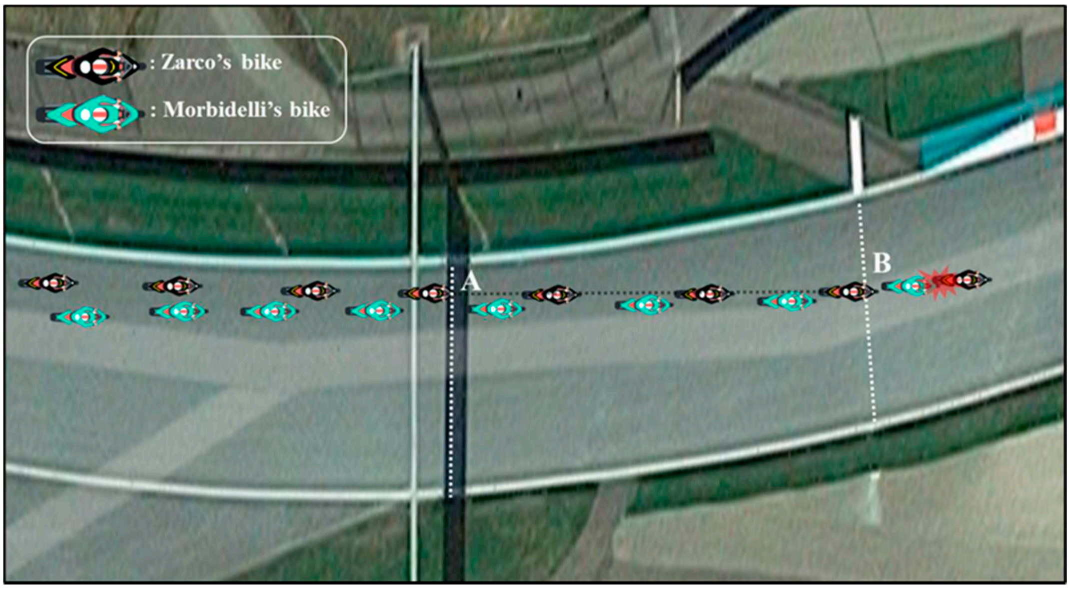


**Figure 7.** Representation of the dynamics of the accident showing that Zarco crossed Morbidelli's trajectory immediately after overtaking him as he moved towards the center of the track.

Zarco's movement towards the middle of the track was found to be greater than that of the other riders, whose movement was analyzed. Regarding the measurements of the time the motorbikes took to travel between the various points in the three different videos, we obtained the following results: based on footage from the first video, Zarco's bike took 0.60 s to travel from point A to point B (44.5 m), at an average speed of 267 ± 7.9 km/h; Morbidelli's bike took 3.93 s to go from point B to point C (205 m), at an average speed of 188 ± 1 km/h, and 0.66 s to travel from point C to point D (14 m), at an average speed of 76 ± 2.3 km/h. Analyzing the second video from Rins' onboard camera, we determined that Zarco covered the 288 m from point A0 to point A in 3.43 s, at an average speed of 302 ± 1.8 km/h, whereas Rins covered the same distance in 3.46 s, travelling at an average speed of 299 ± 1.7 km/h. Moreover, from the same footage, we were able to determine that it took Morbidelli's bike 0.60 s to cover the stretch from point A to point B, 3.93 s from point B to point C, and 0.66 s from point C to point D (confirming the previous measurements). Using the footage from Rossi's onboard camera, we determined that it took Rossi's bike 3.50 s to cover the stretch from point A0 to point A, at a calculated average speed of 296 ± 1.7 km/h, which corresponds to the average speed determined from the actual speeds recorded in the 105 frames analyzed from point A0 to point A (295.6 km/h). Furthermore, we found that Rossi's actual average speed from point A to point B was 266 km/h, and it took him 0.60 s to cover the stretch from point A to point B, with an average indirectly calculated speed of 267 ± 7.9 km/h. These data confirm the reliability of our measurements and hence the quality of the analyses that were carried out based on those measurements. Analyzing Rossi's real speed (exactly 172 frames) from point A to the moment in which he encountered Morbidelli's bike (turn 3), we identified a point in which Rossi appeared to brake harder, as he entered turn 3, reducing his speed by 10 km/hr in 0.03 s, just 0.40 s before encountering Morbidelli's bike (see Figure 8).

