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Special Issue Reprint

Athletes Performance and Analysis in Combat Sports and Martial Arts

Edited by
Łukasz Rydzik, Tadeusz Ambrozy, Wojciech J. Cynarski,
Wojciech Czarny and Wiesław Błach

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Wiesław Błach

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Guest Editors
Łukasz Rydzik
Institute of Sports Sciences
University of Physical Education
Kraków
Poland

Tadeusz Ambrozy
Institute of Sports Sciences
University of Physical Education
Kraków
Poland

Wojciech J. Cynarski
Institute of Physical Culture Studies
University of Rzeszow
Rzeszow
Poland

Wojciech Czarny
Institute of Physical Culture Studies
University of Rzeszow
Rzeszow
Poland

Wiesław Błach
Faculty of Physical Education & Sport
University School of Physical Education
Wroclaw
Poland

Editorial Office
MDPI AG
Grosspeteranlage 5
4052 Basel, Switzerland

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About the Editors

Łukasz Rydzik

Dr. habil. Łukasz Rydzik, Assoc. Prof. at the Academy of Physical Culture, is a university professor at the Academy of Physical Culture in Kraków and a recognized researcher in the field of physical culture sciences. He specializes in technical–tactical analysis and the physiological aspects of combat sports, with a particular focus on kickboxing. He is the author of numerous scientific publications and serves as an editor for international journals. He collaborates with prestigious research centers abroad and is a recipient of the Minister of Science Scholarship and the Gold Badge of Merit for Polish Kickboxing.

Tadeusz Ambrozy

Professor Tadeusz Ambrozy, Ph.D., is a full professor at the Academy of Physical Culture in Kraków and a recognized expert in the field of physical culture sciences. His academic and professional specialization focuses on sports theory, motor preparation, and combat sports, particularly jujitsu and judo. He successfully combines scientific research with practical coaching and holds the highest coaching qualifications in multiple disciplines, including master class trainer titles in judo and ju-jitsu. He received the academic title of professor in 2022. Over his academic career, he has completed numerous postgraduate studies in areas such as public administration, human resource management, national security and crisis management, and nutrition and dietary counseling. He is also certified as a personal trainer, sport manager, and instructor in gymnastics, karate, boxing, swimming, and bodybuilding. Professor Ambrozy has held many leadership positions within academic institutions, including Director of the Institute of Sport Sciences at the Academy of Physical Education in Kraków and Director of the Institute of Humanities and Social Sciences in Nowy Targ. He is the author or co-author of over 400 scientific publications, including 14 monographs and 4 academic textbooks, and has co-edited several scientific volumes. Professor Ambrozy is an active member of scientific organizations such as the Fédération Internationale d'Education Physique (FIEP), the Idokan Poland Association, and the European Association for Security. He also chairs the Dan Commission of the Polish Ju-Jitsu Association. For his contributions, he has received many honors, including the Gold Cross of Merit (2023), the Gold Medal for Long Service (2024), and the Honorary Badge of the City of Kraków. He possesses a 10th dan black belt in ju-jitsu and continues to actively contribute as a coach, referee, and expert in physical culture.

Wojciech J. Cynarski

Prof. Wojciech J. Cynarski, DSc, Ph.D., Eng., is a researcher in the fields of sports sciences and social sciences. He is an active coach in several disciplines of combat sports and holds a high master rank (hanshi) in jujutsu, karate, and kobudo. He serves as president of two scientific societies—the Idokan Poland Association (IPA) and the International Martial Arts & Combat Sports Scientific Society (IMACSSS). He works at the Faculty of Physical Culture Sciences, University of Rzeszow in Rzeszów, Poland. His specialization includes interdisciplinary research in combat sports and martial arts, personal self-defense, and hoplology.

He is the author of 23 books, including scientific monographs and academic textbooks.

Wojciech Czarny

Wojciech Czarny is a professor and dean of the Faculty of Physical Education at the University of Rzeszów. He is the author of several dozen scientific publications with significant international reach, focusing on the promotion of physical activity, healthy lifestyles, and physical education. His academic work includes both theoretical studies and empirical research on physical activity across various social groups. As a member of HEPA Europe (European Network for the Promotion of Health-Enhancing Physical Activity), he is actively involved in developing strategies to support public health through movement. As a respected lecturer and supervisor of numerous master's and doctoral theses, he regularly participates in international scientific conferences, where he presents the results of his research and co-develops European-scale research projects.

Wiesław Błach

Wiesław Błach, DSc in Physical Culture Sciences, is a professor at the University School of Physical Education in Wrocław (AWF Wrocław) and a master-class judo coach. He is the author of over 100 scientific and methodological publications. A distinguished athlete, he is the 1987 European Champion, bronze medalist at the 1985 World Championships, two-time bronze medalist at the European Championships (1986, 1990), and silver medalist at the World University Championships (1982) in judo. He is also an eight-time Polish national champion.

He served as head coach of the national junior team (1993–1994), the Olympic women's team (1994–1997), and the Olympic men's team (2001–2004). As an athlete, coach, and official, he participated in six Olympic Games (1988–2004, 2012), placing 7th at Barcelona. Under his leadership, the Polish women's national team achieved their best Olympic result ever at the Atlanta Games in 1996, earning the country's first Olympic medal in judo—a silver by Aneta Szczepańska. From 1998 to 2000, he coached World Champion Beata Maksymow. His athletes have collectively won 30 medals at the Olympics, World Championships, and European Championships.

From 2006 to 2008, he coached the Belgian national team. He was President of the Polish Judo Association from 2009 to 2014, a board member of the Polish Olympic Committee from 2009 to 2016, and Sports Director of the European Judo Union from 2017 to 2022. Since 2017, he has served as President of the Lower Silesian Judo Association. He is the author of over 100 academic publications and 4 books on judo.

Preface

Combat sports and martial arts have long captured the interest of both enthusiasts of physical activity and scholars across a variety of scientific disciplines. In recent years, their popularity has significantly increased—not only as dynamic and spectacular competitive disciplines but also as rich fields of academic inquiry. These sports offer a unique opportunity to explore the complex interactions of body and mind under extreme effort, psychological pressure, and physical contact.

This publication presents a collection of scientific studies and reflections focused on performance, psychophysical responses, biomechanics, and the structure of combat across various martial arts and combat sports. Our primary goal was to provide a broad and multidisciplinary perspective on these topics in light of the modern challenges faced by athletes and coaches.

Today's scientific tools allow for detailed analyses of physiological and technical parameters during actual sports combat. These analyses not only support the optimization of training processes but also contribute to a deeper understanding of the nature of competitive interaction in contact sports—where tradition, discipline, and advanced technology intertwine.

We hope this volume will serve as a valuable and inspiring resource for researchers, coaches, and athletes alike, offering both practical insights and theoretical foundations for further development.

Łukasz Rydzik, Tadeusz Ambrozy, Wojciech J. Cynarski, Wojciech Czarny, and Wiesław Błach
Guest Editors

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Editorial

Special Issue Athletes' Performance and Analysis in Combat Sports and Martial Arts

Łukasz Rydzik [1,*], Tadeusz Ambroży [1], Wojciech J. Cynarski [2], Wojciech Czarny [2] and Wiesław Błach [3]

1 Institute of Sports Sciences, University of Physical Education, 31-571 Kraków, Poland; tadek@ambrozy.pl
2 Institute of Physical Culture Studies, College of Medical Sciences, University of Rzeszow, 35-310 Rzeszow, Poland; ela_cyn@wp.pl (W.J.C.); wojtekczarny@wp.pl (W.C.)
3 Faculty of Physical Education & Sport, University School of Physical Education, 51-612 Wroclaw, Poland; wieslaw.judo@wp.pl
* Correspondence: lukasz.rydzik@awf.krakow.pl

1. Introduction

Combat sports and martial arts have gained popularity in mainstream culture and are recognized in various realms of physical culture [1,2]. They have captured the interest of researchers in both elite and recreational sports [3–6]. Their advantages lie in their spectacle, multidirectional impact on physical functioning, motor skill development, as well as utilitarian values for self-defense or training for law enforcement [7–10].

Research on athletes allows for the assessment of training progress, identifying an improvement or decline in performance, and appropriately adjusting training loads. Scientific investigations also enable the visualization of detailed physiological responses during combat sports (exercise physiology), the biomechanical analysis of specific actions, and the effectiveness of technical–tactical solutions [11–15]. The goal of the research conducted for this edition of "Athletes Performance and Analysis in Combat Sports and Martial Arts" is to comprehensively present the complex structure of combat in combat sports (in terms of temporal and substantive aspects) and to seek ways to refine the optimal preparation system for tournament fighters. The solutions to this problem are presented through a series of original empirical studies.

These studies form the basis for a comprehensive thematic monograph related to various aspects of fighting arts. The term "fighting arts" is a collective term encompassing different martial arts, combat sports, and self-defense systems, as adopted in the general theory of fighting arts (GTFA) [16]. GTFA, alongside sports sciences (sports theory, sports combat theory, sports psychology), provides the scientific framework and theoretical perspective for this compilation.

Sports sciences influence sports practice, especially in optimizing the sports training process [17,18]. Research results in the field of fighting arts have implications for both competitive combat sports and the role of martial arts in other areas of physical culture (physical education, recreational exercise, physical rehabilitation) [19–24]. Therefore, they are considered applied sciences. In the case of "non-competitive" martial arts (traditional martial arts), their use in lifelong or family recreational activities is significant [25,26]. It is worth noting that the editors of this publication, hailing from various academic centers, are both practitioners (masters) and researchers in fighting arts. This understanding of the relationship between theory and research and their practical application is essential.

The basis for this monographic publication was the Special Issue "Athletes Performance and Analysis in Combat Sports and Martial Arts" in the scientific journal *Applied Sciences*. Among the keywords were various forms of martial arts and combat sports, as well as important concepts for sports sciences: fight analysis, technical and tactical preparation, training control. It is important to mention that this Special Issue received 29 submissions, of which 11 were accepted. The thematic summary is based on the content of these eleven

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works, originating from research centers in different countries and resulting from studies in Olympic judo (five works), classical wrestling, taekwondo, MMA, karate (in various styles), sport ju-jitsu, and comparative studies across different combat sport disciplines. The topics mainly covered biotechnical and biomedical aspects, as well as sports psychology—the level of aggressiveness. This multidisciplinary approach is characteristic of sports sciences, as only through such an approach can we gain a relatively complete understanding of this segment of human reality.