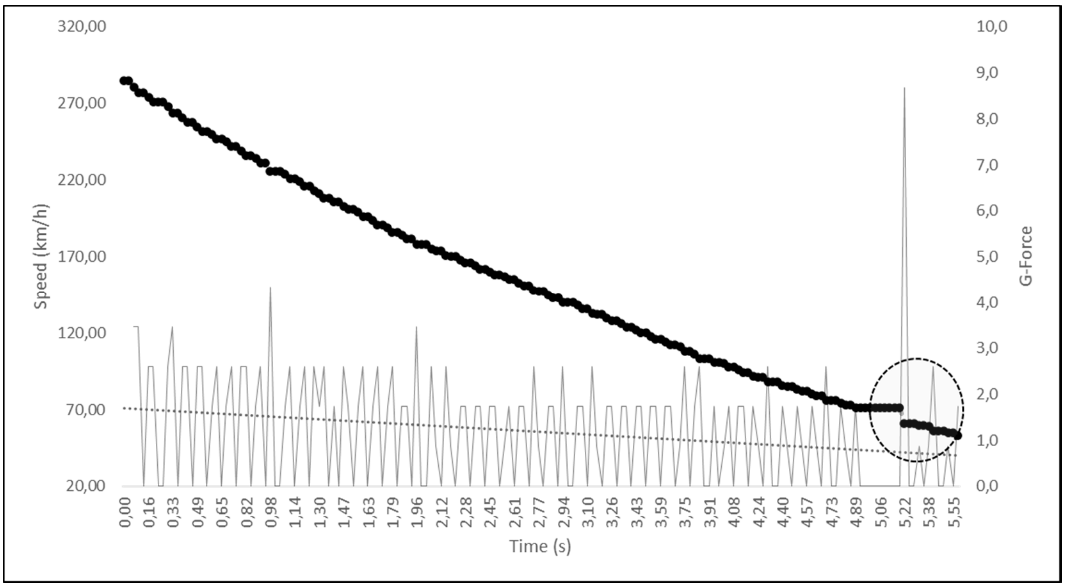


**Figure 8.** Rossi's actual speed and instantaneous G-Force peak from point A to the point where he narrowly missed colliding with Morbidelli's bike. The circled area shows the moment in which Rossi braked, reducing his speed by 10 km/h in 0.03 s.

However, a deceleration of this magnitude is highly unlikely because, even if it were just for an instant, it would reach about 9 G. The braking system manufacturer, Brembo, claims that the "average" deceleration in the approach to turn 3 at the 2019 Austrian MotoGP was 1.23 G, and this value is in line with that which was analyzed here (from 285 to 53 km/h in 5.58 s, corresponding to an average of 1.2 ± 1.2 G). However, deceleration peaks are possible because rapid deceleration may occur with both sudden downshifting and with variations in the pressure applied by the rider to the brake lever. Indeed, analyzing the frame-by-frame G forces from Rossi's deceleration curve (see Figure 8), we obtained instantaneous peaks that were even higher than 3.4 G. Hence, we proceeded to correct a possible data transmission error and/or lag by applying a moving average of five frames to reduce the G-force peak. Rossi's deceleration thus appears more plausible. Indeed, as he rode through turn 3, he probably applied additional pressure to his brake lever, reducing his speed by 16.7 km/h in the 0.42 s before he encountered Morbidelli's bike. We then developed two different hypothetical braking scenarios 15 frames before Morbidelli's bike crossed Rossi's path: in scenario 1, we hypothesized what would have occurred if Rossi had reduced his speed by 12.7 km/h, while in scenario 2, we postulated what would have occurred if he had reduced his speed by 8.7 km/h (see Figure 9).

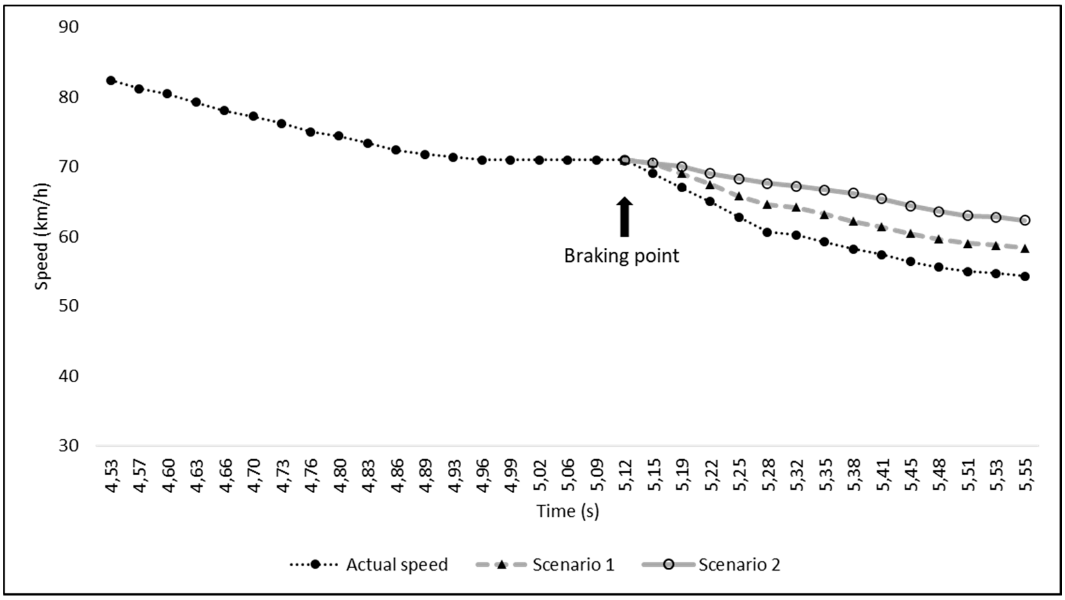


**Figure 9.** Rossi's actual speed (moving an average of 5 points), 33 frames before the point where he narrowly missed colliding with Morbidelli's careening bike. As described in the legend, the solid dots represent Rossi's real speed and the solid triangles represent the speed in hypothetical scenario 1, while the empty dots represent the speed in scenario 2.

Based on the calculation of the distance that would have been covered in the first hypothetical scenario, Rossi would have been 40 cm ahead of where he actually was on the track, while in the case of the second scenario, he would have been 76 cm ahead (see Figure 10). In addition, from the analysis of the frame in which Rossi encountered Morbidelli's bike, we determined that the bike missed Rossi by just 20 cm. We also represented the points in which Morbidelli's bike would have struck Rossi in the two hypothetical scenarios (see Figure 10).

Finally, based on footage from the first two videos, we can estimate with a good degree of accuracy that the speed of Morbidelli's bike as it tumbled across turn 3 was about 76 km/h or 21.1 m/s. If it had struck Rossi at that speed, the consequences would certainly have been catastrophic. To have a more precise idea of those possible consequences, we would need to know the deceleration time of the bike following its impact with the rider. Fortunately, there was no impact, and thus, we were not able to calculate the deceleration time. We therefore calculated the force of the impact by hypothesizing that if the motorbike (150-kg) impacted an air-fence (soft-wall safety barrier) and we were to see a 2-m deformation of the barrier, we could calculate the deceleration time in the following manner Equation (1):

$$\text{Deceleration Time (impact duration)} = (2 \times 2\ \text{m})/(21.1\ \text{m/s}) = 0.19\ \text{s} \quad (1)$$

Hence, we would obtain the impact force (IF) Equation (2):

$$IF = (150\ kg \times 21.1\ m/s)/(0.19\ s) = 16.657\ kN = 1698\ kg \quad (2)$$

The formula can easily be extended to calculate the approximate maximum impact force (peak impact force) by multiplying the resulting average impact force by two: 33.314 kN = 3396 kg.


**Figure 10.** The frame capturing the exact instant when Morbidelli's bike crossed Rossi's path. Kinovea was used to measure the distances based on the measurement of the rear wheel of Morbidelli's bike. Specifically, the white arrows indicate the 60-cm diameter of Morbidelli's rear wheel (black circle); the green arrows represent the exact distance between Rossi's front wheel and Morbidelli's rear wheel; the yellow and red arrows indicate the distance that Rossi's bike would have covered if he had slowed down according to scenario 1 (about 40 cm) and scenario 2 (about 76 cm), respectively.