2. Combat Sports in Scientific Research

The first of the mentioned articles, entitled "Rapid Weight Loss Coupled with Sport-Specific Training Impairs Heart Rate Recovery in Greco-Roman Wrestlers", focuses on research into the impact of rapid weight loss and intense sport-specific training on the body's ability to recover its heart rate. The results of this study suggest that the combined effects of these two factors can negatively affect the body's ability to return to a resting state, especially in the case of sudden weight loss, which is often practiced by wrestlers. This is significant because effective heart recovery is crucial for maintaining the health and performance of athletes [27].

The second article, "Contributions of Body Segments to the Toe Velocity during Taekwondo Roundhouse Kick", analyzes the influence of various body segment movements on the velocity of the roundhouse kick in taekwondo. The study reveals that movements of the thigh and torso significantly impact the kick's velocity. This research can assist coaches and athletes in gaining a better understanding of the biomechanics of taekwondo kicks and adapting their training for increased effectiveness [28]. The third study, "Defining the Influence of Fatigue Protocol on Kinematic Parameters of Ippon Seoi Nage", focuses on the analysis of how fatigue affects the kinematic parameters of the ippon seoi nage throw in judo. The results suggest that fatigue can significantly impact the execution of this technique, which is crucial for judo athletes who need to maintain full control over their movements even in high-intensity situations [29]. The fourth paper, "When and How a Judo Contest Ends: Analysis of Scores, Penalties, Rounds and Temporal Units in 2018, 2019 and 2021 World Championships", provides an analysis of how judo matches concluded during the World Championships in 2018, 2019, and 2021. The results show that most matches ended with a technical score, and the activity and effectiveness of attacks were highest at the beginning of the match. This information can be valuable for judo athletes in developing match strategies and gaining a better understanding of the factors that determine match outcomes [30]. The fifth publication, "Physical and Morphological Differences between Young Elite Taekwondo and Karate Players", presents a comparison of body morphology and strength between young taekwondo and karate athletes. The results indicate differences in body composition and muscle strength between these two disciplines. This can help coaches and athletes better tailor their training to the specific requirements of their sport and identify the benefits of cross-training in different martial arts [31]. The sixth and final article, "Analysis of Combat in Sport JU-JITSU during the World Championships in Fighting Formula", focuses on the analysis of combat in the sport ju-jitsu during the World Championships in the fighting formula. The results suggest that most matches end based on technical point advantages, and the activity and effectiveness of attacks are highest at the beginning of the match. This information is crucial for athletes looking to develop effective strategies for this specific form of ju-jitsu competition. The insights gained from this analysis can also be used to construct training units based on the real structure of ju-jitsu combat [32].

3. Future Scientific Challenges in Combat Sports and Martial Arts

Even though this Special Issue has now concluded, there is an expectation for further research in the areas of motor preparation and technical–tactical training in combat sports. It can be anticipated that in the future, there will be a need for more detailed analyses to ensure even greater effectiveness in combat, given the rapidly evolving and increasingly sophisticated nature of competition in combat sports. In such cases, one must be prepared to employ appropriate strategies in preparation for competitions, based on the results of ongoing monitoring and the utilization of research findings in this field, as well as current forecasts regarding future competition.

4. Conclusions

Overall, the obtained results suggest that the use of rapid weight loss (RWL) techniques along with intensive training may lead to higher heart rate (HR) values during the preparatory period before wrestling competitions. This can have a negative impact on aerobic fitness and the proper preparation of athletes for competition. Tools such as handgrip strength measurement and the Ditrich rod can be useful in selecting karate athletes. It has been indicated that there are differences in morphological structure and strength among young elite karate and taekwondo athletes.... In sport ju-jitsu, most matches end with a point victory, and the highest activity is observed at the beginning of the match. All the suggestions presented have practical value and should be utilized in sports training planning strategies.

As is evident from the provided compilation, this Special Issue serves as a comprehensive source of knowledge for all enthusiasts of combat sports and martial arts, including athletes and coaches. Each article contributes valuable insights into understanding these disciplines and their impact on the human body while also inspiring further research in this field.

Acknowledgments: The presented Special Issue could not have come to fruition without the dedication of many talented authors, diligent and experienced reviewers, and the committed editorial team of the journal *Applied Sciences*. Congratulations are extended to all the authors. The opinions, comments, and suggestions of reviewers and editors helped authors refine their articles and give them their final shape. We would like to express our deep gratitude to all the reviewers for their valuable insights. We thank both the authors and reviewers for their significant contributions to the development of this exceptional set of scientific publications. We also cannot forget the management and staff at MDPI, to whom we extend our congratulations not only for their unwavering editorial support, which contributed to the success of this project, but also for launching the journal *Applied Sciences*. This is an international, peer-reviewed journal that is freely accessible to readers and covers a wide range of knowledge within the described and presented scientific disciplines.

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Article

Muscle Power and Body Composition of Ranked and Unranked Brazilian Jiu-Jitsu Athletes: A Pilot Study

Adriano Neves Breithaupt [1] and Ricardo Luís Fernandes Guerra [2,*]

[1] Physical Education Course, Federal University of Sao Paulo—UNIFESP, Santos 11010-908, SP, Brazil; adriano.breithaupt@unifesp.br
[2] Sports Science Laboratory, Human Movement Sciences Department, Federal University of Sao Paulo—UNIFESP, Santos 11010-908, SP, Brazil
* Correspondence: ricardo.guerra@unifesp.br; Tel.: +55-13-99769-1454

Abstract: Background: Brazilian Jiu-Jitsu (BJJ) is a martial art in which practitioners require a variety of technical and biomotor skills for optimal performance. The International Brazilian Jiu-Jitsu Federation (IBJJF) awards points to athletes who win first, second, and third place in their competitions, but it is not known whether there are differences between ranked and unranked athletes. Therefore, the objective was to evaluate and compare the muscular strength and body composition of IBJJF-ranked and unranked athletes. Methods: Eight athletes ranked (RG = 3–1st, 24th, and 26th) or not (NRG = 5) by the IBJJF participated in this study and underwent lower and upper limb power and body composition tests. Results: despite percentage differences in favor of RG, there were no differences ($p > 0.05$) between the groups for the variables analyzed. Conclusions: there is no difference in muscular power and body composition between ranked and unranked athletes. This state of affairs suggests the complexity of athletic performance in Brazilian Jiu-Jitsu (BJJ) and thus highlights the need to consider other aspects in addition to those evaluated, such as technique, tactics, and psychological factors, which can play a crucial role in the performance of athletes.

Keywords: martial art; grappling; combat sports; strength fitness; sports performance; fights; competition; muscle mass; ranking

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1. Introduction

The word jiu-jitsu is synonymous with Ju-Jutsu, which means "gentle art" in Japanese [1]. Brazilian Jiu-Jitsu (BJJ) is an intermittent grappling martial art in which the athletes aim to immobilize and finish the fight using joint locks (fist, elbow, knee, and ankle locks), chokes, and pressure techniques. It began in 1917 with the arrival in Brazil of Mitsuyo Maeda, also known as Count Koma, a renowned Japanese martial artist who, upon his arrival, gave several martial arts demonstrations, the first of which was attended by Carlos Gracie, who, despite not having the physical aptitude for fighting, became interested in the practices [2,3]. Thus, brothers Carlos and Hélio Gracie developed BJJ based on the use of movements and actions that allow individuals with less muscle mass to dominate stronger opponents [4].

The popularization of BJJ happened due to the good performance of Brazilian fighters in international Mix Martial Arts events, which also promoted the practice of BJJ as a sport. The first Brazilian Jiu-Jitsu World Championship was held in 1996, and since then, the number of practitioners and athletes has increased significantly. In this scenario, in addition to submissions (such as joint locks, chokes, etc.), the athletes' goals include taking dominant positions (mount, knee on belly, back control), performing specialized sweeps, and breaking the opponent's guard (guard passes). These actions are rewarded with technical points and, in a practical sense, allow for the neutralization of an aggressor [3,5].

In the context of adult BJJ, there are nine weight categories in addition to the open category, divided into five belt categories, with fights lasting between 5 and 10 min, depending on the age group and belt of the fighter, with the adult black belt category having the longest duration [3]. The ranking of the athletes is based on the points that competitors receive for first, second, or third place in tournaments affiliated with the International Brazilian Jiu-Jitsu Federation (IBJJF) [6].

Recent research indicates that high-intensity strength training is advantageous for the physiological conditioning of BJJ athletes. It is crucial to enhance the manifestations of maximum strength, power, muscular endurance, and flexibility to optimize the athletic performance of these athletes, particularly competitors [7–9].

In this context, the capacity to generate substantial strength and power in the upper extremities is crucial for executing technical maneuvers that result in victory over an opponent. This attribute is highly sought after in athletes engaged in grappling martial arts [9–12]. Furthermore, at the highest level of competition, these athletes demonstrate exceptional levels of dynamic strength, muscular endurance, power, and anaerobic capacity, as well as superior aerobic capacity. These attributes appear to be more pronounced in the upper body than in the lower body, indicating that training programs should prioritize the development of the upper body. However, it is noteworthy that muscular power may be more highly developed in the lower body [10,13]; it is, therefore, essential to measure and understand these conditions.

It is established that muscle power tests can be conducted through the use of jumping (for lower extremities) and throwing (for upper extremities) exercises [14,15]. A study conducted with Finnish judo players [16] utilizing the vertical jump platform demonstrated that athletes engaged in competitive activities exhibited augmented power output in lower limb muscles relative to their non-competing counterparts. Another study [14] showed that experienced jiu-jitsu athletes (mean age 28 ± 5 years, 11 ± 4 years of training experience, brown and black belts) have high lower limb power, reaching a mean of 41 ± 5 cm in the countermovement jump. In addition, the body composition characteristics of these athletes showed a predominance of the somatotype mesomorphic component, low % body fat, and high amount of muscle mass, which are important factors to consider when it comes to high performance. However, it remains unclear whether there are differences between the muscular power and body composition of ranked and unranked BJJ athletes.