## 4. Discussion

In the present report, using low-cost instruments, we performed a quali-quantitative analysis of the dynamics of the accident involving Zarco, Morbidelli, Rossi, and Viñales during the 2020 Austrian MotoGP. To our knowledge, this is the first time that a video analysis has been applied to an accident in a motorcycle race, whereas analyses of this kind are common for ordinary traffic accidents [12,13]. From our analyses, we were able to calculate that, in the straightaway leading into turn 2 (from A0 to A), Zarco was travelling at a higher average speed (302 ± 1.8 km/h) than either Rins or Rossi (299 ± 1.7 and 296 ± 1.7 km/h, respectively), probably because he was drafting off Morbidelli as he overtook him. In addition, from the average speeds of Zarco and Rossi in the stretch from point A to point B (266 km/h), we can conclude that the accident occurred as the riders were slowing down. Our analysis of the trajectories showed that, after point B, all the riders tended to move towards the middle of the track because of the layout of the circuit. However, the movement of Zarco's bike (2.92 m) was greater than that of all the other riders' bikes that were taken into consideration. Moreover, if we trace the trajectory of Zarco and Morbidelli (Figures 6 and 7), we clearly see that, as he overtook Morbidelli, Zarco crossed his trajectory as he proceeded towards the middle of the track, just as Morbidelli did after having been overtaken, with his front wheel extremely close to Zarco's rear wheel. It seems clear that Zarco made a risky maneuver choosing to pass Morbidelli at that point in the track and then moving towards the center of the track, knowing that the other rider was exceedingly close. Based on these analyses, it would seem that the layout of the track contributed to the scenario that played out, leading to the accident, and therefore, possible changes in the circuit might be considered. However, few data are available on the relative safety of motor racing circuit layouts. In fact, to the best of our knowledge, there is only one study [14] that analyzed whether changing the configuration of a motor racing circuit makes it safer. This particular study showed that the introduction of two bends into the fastest part of the track (similar to the one analyzed here) led to a decrease in the seriousness of auto racing accidents; however, these changes in the track seem to have resulted in a tendency for motorcycle racers to suffer slightly more serious injuries [14]. Hence, the decisions riders make to undertake or not to undertake certain maneuvers remain a key determining factor. Regarding the frame by frame analysis of Rossi's speed as he entered and then rounded turn 3, it is very interesting to note his sudden deceleration, which, from a qualitative analysis of the images, appears to have been the result of his drawing too close to Vinales. If this was indeed the case, the presence of Vinales ahead of Rossi may have saved Rossi's life or, in any case, led to his narrow avoidance of the collision. Indeed, if Rossi had braked slightly less, as hypothesized in scenarios 1 and 2, he would have been struck directly by Morbidelli's bike. Finally, based on our analysis of the first and second video and the distance measured between points C and D, we calculated that Morbidelli's bike travelled across curve 3 at a speed of 76 ± 2.3 km/h. Considering that a MotoGP bike weighs 150 kg, we hypothesized what the impact of the bike would be at that speed against air-fence barriers, obtaining a peak impact force of 33.3 kN. The tolerance of the human body to kinetic forces released in ordinary road accidents is limited. Injury is broadly related to the amount of kinetic energy applied to the human frame [15]. For example, a study estimated that the tolerance of the whole human neck to injury in tensile loading is as low as 3.1 kN for subjects with no pre-impact awareness and as high as 3.7 kN for subjects with a tensed cervical spine resulting from sufficient pre-impact awareness [16]. Considering that the peak impact force that we calculated was nine times higher than the maximum force tolerated by the human neck, if Morbidelli's bike had struck Rossi at neck level, he would have had little chance of surviving the impact. On the other hand, if this impact had been absorbed by his entire body, we estimate that the impact force would have been comparable to the impact of a 65 kg (V. Rossi's weight) body falling from a height of about 15 m (the fourth floor of a building). Although it is impossible to make further hypotheses regarding the possible consequences of the impact of Morbidelli's bike against Rossi because of the countless unpredictable variables in play, our calculations help us to imagine the severity of such an impact.

*Limits and Strengths of the Study*

Although the video frame rate limited precision to 0.03 s, we accounted for this error when calculating the speeds, showing that the upper and lower average error estimates were marginal and did not affect the quality of the analyses. In addition, the distances between the various points, though calculated precisely, taking into account the actual trajectories of the riders and their bikes, may contain some errors due to the different angles of the footage. Overall, our analysis allowed us to accurately describe the dynamics of the accident and its potentially catastrophic effects, while clearing up doubts regarding the speeds, distances, and trajectories of the riders who were involved.

## 5. Conclusions

This study, through a quali-quantitative analysis, helps us to gain a deeper understanding of the main causes and dynamics of the accident at the 2020 Austrian MotoGP Grand Prix, as well as the speeds of the motorcycles involved. Furthermore, we showed how V. Rossi narrowly avoided being struck by Morbidelli's bike and what the consequences of other potentially tragic scenarios would have been if Rossi had braked differently or if he simply had not had his teammate in front of him. In addition, we have shown that, in the Austrian circuit, overtaking on the outside of the track in the straightaway between turn 1 and turn 2 is very risky, in particular, if it is completed at the end of turn 2 or at the point we have identified as point A. Hence, in light of our findings, regarding the riskiness of such a maneuver, it may be advisable for riders to be particularly prudent when attempting such a maneuver or not to repeat the same or a similar trajectory in this section of the Red Bull Ring circuit to overtake another rider in future races. Overall, this method could be used in future investigations to improve safety conditions and to gain a better understanding of the particular dynamics of specific sport motorcycle accidents.

**Supplementary Materials:** The following are available online at http://www.mdpi.com/1660-4601/17/21/7989/s1, Video S1: AUSGP2020.

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