This information could inform the development of initiatives that enhance the efficacy of current guidelines for monitoring and training BJJ athletes, thus benefiting all stakeholders in the sport. In view of the above, the aim of this study was to evaluate and compare muscle power and body composition of IBJJF-ranked and unranked athletes.

2. Materials and Methods

This quantitative, cross-sectional, and descriptive study was approved by the Research Ethics Committee of the Federal University of São Paulo (protocol number 0598/2023, date of approval 29 November 2023) and was conducted in accordance with the Declaration of Helsinki and all applicable rules and regulations pertaining to research involving human subjects. Following a comprehensive explanation of the research procedures, each participant provided written informed consent in the form of an informed consent form.

2.1. Assessment and Recruitment Environment

Participants were recruited (for convenience) after an initial telephone contact through their respective coaches (who were duly informed about the research through prior contact by the principal investigator), followed by a face-to-face contact at their respective training sites at the end of the training sessions.

The volunteers responded to an anamnesis, which was used to ascertain their state of health and any history of injury that might have precluded their participation in the study. The guiding question was, "Have you sustained or do you currently have an injury within the past three months?" Based on the participants' responses, the researchers determined whether it was appropriate for the athlete to refrain from taking part in the study.

The data collection was conducted in the Sports Sciences laboratory at the Federal University of São Paulo, where the conditions of privacy, ventilation, light, and temperature were strictly controlled. The proposed assessments and tests were carried out on a single day, with each participant completing approximately 35 min of testing.

2.2. Participants, Inclusion and Exclusion Criteria

Eight professional male jiu-jitsu athletes met the criteria and were assessed. To be included in the study, the athletes were informed of the specifics of the research and met the inclusion criteria: they were between the ages of 18 and 35, had not sustained an injury in the previous three months, and did not have any medical contraindications to physical activity. The only exclusion criterion was that the athletes were not involved in IBJJF competitions.

The athletes (black and brown belt) were divided into two groups based on their ranking on the IBJJF world circuit: the Ranked Group (RG = 03, black belt = 02), comprising the top performers (ranked 1st, 24th, and 26th in their categories), and the Non-Ranked Group (NRG = 05, black belt = 01), comprising those with less significant results in the big leagues.

All athletes (from medium and medium-heavy categories) had the same training characteristics with 150 $\pm$ 30 min of specific jiu-jitsu training (on the mats) combined with 90 $\pm$ 20 min of general physical training (including upper/lower limb and core strength and power on gym equipment) with a frequency of 5 $\pm$ 1 times per week.

The athletes (n = 8) were 24.00 $\pm$ 4.14 years old, 84.61 $\pm$ 13.33 kg in body mass, 1.79 $\pm$ 0.09 m in height, 26.43 $\pm$ 2.65 in body mass index, 9.50 $\pm$ 2.00 years of sport experience and 6.90 $\pm$ 1.3 years of competitive experience.

2.3. Anthropometric and Body Composition Assessment

Body mass and height were measured using a Sanny™ (Sunny Group, Yuyao, China) anthropometric scale (model: Digital with stadiometer), which is accurate to 100 g and 0.1 cm, respectively, according to the methodology previously outlined in reference [17].

Body composition was assessed via the tetrapolar bioelectrical impedance method with the BC-558 Ironman™ Segmental Body Composition Monitor (Tanita Corp., Tokyo, Japan), equipment, considered to be a fast, non-invasive, and economically viable method to indirectly estimate the values of lean, fat and bone mass, total body water and basal metabolic rate by using regression equations. The procedures and recommendations for this evaluation were carried out in accordance with the literature [18].

2.4. Lower Limb Power Assessment

To evaluate lower limb power, vertical jumps were conducted under the following conditions: The jumping exercises performed were the Squat Jump (SJ) and the Counter Movement Jump (CMJ). An optical measurement system, the Opto Jump Next™ (Microgate, Bolzano, Italy), was used to collect the data. Each transmission bar contained 96 LED lights (1.0416 cm resolution) in continuous communication with the receiving cell, measuring the contact times during the jumps with an accuracy of 1/1000 per second.

Prior to data collection, the athletes performed a short warm-up (15 min) consisting of 6 min of light jogging, 5 min of dynamic stretching, and 4 min of exercise at the participant's discretion, followed by familiarization with the vertical jump protocol. Each subject performed three familiarization attempts, followed by three additional attempts for each jump condition (squat jump and countermovement jump), with a 30 s interval between them. To analyze the data, the height average (m) of the three valid jumps was calculated, and the relative power (W/kg) was determined for both CMJ and SJ.

In the SJ, the athlete assumed a static position with the knee angle at approximately 90°, attempting to maintain a vertical alignment of the trunk and with the hands positioned on the waist. At the assessor's command, the athlete performed a maximum vertical jump from a single concentric action. In the CMJ, the athlete commenced from a static standing position with their hands on their waist and proceeded to perform a maximum vertical jump utilizing the stretch–shortening cycle. The assessor directed the subjects to flex their knees to an angle of approximately 90° in the eccentric phase and jump as high as possible, utilizing the elastic energy generated. In both tests, the subjects were prohibited from flexing their knees during the flight phase of the jumps [19–21].

2.5. Upper Limb Power Assessment

The aforementioned procedure was conducted in accordance with the established protocols for medicine ball throwing (MBT), as previously proposed in reference [22].

To conduct the test, the subject was instructed to remain seated with their back against the vertical backrest and their thighs resting horizontally. The three-kilogram medicine ball (Dynamax Inc®, Dallas, TX, USA) was positioned at the height of the sternum (A). The throw was executed with both hands in a manner that did not involve any movement of the trunk over the support. In the event that the individual did not adhere to the established standards, the attempt was deemed invalid. The distance of the medicine ball throw was measured from point A to its initial contact with the ground (B). Each participant performed three throws, with a 30 s interval between each attempt. For the purposes of analysis, the mean of the three valid attempts was calculated [22], and the absolute (m) and relative distance (m/kg) were determined.

2.6. Statistical Analysis

The data were analyzed using an Excel spreadsheet (Windows®) for subsequent calculation. The mean, standard deviation (SD), median, and interquartile range (IQR) were used to describe the numerical variables.

A Student's *t*-test for independent samples was employed to ascertain the statistical significance of the observed differences between the groups with respect to the numerical variables under investigation. Prior to conducting the test, the assumptions underlying its application were evaluated using the Shapiro–Wilk normality test and Levene's homogeneity test. The chosen significance level was set at 5%. The effect size (ES) was calculated afterward and interpreted according to Cohen's criteria: <0.2 = trivial, 0.2–0.6 = small, 0.6–1.2 = moderate, 1.2–2.0 = large, 2.0–4.0 = very large, and 4.0 = extremely large [23].

The statistical analysis was performed using the R Core Team software, v4.1.2 [24].

3. Results

No statistically significant differences were identified. The observed effect size was trivial for the variables medicine ball throwing relative power (m/kg), CMJ (m), and SJ (m) and small for all other variables except age, which was moderate. Nevertheless, it is worth noting that the RG obtained higher percentage values than the NRG in all the variables analyzed, except for body fat % (Tables 1 and 2).

Table 1. Descriptive and comparative measures of the anthropometric and body composition variables studied in Ranked (RG = 3) and Unranked (NRG = 5) Brazilian Jiu-Jitsu athletes.

Variable	Group	Mean	SD	Median	IQR	Delta %	*p*-Value	ES
Age (years)	NRG	22.00	3.08	22.00	2.00	24.22	0.115	−0.61
	RG	27.33	3.79	29.00	3.50			
Height (m)	NRG	1.75	0.09	1.74	0.05	5.14	0.139	−0.50
	RG	1.84	0.06	1.85	0.06			
Body Mass (kg)	NRG	82.38	16.77	83.40	8.30	7.22	0.493	−0.23
	RG	88.33	5.13	87.00	5.00			
Body Fat (%)	NRG	12.12	2.86	11.90	2.60	−20.21	0.334	0.37
	RG	9.67	3.17	8.20	2.90			
Body Water (%)	NRG	64.26	3.46	64.00	3.00	5.39	0.210	−0.46
	RG	67.73	3.17	68.10	3.15			
Bone Mass (ua)	NRG	3.52	0.50	3.60	0.20	13.63	0.128	−0.51
	RG	4.00	0.26	4.10	0.25			
Lean Mass (kg)	NRG	67.46	10.65	68.60	5.80	14.43	0.136	−0.50
	RG	77.20	5.27	77.70	5.25			
BMR (Kcal)	NRG	2110.20	353.47	2124.00	184.00	13.11	0.180	−0.45
	RG	2387.00	155.56	2382.00	155.50			

BMR, Basal Metabolic Rate.

Table 2. Descriptive and comparative measures of the muscle power variables studied in Ranked (RG = 3) and Unranked (NRG = 5) Brazilian Jiu-Jitsu athletes.

Variable	Group	Mean	SD	Median	IQR	Delta %	*p*-Value	ES
MBT (m)	NRG	4.87	0.59	5.06	0.18	8.82	0.299	−0.37
	RG	5.30	0.46	5.45	0.44			
MBT RP (m/Kg)	NRG	0.06	0.00	0.06	0.00	0.66	0.927	−0.02
	RG	0.06	0.01	0.06	0.01			
SJ (m)	NRG	0.30	0.04	0.28	0.02	3.33	0.629	−0.16
	RG	0.31	0.02	0.30	0.02			
SJ RP (W/Kg)	NRG	49.62	9.84	50.86	11.55	8.45	0.411	−0.28
	RG	54.20	4.72	51.95	4.30			
CMJ (m)	NRG	0.35	0.03	0.34	0.03	2.85	0.949	−0.04
	RG	0.36	0.06	0.35	0.06			
CMJ RP (W/Kg)	NRG	54.06	10.94	53.47	8.82	7.28	0.519	−0.22
	RG	58.31	6.62	61.75	5.90			

MBT, Medicine Ball Throwing; RP, Relative Power; SJ, Squat Jump; CMJ, Counter Movement Jump.

4. Discussion

The aim of this study was to evaluate and compare muscle power and body composition of IBJJF-ranked and unranked athletes. The primary finding was that no significant differences were observed between the experimental groups. Nevertheless, percentage variations were noted with superior outcomes for the RG in comparison to the NRG across all variables, with the exception of body fat %.

In this context, athletes who have achieved a high ranking tend to be older, which may be related to greater experience. The moderate ES and the larger percentage difference (24.22%) found between the groups are consistent with this when looking at the Age variable. They also tend to have greater height, body mass, bone mineral density, percentage of body water, lean mass, absolute and relative power of the upper and lower limbs, and a lower percentage of body fat. These results become even more interesting when we consider that the athletes studied here had very similar training regimes and structures (frequency, volume, and environment).

Although not significant, RG had 14.43% and 13.11% more lean mass and BMR and 20.21% less fat than NRG. These results are in line with previous findings [7,25], which reported that a greater amount of lean mass is associated with improved performance in athletes from various sports disciplines. Moreover, other studies have also identified low body fat percentages (9–12%), with values comparable to those observed in our study [9,10,14], and without differences between novice and expert athletes or between elite and non-elite athletes [7].

In regard to upper limb muscle power, the findings of this study indicate an average distance of 4.87 m in the medicine ball throw for NRG, which is higher than the results reported by Andreato et al. [7] in non-advanced or non-elite athletes (3.8 m and 4.2 m, respectively). With regard to the upper limb muscle power of the RG, this was observed to be higher (5.3 m) than the results obtained in professional athletes (4.9 m) [26]. Nevertheless, no distinction was observed between RG and NRG when the data were analyzed in either absolute (m) or relative form (m/kg). Additionally, the smallest percentage difference was identified between the groups for the relative data (MBT RP = 0.66%).

The capacity to perform a jumping maneuver can serve as a differentiating factor among groups with disparate levels of conditioning and competitiveness within the context of Brazilian Jiu-Jitsu [27]. The mean jump height was found to be 30 and 31 cm in the squat jump (SJ) and 35 and 36 cm in the countermovement jump (CMJ) for the NRG and the RG, respectively. These values are consistent with the reported range of 30 to 45 cm in the literature [7]. Other studies [9,14,26] demonstrated an average of around 40 cm for the CMJ in professional or non-professional athletes; however, they did not report values for relative power, a variable of paramount importance when comparing differences in body mass or categories. Nevertheless, no differences were observed between groups when the data were analyzed in absolute terms (height in meters) or in relative terms (W/kg). However, there were percentage differences in the relative power of the lower limbs in the SJ (8.45%) and CMJ (7.28%) tests.

It is known that better-ranked athletes in fighting sports tend to be in better physical condition [28]. Our results, however, allow us to weigh up this statement. Thus, the discussion about sporting success in BJJ reveals interesting nuances that transcend the condition of muscle power and body composition, as well as the old dilemma about the short duration of IBJJF fights compared to the old challenges and classic training methods, which incites deeper reflections on the relationship between power and performance in the current scenario of competitive BJJ.

Although variables such as power and body composition have traditionally been considered key indicators of athletic performance in various recent sporting contexts [14,26,28–31], our data suggests that there may be more to the direct application of power and body composition variables as the main predictors of performance in BJJ.

The comparative analysis of the data, including prominent athletes such as the top-ranked athlete and the current world champion, revealed no significant differences between ranked and unranked athletes. These findings do not diminish the significance of muscle power and body composition in the athletic domain. However, they suggest that their relationship with performance in BJJ is more intricate, underscoring the necessity for a more comprehensive assessment of these athletes, one that considers not only physical attributes but also technical, tactical, and psychological factors [30,32]. Moreover, the dearth of literature predicting relative performance for muscle power and body composition underscores the necessity for future research to investigate additional variables pertinent to BJJ performance.

Prior research has highlighted the significance of weight control strategies and the prevalence of the mesomorphic somatotype among elite Brazilian Jiu-Jitsu (BJJ) athletes [33,34]. However, our findings indicate that success in this sport may be attributable to a distinctive and multifaceted combination of variables that remain to be fully elucidated [35]. In this context, it is reasonable to list the possible differences between champions and non-champions. These include, but are not limited to, differences in experience and maturity, a higher technical and tactical level, and the psychological profile of a winner in competing athletes [36,37].

In light of the exploratory nature of this study, it is imperative to acknowledge the inherent limitations and the necessity of replicating and expanding the research. Further studies, with a larger sample size and additional variables, may provide valuable insights for a more comprehensive understanding of the determinants of success in BJJ, including in women. Nevertheless, this pilot study provides a foundation for future research, emphasizing the complexity of sporting performance in BJJ and underscoring the necessity for a more holistic approach to analyzing the variables that influence athletes' success in this sport.

5. Conclusions

There were no significant differences between the lower and upper limb power and body composition of IBJJF-ranked and non-ranked athletes. This finding underscores the intricate nature of sports performance in Brazilian Jiu-Jitsu (BJJ) and thus highlights the need to consider aspects other than those evaluated, such as technique, tactics, and psychological factors, which can play a pivotal role in the performance of these athletes.

Pratical Implications

The minimal differences between well-ranked and unranked athletes revealed by this study do not indicate that such differences are inconsequential. Rather, they underscore the necessity to consider additional factors, such as technique, tactics, and psychological elements, since jiu-jitsu is a notoriously difficult sport to master, and its practitioners must also maintain a high volume of specific training. Other disciplines could benefit from this approach, especially contemporary sports (which have not been explored scientifically enough), in order to identify and improve the determinants of optimal sporting performance. In this context, it would be advisable to organize and implement training sessions (workshops) for coaches, athletes, and other individuals involved in the jiu-jitsu community regarding the importance of body composition and muscular fitness, as well as other factors that determine sporting performance in the discipline.

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Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Article

The Association between Body Composition and the Parameters of Muscle Fitness in Selected Young Judokas

Nikola Milošević [1], Dušan Stupar [2,*], Nemanja Stanković [1], Saša Pantelić [1], Nikola Stojanović [1], Stevan Stamenković [1], Nebojša Trajković [1] and Igor Potparić [3]

[1] Faculty of Sport and Physical Education, University of Niš, 18000 Niš, Serbia; milosevicn@yahoo.com (N.M.); nemanjastankovic84@hotmail.com (N.S.); spantelic2002@yahoo.com (S.P.); nikola987_nish@hotmail.com (N.S.); stevajudo@yahoo.com (S.S.); nele_trajce@yahoo.com (N.T.)

[2] Faculty of Sport and Tourism, Educons University, 21000 Novi Sad, Serbia

[3] Faculty of Medicine, University of Ljubljana, 1000 Ljubljana, Slovenia; igor.potparic@gmail.com

* Correspondence: dusan.stupar@tims.edu.rs

Abstract: This study aimed to determine the influence of body composition on the muscle fitness of selected judokas. This study was conducted on a sample of 23 judokas (cadets n = 12, juniors n = 11), members of the male national team of Serbia. The assessment of body composition was performed using the InBody 720 (Biospace Co., Ltd., Seoul, Republic of Korea) and calipers. Muscle fitness was assessed using “Optojump” (Microgate, Bolzano, Italy), Fitrodine Premium (Fitronic, Bratislava, Slovakia), and a digital force instrument IMADA Z2H-1100 (Imada Inc., Northbrook, IL, USA). Regression analysis revealed a notable association between muscle mass and measures of explosive strength (countermovement jump (CMJ) $p = 0.023$; drop jump (DJ) $p = 0.026$). Moreover, this study’s results showed that back extension ($p = 0.006$; $R^2 = 0.61$) and hand grip ($p = 0.009$; $R^2 = 0.52$) provide a strong positive association with muscle mass. The findings suggest that tailored training and nutritional strategies that improve muscle mass might significantly enhance muscle fitness in young judokas, optimizing their performance.

Keywords: morphological characteristics; strength; martial arts

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1. Introduction

Today, judo is one of the most popular martial arts, where physical performance and body composition are crucial elements that significantly impact an athlete’s success [1]. High levels of strength, endurance, and agility, coupled with optimal body composition, characterized by a favorable balance of muscle mass and minimal body fat, are essential for executing techniques with precision and power, allowing judokas to gain an advantage over their opponents [2]. Moreover, top-elite judokas are significantly superior in all upper-body neuromuscular attributes compared to lower-level judokas [3]. This superiority is critical as it enables elite judokas to perform more powerful and effective throws, maintain superior grip strength, and exhibit greater overall endurance and resilience during matches, which are essential qualities for success at the highest levels of competition. The physiological profile of elite judokas is characterized by remarkable muscle strength, with bench press values often exceeding 1.5 times their body weight and leg press values reaching up to 3 times their body weight. The ability to generate such force directly contributes to the athletes’ competitive performance, making muscle strength one of the key determinants of success in judo [2].

Previous studies have examined the optimal level of physical readiness necessary for top sports performance [4], the psychological profile of elite judokas [5], the anthropometric profiles of competitors in different weight categories [6], the effects of specific training programs on anthropological characteristics [7], and the biomechanical efficiency of judokas to reduce the number of fight injuries [8]. Additionally, research has established that competitive success in judo is influenced by various factors such as muscle strength, endurance, anaerobic power, aerobic capacity, flexibility, and the technical efficiency of judokas [9]. However, these studies often lack specific numerical data and detailed analysis of the physiological profiles of elite judokas, particularly how their body composition relates to fitness components such as strength and agility.

This study builds upon these findings by focusing on the associations between body composition and muscle fitness parameters among elite judokas. Strength is one of the most dominant fitness parameters in judo. During a fight, judokas activate a significant portion of their muscle mass in both the upper body and lower extremities. Elite senior judokas are known for their high muscle strength and upper-body muscle endurance, which are critical for executing and resisting throws, maintaining grips, and ensuring quick recovery during a match [1]. Previous studies have indicated that the arm and forearm flexor muscles are crucial due to judo's direct physical contact and gripping actions [10]. Therefore, understanding how muscle mass distribution relates to these strength attributes can provide valuable insights for optimizing training and performance.

The body composition of athletes depends on several factors: age, gender, health status, genetic factors, diet, and training process [11]. This implies that the training process could be adjusted if the factors affecting sports performance are clearly defined [12]. The training process of judokas can vary depending on the weight category of the competitors, so systems and training methods are chosen to meet the needs of light, medium, and heavy categories. One way to gain an advantage over the competition is to enter a lighter-weight category by adjusting body weight while aiming to maintain muscle mass and lose body fat [13]. In judo, a growing problem is losing body weight before competing in the desired weight category [14]. Therefore, efforts are made to define the optimal body composition.

Consequently, the question arises: what association does body composition have with the muscle fitness of top judokas? It is well established that the mesomorphic somatotype, characterized by a large percentage of muscle mass and a low percentage of body fat, is typical for judokas [15]. Elite judokas should maintain a body fat percentage below 10% through a programmed training process and proper diet [1], except in the heavy and super-heavy categories (up to 100 kg and over 100 kg). Research has shown that Olympic and world medalists have less than 10% body fat [2,16].

While the association between body composition and the strength of top judokas is an important area, it has not been sufficiently researched. This study, therefore, might have practical implications for the fields of sports science and martial arts. It aims to determine the associations between body composition and the muscle fitness of the elite judokas. Our focus on this specific issue might be a valuable addition to the existing body of research. However, it also highlights the need for further research in this area.

2. Materials and Methods

2.1. Participants

The sample consisted of 23 male judokas from the broader composition of Serbia's national team, categorized into various weight classes: 55 kg, 60 kg, 66 kg, 73 kg, 81 kg, 90 kg, and 100 kg. This range of weight classes ensures a representative sample of judokas across different competitive categories, providing a comprehensive understanding of the relationships between body composition and muscle fitness across a spectrum of athletes. Each weight class was chosen to align with the standard weight categories used in judo competitions.

Participants were recruited during a national team training camp. The recruitment process included the following criteria: all participants had to undergo a medical examination, have no health problems ten days before testing, have no injuries that could affect the test results, and obtain parental consent for participation if they were under 18. Exclusion criteria from this study included being in a period of intensive weight loss, feeling accumulated fatigue from previous training, and not feeling sufficiently motivated to participate.

This recruitment strategy ensured that the participants were in optimal condition for the assessments, thus providing reliable data for this study.

All participants voluntarily participated in this study after being informed about the procedures, and each participant could withdraw from this study at any time during the testing. This study was previously approved by the Ethics Committee of the Faculty of Sport and Physical Education (R. 03-1912/43, approved 11 April 2019). Measurements were carried out by highly qualified experts with previous experience in the mentioned measurements. This study followed the Helsinki Declaration and recommendations for research involving human subjects.

2.2. Study Design

This study investigated the association between body composition and muscle fitness in young judokas. Body composition measurements included assessments of muscle mass, body fat percentage, and lean mass. Muscle fitness was evaluated using a series of standardized tests: countermovement jump, drop jump, and bench press throw were used to assess explosive power; isometric deadlift, standing leg extension, and hand grip tests measured isometric strength; and trunk flexion, push-ups, and back extension tests evaluated local muscular endurance.

The test sequence was carefully planned to eliminate the possibility of fatigue affecting subsequent test results. All tests were conducted following a standardized warm-up and based on established recommendations for their execution. Participants were thoroughly briefed on the test procedures, which were demonstrated before each measurement. Additionally, participants were instructed not to train for at least 24 h before testing and to maintain consistent eating, sleeping, and other habits. The measurements were conducted in the halls of the National Youth Camp "Karataš" (Institute for Sport and Sports Medicine of the Republic of Serbia). The hall temperature was maintained at approximately 20 °C to ensure proper measurement conditions, and participants wore appropriate sports attire (shorts, shirts, shoes).

2.3. Measures and Procedures

2.3.1. Anthropometric Measurements and Body Composition

Anthropometric measurements were conducted following the recommendations of Eston & Reilly [17] and included measurements of body height, body mass, and five skinfold thicknesses (triceps, back, abdomen, thigh, and calf). Body height measurement was performed with a Martin anthropometer (GPM, Lugano, Switzerland) (measurement accuracy 0.1 cm). Subcutaneous fat tissue was measured with a "John Bull" caliper (CMS instruments, London, UK) with an accuracy of 0.2 mm. The pressure on the caliper tips was constant at 10 g/mm^2, and the results were read two seconds after this pressure was achieved. Total subcutaneous adiposity was calculated by summing the measured skinfolds (triceps, back, abdomen, thigh, and calf).

Body composition was assessed using bioelectrical impedance analysis, utilizing the Segmental Body Composition Analyzer InBody 720 (Biospace Co., Ltd., Seoul, Republic of Korea), a valid and reliable method for assessing body composition in this population [18]. Parameters measured during the assessment were body fat percentage (BF%), muscle mass percentage (MM%), lean body mass percentage (LBM%), and body mass.

2.3.2. Muscle Fitness

Muscle fitness was classified into three dimensions: explosive, isometric, and local muscular endurance.

Three tests were applied to measure explosive power or muscle potential in dynamic conditions: countermovement jump free arms (CMJ), drop jump (DJ), and bench press (BP), measured using the "Optojump" system (Microgate, Bolzano, Italy) and Fitrodine Premium (Fitronic, Bratislava, Slovakia). These tests have been used in previous studies and have shown good validity and reliability [19–21].

2.3.3. Countermovement Jump

Participants performed countermovement jump free arms (CMJ) by jumping from a half-squat position. The subjects were allowed to swing their arms during the jump. Each subject performed three trials, and the highest jump performance (cm) was recorded.

2.3.4. Drop Jump

The drop jump (DJ) was performed by having participants stand upright with slight knee flexion and arms free beside the body on the edge of a box 40 cm high, with the front of the feet hanging off the box. On the signal from the measurer, the participant would "drop" from the box to the ground, preparing the body for landing by flexing the knees and hips slightly. Upon landing, they would squat to an approximately 90° angle between the lower leg and thigh without pausing, swinging the arms forward and upward, performing the highest possible jump, and landing on both feet simultaneously. The verbal cue was to jump as high as possible. Each subject performed three trials, and the highest jump performance (cm) and the corresponding vertical force after the drop (N) were recorded.

2.3.5. Bench Press Throw

The bench press throw (BPT) was conducted in three sets with one repetition per set, utilizing a load corresponding to 70% of the participant's body mass. Participants laid supine on a bench with their feet firmly placed on the floor and their hands gripping the barbell at shoulder width. The exercise commenced from the raised position, where the barbell was held with fully extended arms. The barbell was then lowered to the chest in a controlled manner, followed by an explosive upward movement performed in a ballistic fashion, effectively "throwing" the barbell. The primary parameter measured during this test was the maximal force (Fmax), recorded in Newtons (N). This methodology is validated by the study conducted by Sayers et al. [22].

A digital force gauge IMADA Z2H-1100 (IMADA Inc., Northbrook, IL, USA) with the WinWedge 3.4 program (TAL Technologies, Philadelphia, PA, USA) and a hand dynamometer with the Physical Ability Tests program assessed muscle potential in static conditions or absolute strength. The values of the achieved results were read in Newtons (N). The tests were conducted after 5 min of individual warm-up, with two attempts for each test and a two-minute break between tests.

2.3.6. Isometric Standing Leg Extension

The isometric standing leg extension (SLE) was performed by having participants stand on a platform, holding the dynamometer behind and below their backs. The dynamometer was hooked by a chain to a stand on which the participants stood. The knee joint angle was 120°, the back was straight, and the feet were 10–15 cm apart, with the entire surface of the feet on the platform. The chain connecting the digital force gauge to the stand was fully tightened. On the measurer's signal, the participant pulled the dynamometer upward for three to five seconds, trying to straighten the knees. Each subject performed two trials, and the highest force output was recorded.

2.3.7. Isometric Deadlift

The isometric deadlift (DL) was performed by having participants stand on a platform holding the dynamometer in front of themselves at the level of the first third of the thigh. The dynamometer was hooked by a chain to a stand on which the participants stood. The legs were straight at the knee joint, the feet 10–15 cm apart with the entire surface of the feet on the platform, and the back slightly bent forward. The chain connecting the digital force gauge to the stand was fully tightened. The hip angle was maintained at approximately 130 degrees. On the measurer's signal, the participants pulled the dynamometer upward with their backs for three to five seconds. Each subject performed two trials, and the highest force output was recorded.

2.3.8. Handgrip Strength

For assessing handgrip strength (handgrip strength test, HST), a hand dynamometer with an adjustable grip and a computer with appropriate software that detects the force produced on the hand dynamometer with the Physical Ability Tests program were used. The participants were to perform a maximum grip on the dynamometer with their stronger hand without interruption and hold for at least two seconds. The position of the participant's hand during the test was extended at the elbow joint and placed next to the participant's body [23]. Each subject performed three trials, and the highest force output was recorded.

The following tests assessed local muscular endurance: trunk flexion on a bench, push-ups, and back extension performed until exhaustion. The total number of successfully performed attempts was the final test result (rep).

2.3.9. Trunk Flexion

Trunk flexion (TF) was performed by having the participant sit on the edge of a bench with knees bent at a 90° angle, feet placed at hip width, and hands crossed at the back of the head. On the measurer's signal, the participant performed the maximum number of repetitions of sitting up and lowering the trunk to a horizontal position. The task was to perform the exercise until exhaustion, with the measurer counting correctly performed attempts at trunk lifting [24].

2.3.10. Push-Ups

Push-ups (PUs) were performed by having the participant take a prone position on a mat with hands placed on the mat. From the starting position, the participant touched the ground with the chin at least 10 cm in front of the line where the hands were placed by bending the arms at the elbows and lowering the trunk, ensuring that the bent elbows stayed close to the body without separating from it. The task was to perform the exercise until exhaustion. The measurer's task was to count attempts that were correctly performed. As tested in previous research, the test has satisfactory validity and reliability [25].

2.3.11. Back Extension

The parallel Roman chair dynamic trunk extension (PRC-DTE) was performed by having the participant lie prone on a box with the iliac crest at the edge, the trunk hanging vertically down, legs fixed, and hands crossed across the chest. The participant began in a neutral alignment with 180° between the back and legs, arms folded across the chest. From this position, the participant flexed forward at the waist to a 90° angle, then extended the back to return to neutral alignment, following a system of 3 s beeps. The test continued until the participant could no longer maintain the pace or voluntarily stop, with the total number of correctly paced repetitions recorded. Two spotters ensured the participant's safety throughout the test. Hannibal et al. have proven this test's reliability [26].

2.4. Statistical Analysis

Data were processed using the Statistical Package for Social Sciences, SPSS (v20.0, SPSS Inc., Chicago, IL, USA). For each variable, the basic parameters of descriptive statistics were calculated: mean value (mean), standard deviation (±SD), and confidence intervals (95% CI). The association between body composition and muscle fitness was determined using regression analysis (enter method), and individual influences were determined using the beta coefficient (β). Statistical significance was set at $p < 0.05$.

3. Results

Table 1 shows the basic descriptive characteristics of elite judokas.

Table 1. The values of the basic descriptive parameters.

Variable	Mean ± SD	95% CI
Body Mass (kg)	70.15 ± 10.95	65.42–74.89
Body Fat (%)	10.95 ± 2.84	9.72–12.18
Muscle Mass (%)	52.53 ± 1.38	51.93–53.12
Lean Body Mass (%)	89.02 ± 2.86	87.78–90.26
Skinfold Thickness—Triceps (mm)	9.87 ± 2.26	8.89–10.84
Skinfold Thickness—Back (mm)	10.91 ± 2.98	9.62–12.20
Skinfold Thickness—Abdomen (mm)	10.69 ± 5.47	8.32–13.06
Skinfold Thickness—Thigh (mm)	9.34 ± 2.67	8.19–10.50
Skinfold Thickness—Calf (mm)	12.08 ± 3.17	10.71–13.46
Total Skinfolds (mm)	52.91 ± 13.35	47.13–58.68
CMJ (cm)	34.12 ± 4.97	31.97–36.27
DJ (Fmax)	34.18 ± 5.74	31.69–36.66
DJ (cm)	39.52 ± 6.11	36.88–42.16
Bench Press Throw (Fmax) (N)	1170.61 ± 369.91	1010.65–1330.58
Back (Fmax) (N)	1586.52 ± 236.11	1484.41–1688.62
Legs (Fmax) (N)	1418.69 ± 200.45	1332.01–1505.37
Handgrip strength (Fmax) (N)	420.21 ± 67.36	391.08–449.34
Push-ups (rep)	45.30 ± 14.13	39.19–51.41
Trunk Flexion (rep)	10.73 ± 62.58	78.67–132.80
Back Extensions (rep)	73.69 ± 25.22	62.78–84.60

Legend: Mean—arithmetic mean; SD—standard deviation; 95% CI = confidence intervals; CMJ—countermovement jump; DJ—drop jump.

Figure 1 reveals the association between muscle mass and various measures of explosive strength, isometric strength, and local muscular endurance. The bench press panel indicates a strong positive relationship between muscle mass and maximal force output, highlighting muscle mass association with explosive strength. Similarly, the countermovement jump (CMJ) panel underscores a significant association between muscle mass and jump height, while the drop jump (DJ) panels, regarding jump height and force relative to body mass, showed a significant positive association between muscle mass and performance.

Figure 1 also provides insights into the association between muscle mass and muscle potential in isometric conditions. The back extension and hand grip panels show a strong positive association with muscle mass. However, despite a positive trend, the leg extension panel shows no statistical significance. In contrast, the push-ups, trunk flexion, and back extension panels display weak and non-significant associations.

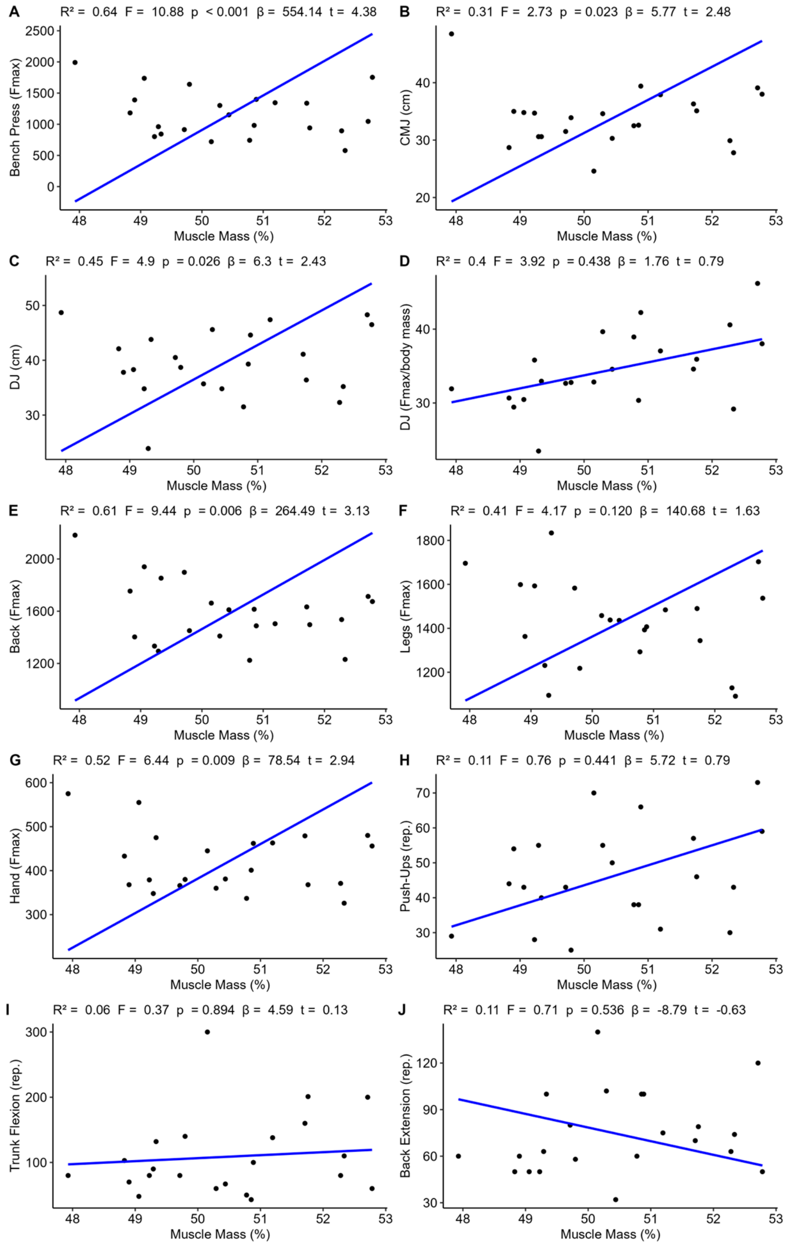

Figure 1. Relationship between muscle mass and various performance metrics. This figure shows the association between muscle mass and measures of explosive strength (panels (**A**–**D**)), isometric strength (panels (**E**–**G**)), and local muscular endurance (panels (**H**–**J**)). Each panel presents the observed data points and the fitted regression line with muscle mass as the predictor. The output statistics in each panel include R^2 (coefficient of determination), F (F-statistic), *p* (*p*-value), β (beta coefficient), and t (t-value).

4. Discussion

This study investigates the association between body composition and muscle fitness parameters in young judokas. We examined key indicators of body composition, including fat mass, muscle mass, and lean body mass, alongside muscle fitness parameters such as muscular strength, endurance, and power. Our findings reveal significant associations between body composition and muscle fitness, underscoring the critical role of optimal body composition in the physical performance of young judokas.

Given the sport's demand for explosive movements and sustained physical exertion, Torres-Luque et al. [27] emphasize that physical and physiological characteristics, such as muscle mass and aerobic endurance, are critical for success in judo. However, it is well documented that body composition plays a pivotal role in judo performance. Junior et al. [28] found that lean body mass is a key determinant of performance, influencing both strength and specific physical fitness. This is supported by Clarys et al. [29], who demonstrated that accurate estimation and maintenance of optimal body composition in adolescent judokas are crucial for their development and competitive success. Further, body composition is critically important for performance in judokas due to its direct impact on strength, agility, endurance, and overall physical efficiency. Lean body mass, particularly muscle mass, generates the explosive power needed for throws, holds, and counter-movements intrinsic to judo. Studies such as those by Junior et al. [28] have shown that judokas with higher lean body mass tend to perform better, as muscle strength is a significant predictor of success in this sport. Moreover, Torres-Luque et al. [27] emphasized that judokas must balance muscle mass and minimal body fat to optimize performance.

Our results revealed a notable association between muscle mass and measures of explosive strength, as evidenced by significant correlations in the CMJ (p = 0.023) and DJ (p = 0.026). These findings highlight the direct impact of muscle strength and explosive power on the competitive performance of elite judo athletes. The association between body composition and muscle fitness parameters in young judokas is underscored by several key studies, revealing intricate interdependencies that influence athletic performance. Tavares Junior et al. [30] demonstrated a significant correlation between handgrip strength and body composition parameters, emphasizing the importance of muscle mass in enhancing grip strength, a critical component in judo performance. Similarly, Junior et al. [28] identified body composition, particularly lean body mass, and specific physical fitness factors, such as strength and endurance, as crucial determinants for distinguishing performance levels among judokas. Furthermore, Witkowski et al. [31] highlighted the variation in body composition and motor potential across different weight categories, suggesting that optimal body composition tailored to weight class can significantly impact an athlete's motor abilities and overall performance. These findings collectively suggest that targeted training and nutritional strategies focusing on improving body composition and specific muscle fitness parameters can substantially enhance the performance of young judokas.

The results of the current study also demonstrated that back extension (p = 0.006; R^2 = 0.61) and hand grip strength (p = 0.009; R^2 = 0.52) exhibit a strong positive association with muscle mass. This indicates that greater muscle mass significantly contributes to higher performance in these strength measures, underscoring the importance of muscular development in elite judo athletes. These results align with previous studies showing a significant correlation between body composition and strength, particularly explosive and isometric strength [32,33]. A similar study on Polish national and international rank competitors found a statistically significant correlation between lean body mass and hand-grip strength [31]. In contrast, the tests of repetitive strength did not have a statistically significant correlation with the body composition of the competitors. This is in line with the results obtained in our study. The same research also found a correlation between absolute strength tests and body mass and body fat percentage. This justifies the fact that competitors from higher weight categories, who also have a higher body fat percentage, recorded better results in absolute strength tests.

There is a significant impact of muscle mass % on DJ height, bench press throw Fmax, and absolute strength (back Fmax and hand Fmax). Muscle mass is one of the crucial determinants of performance in judo, significantly impacting an athlete's strength, power, and overall effectiveness in competition. According to Detanico et al. [34], muscle mass is particularly influential in young judo athletes, where somatic maturation, growth, and training experience collectively shape their physical capabilities. This study highlights that increased muscle mass can enhance physical performance metrics such as explosive and absolute strength. In judo, where the ability to execute powerful throws, maintain holds, and resist opponents' maneuvers is essential, greater muscle mass translates into more effective performance. Muscle mass contributes to higher levels of anaerobic power and muscular endurance, allowing athletes to perform explosive techniques repeatedly throughout a match without significant fatigue. Consequently, targeted training programs to increase muscle mass should be a fundamental aspect of judo training regimens, especially for developing athletes.

However, this study is not without shortcomings. This study's cross-sectional design limits the ability to infer causality, and we can only discuss associations, not causal relationships, between body composition and muscle fitness parameters. The relatively small sample size may increase the likelihood of Type II errors, potentially underestimating the strength of associations between variables. Additionally, while participants were top-level athletes within their respective categories, the combined analysis of cadets and juniors without detailed differentiation could influence the findings. Furthermore, this study included only male judokas, limiting the generalizability of the findings to female judokas. This study did not account for the participants' nutritional habits, specific training regimens, or other lifestyle factors that could influence muscle fitness. Additionally, including various weight categories without specific analyses might obscure the weight class's potential differences and influences on the results. This oversight limits the granularity of our findings, as different weight categories may have distinct physical and physiological profiles that affect muscle fitness parameters differently. Moreover, the variability in the accuracy and precision of measurement techniques for body composition and muscle fitness parameters can affect the reliability of the results.

Despite these limitations, this study has several strengths. One significant strength is the focus on young elite judokas, providing specific insights into this athlete population's body composition and muscle fitness. Multiple regression analysis allows for a detailed examination of the relationships between body composition and various muscle fitness parameters, offering a comprehensive understanding of how different body composition metrics contribute to performance outcomes. Our study also highlights the importance of muscle mass for strength and explosive power, which are critical components of judo performance, underscoring the potential benefits of targeted training programs that emphasize muscle mass development. The comprehensive dataset includes a range of performance metrics, providing a robust analysis of the association between body composition and various aspects of muscle fitness. Furthermore, the findings can inform tailored interventions to optimize physical conditioning in young judokas, contributing to their overall athletic development and competitive success. This study's design and methodology can be easily replicated in environments with limited resources, making it valuable for practical implementation.

5. Conclusions

The association between body composition and muscle fitness parameters in young judokas is critical for their competitive performance and overall athletic development. Our study has shown that optimal body composition, characterized by high muscle mass, is associated with greater strength and explosive power in young judokas. Tailored training and nutritional strategies focusing on improving body composition are fundamental for optimizing young judokas' physical fitness and competitive success. Future studies should examine the association between body composition and other fitness parameters and include female participants to further investigate the relationship between body composition and physical performance in judo.

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Differences in Impact Force between Side Kicks and Turning Kicks in Male Practitioners of Taekwon-Do—Case Studies

Tomasz Góra [1], Dariusz Mosler [1], Józef Langfort [1,2] and Jacek Wąsik [1,*]

[1] Institute of Physical Culture Sciences, Jan Dlugosz University in Częstochowa, 42-200 Częstochowa, Poland; t.gora@ujd.edu.pl (T.G.); d.mosler@ujd.edu.pl (D.M.); j.langfort@awf.katowice.pl (J.L.)
[2] Institute of Sport Sciences, The Jerzy Kukuczka Academy of Physical Education, 40-065 Katowice, Poland
* Correspondence: j.wasik@ujd.edu.pl

Abstract: The purpose of this study was to understand the different forces exerted between the side kick and turning kick in taekwon-do, which would add knowledge to the field, as well as help inform future research. Eighty kicks performed by four elite ITF (International Taekwon-do Federation) athletes (age: 28.5 ± 7.2 years; body mass: 77.5 ± 6.7 kg; height: 180.0 ± 1.6 cm) were analysed. Participants performed a series of turning and side kicks with the right and left leg to the target. The impact-force-measuring apparatus was a training shield mounted on a force plate manufactured by AMTI, model MC12-2K. The mean resultant impact force for the turning kick was significantly lower than the mean resultant impact force for the side kick. There were no significant differences in the impact force between turning kicks performed with either the right or left leg. With regard to the correlations for the turning kick performed by both legs, there was almost a full correlation between F_Z and the resultant impact force (r = 0.988 for the right leg and r = 0.994 for the left leg). The side kicks' significantly higher resultant force (4429.77 ± 1361.25 N) than that of a turning kick (2648.98 ± 441.41 N) could be due to more effective mass being used. The turning kick peaked in a shorter time; this indicates that a turning kick has a shorter contact time with the target. The strong correlations between F_z and the resultant impact force in both kicks could be due to the direction of the kicks, suggesting that the force in the Z axis was the most important direction.

Keywords: turning kick; side kick; taekwon-do; movement analysis; lateralization; strength kicks

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1. Introduction

Researchers have been quantifying the velocity and strength of martial arts practitioners' kicks for many years using a variety of devices, including but not limited to a triaxial accelerometer and force plates [1–3]. The reported impact force values for the taekwon-do turning kick ranged from 1800 N [4] to 6400 N [5]. The large range of the impact force values for a roundhouse kick could be due to some studies quantifying the peak, mean, or another form of impact force, whilst other studies did not specify said force [6]. Furthermore, the differences in the methodology of quantifying impact force could have had an impact on the impact force values. Despite the variety of methodologies used in obtaining impact force values, force plates are considered the gold standard in biomechanics laboratories for quantifying external force in martial arts kicks, as well as in sports [7,8]. This is partly due to force plates sampling at a higher frequency than video analysis and motion capture, as well as quantifying the impact force of kicks and strikes directly [6].

Perfecting technique in taekwon-do is a key component of training, influencing effectiveness in combat [6,9,10]. The ability to generate significant striking power and speed is a fundamental element in both attack and defence techniques. In traditional taekwon-do (International Taekwon-do Federation), individual sport competition is based on four competitions: formal systems, sport fighting, special techniques, and strength tests [11]. The direct confrontation of participants in sport fighting is based on scoring points through effective strikes. Side kicks and turning kicks are among the most commonly used forms of attack and counterattack and are, therefore, an important part of athlete training and competition [4,12,13]. Therefore, the ability to properly teach and apply these types of strikes is one of the basic skills of athletes in this martial art. The main difference between these techniques lies in the direction of the strike; in a spin kick, the foot moves in an arc along the axis of the body, whereas in a side kick, the foot moves laterally towards the opponent [3,11].

This study found that in men, the impact force of the side kick (461 N) was lower than that of the roundhouse kick (518 N), while in women, it was 408 N and 406 N, respectively [14]. This study noted that the nature of the side kick allows for an increased proportion of mass to be used to increase force. A different study on impact force and effective mass demonstrated that although there was a higher percentage of effective mass in a side kick (43.4%) than in a turning kick (36.6%), the impact force of a side kick (2406.9 N) was greater than a turning kick (2330.7 N) [15]. In other studies, researchers have reported different turning kick force values. For example, Gavagan et al. reported a force of 1547 N [16], while Li et al. reported a force of approximately 2940 N for men and 2401 N for women [17]. Research suggests that movement technique and gender can significantly influence athletic performance, but their importance can vary depending on a number of factors [10,18,19]. Deliu et al. [20] noted that in combat sports, during the execution of kicks, some biomechanical variables are not lateralised. By contrast, Górski and Orysiak [21] reported that there are significant differences in the strength of turning kicks in taekwon-do. The issue is therefore unresolved and requires further research.

All studies reported so far on impact force have only investigated the resultant impact force and not the impact force in different planes, despite noting that turning kicks and side kicks are multiplanar [6]. To the author's knowledge, no research has investigated the impact force in different planes, which could play an important role in impact power and impact force.

The aim of this study was three-fold: (1) to investigate if there are differences in the forces achieved between the turning kick and the side kick, (2) to investigate if there are significant differences between, and across, the impact force of the left and right leg, and (3) to investigate the correlations between the resultant force of the kicks under study and other selected variables. The purpose of this study was to understand the differences between the side kick and turning kick in taekwon-do, which would add knowledge to the field, as well as help inform future research.

The responses to the following questions align with current trends in sports biomechanics for martial arts. The practical objective of this study is to provide recommendations for practitioners and trainers to optimize technique performance and enhance training methods.

2. Materials and Methods

2.1. Participants

Eighty kicks performed by four elite ITF (International Taekwon-do Federation) athletes (age: 28.5 ± 7.2 years; body mass: 77.5 ± 6.7 kg; height: 180.0 ± 1.6 cm) were analysed. The prerequisites for inclusion in the study group were the following: male sex, at least 18 years of age, possession of a minimum of 1 DAN (black belt) or higher, a minimum of 8 years of training experience, active participation in sports competitions at the national level for at least 4 years, winning a minimum Polish champion title, and no injuries. All players declared a preference for right-leg kicks. The measurement conditions were standardized for all subjects, conducted in the morning at a consistent room temperature. The participants were briefed on the testing procedures and voluntarily consented to take part in the data collection. The Committee on Research Involving Human Subjects at Jan Długosz University reviewed and approved the study protocol, confirming that it complied with ethical standards for research involving human participants (KE-O/4/2022).

2.2. Equipment

A force plate was used to measure the impact force. It was padded with a training disc to prevent direct contact with the force plate and was mounted on a stable structure (AMTI, model MC12-2K, 2000 series, Watertown, MA, USA) (Figure 1). The force plate axes were defined as follows: (F_x)-force in the medial-lateral direction, (F_y)-force in the vertical plane, and (F_z)-force in the anterior–posterior direction relative to the athletes (Figure 2). The force plate measured 305 × 406 × 79 mm and could measure forces up to 4500 N for F_x and F_y and 9000 N for F_z, with a sampling rate of 750 Hz. The device was synchronised in time and space with the Noraxon system (MR3 3.18).

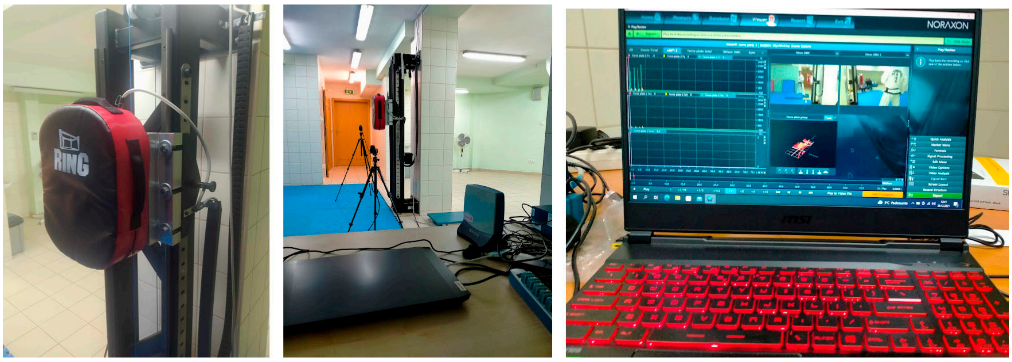

Figure 1. Strike pad placed on a force plate AMTI MC12-2K, with fittings and software interface on the computer.

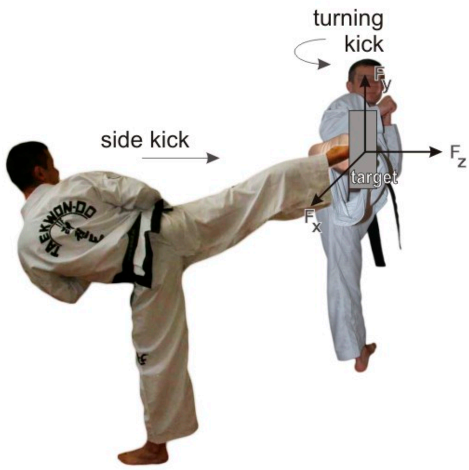

Figure 2. The positioning of the athlete according to the type of kick to the target of the strike in the Cartesian system.

2.3. Protocol

Data collection took place at the Center for Human Movement Analysis, Jan Dlugosz University, Czestochowa (Poland). The participants began with a self-selected 10 min warm-up. Following the warm-up, they performed five side kicks (yop chagi) with their right leg, starting from a sport stance, aiming at the target. After a one-minute rest, they executed five turning kicks (dollyo chagi) with their right leg from the sport stance to the target (Figure 2). This procedure was then repeated for the left leg for all participants. They were instructed to kick with maximum effort to achieve the highest impact force possible, with no time constraints for performing the kicks. In total, 80 attempts were recorded.

2.4. Data Processing and Data Analysis

After data collection, all recorded trials were exported from Noraxton 3.18 with Myomotion module (Scottsdale, AZ, USA) to Excel, Microsoft Office Professional Plus 2010, to obtain the resultant impact force in the side kick and pivot kick, where a force-time history was created. Kinetic data for 20 kicks (five side kicks and five turning kicks per leg) for each participant, totalling 80 kicks for all four participants, were then exported from Noraxon and imported into Microsoft Excel. The resultant impact force (F) was calculated using a vector norm in Euclidean space. Changes in the resultant reaction force were recorded as a function of time to determine the force value relative to the XYZ axis.

2.5. Statistical Analysis

After preliminary data analysis, group mean, minimum, maximum, and standard deviation were calculated for F_x, F_y, F_z, and F values for each kick, for each leg, and for both legs. Statistical significance between the analysed groups was determined using the Mann–Whitney U test. The Spearman correlation test was used to determine the correlation between the selected variables. Thresholds for qualitative descriptors of correlations were interpreted as trivial (0.0–0.09), small (0.10–0.29), moderate (0.30–0.49), large (0.50–0.69), very large (0.70–0.89), nearly perfect (0.90–0.99), and perfect (1.0) [22].

All calculations were performed using Statistica 13 (TIBCO software). Statistical significance was set at $p < 0.05$. The sample size was estimated using G*Power software (version 3.1.9.2; Kiel University, Kiel, Germany) [23], resulting in a minimum requirement of 70 measurement positions, with parameters of $\alpha = 0.05$, effect size f = 0.9, and $\beta = 0.95$.

3. Results

The data revealed that the resultant force in the side kicks was significantly higher and peaked later in than in the turning kicks (Figure 3). Regarding the differences in the impact force between the left and right legs, concerning the side kicks, the right leg produced a significantly higher ($p < 0.01$) F_x than the left leg (Table 1).

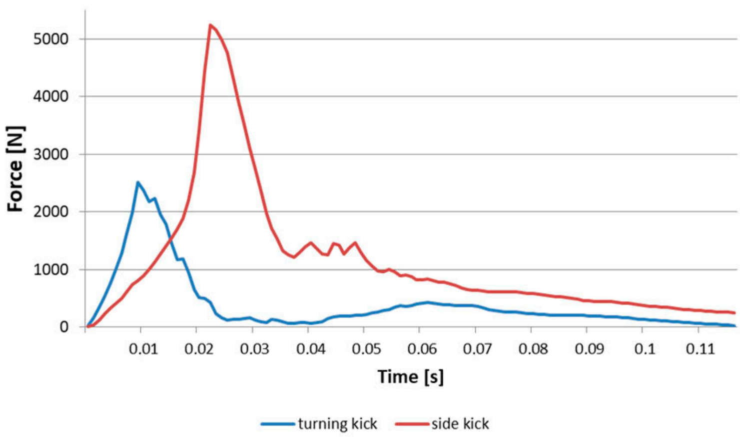

Figure 3. Example graph of the force change of selected kicks as a function of time for a single measurement.

Table 1. Descriptive statistics of selected kicks, with statistical differences calculated using the Mann–Whitney U test.

Kind of Kick	Axis of Force	Indicator	Force [N]		
			Right Leg	Left Leg	Total
Turning kick	F_x	Mean	228.53	248.58	238.55
		SD	99.12	145.30	123.18
		Minimum	89.68	81.85	81.85
		Maximum	506.36	538.64	538.64
		SS	U = 0.36; p = 0.715		-

Table 1. *Cont.*

Kind of Kick	Axis of Force	Indicator	Force [N]		
			Right Leg	Left Leg	Total
Turning kick	F_y	Mean	134.30	105.18	119.74
		SD	58.02	56.20	58.28
		Minimum	44.23	19.56	19.56
		Maximum	264.14	222.82	264.14
		SS	U = 1.58; p = 0.114		-
	F_z	Mean	2844.48	2549.98	2697.23
		SD	624.18	433.26	550.90
		Minimum	1857.90	1406.04	1406.04
		Maximum	4230.87	3247.66	4230.87
		SS	U = 1.31; p = 0.190		-
	F	Mean	2921.76	2648.98	2785.37
		SD	669.23	441.41	576.36
		Minimum	1898.66	1456.15	1456.15
		Maximum	4383.13	3344.36	4383.13
		SS	U = 0.98; p = 0.323		-
Side kick	F_x	Mean	1200.33	403.00	801.66
		SD	273.40	101.48	452.15
		Minimum	521.68	218.16	218.16
		Maximum	1499.72	612.99	1499.72
		SS	U = 5.34; p < 0.001		-
	F_y	Mean	148.53	127.58	138.05
		SD	59.48	70.94	65.48
		Minimum	34.50	37.96	34.50
		Maximum	261.01	293.59	293.59
		SS	U = 1.50; p = 0.133		-
	F_z	Mean	4614.31	4275.26	4444.79
		SD	1287.88	1376.73	1327.00
		Minimum	1575.25	1602.86	1575.25
		Maximum	5911.26	5840.10	5911.26
		SS	U = 1.05; p = 0.291		-
	F	Mean	4754.11	4429.77	4591.94
		SD	1290.31	1361.25	1319.40
		Minimum	1594.11	1691.45	1594.11
		Maximum	6099.03	5993.34	6099.03
		SS	U = 1.01; p = 0.310		-

SD—standard deviation; SS—statistical significance; Total—the mean force of the right and left legs; U—Test statistic result for the Mann–Whitney U test; *p*—statistical significance value.

The side kicks produced a significantly higher ($p < 0.01$) F_x, F_z, and resultant force than the turning kicks, with no significant differences between F_x and F_y in the turning kicks and side kicks (Table 2).

Table 2. Differences between force values for each axis between both presented techniques.

Kind of Kick	Axis of Force	Turning Kick		Side Kick		D [N]	U	*p*
		Mean Resultant Force [N]	SD [N]	Mean Resultant Force [N]	SD [N]			
Both lower limbs	F_x	238.56	123.19	801.66	452.15	563.1	−7.60	<0.001
	F_y	119.75	58.28	138.05	65.48	18.3	−1.32	0.190
	F_z	2697.24	550.91	4444.79	1327.00	1747.55	−7.69	<0.001
	F	2785.37	576.37	4591.94	1319.40	1806.57	−7.94	<0.001
Right lower limb	F_x	228.53	99.12	1200.33	273.40	971.8	−14.94	<0.001
	F_y	134.31	58.03	148.53	59.48	14.22	−0.77	0.449
	F_z	2844.49	624.18	4614.31	1287.88	1769.82	−5.53	<0.001
	F	2921.76	669.24	4754.11	1290.31	1832.35	−5.64	<0.001
Left lower limb	F_x	248.59	145.30	403.00	101.48	154.41	−3.90	<0.001
	F_y	105.18	56.21	127.58	70.94	22.4	−1.11	0.275
	F_z	2549.98	433.27	4275.26	1376.73	1725.28	−5.35	<0.001
	F	2648.98	441.41	4429.77	1361.25	1780.79	−5.57	<0.001

SD—standard deviation; D—the difference between the strength of the kicks; U—Test statistic result for the Mann–Whitney U test; *p*—statistical significance value.

With regard to the turning kicks, there was almost a full correlation between F_z and the resultant impact force value (r = 0.988 for right, and r = 0.994 for left leg) within and across both kicking legs. Furthermore, for turning kicks with the right leg, which was the participants' preferred kicking leg, there was a medium, negative correlation between F_x and $F_{z.}$, and the resultant impact force did not shift significantly upwards of the target (F_y) (Table 3). Similarly, with regard to the side kicks, there was a strong positive correlation between the resultant impact force and F_z for the right and left legs (r = 0.805, 0.783, respectively) and significant positive correlations in the left leg for F_x with F_y and F_z separately.

Table 3. Results of Spearman's correlation coefficients between force indicators for turning kicks and side kicks.

Limb	Axis of Force	Turning Kick			Side Kick		
		F_y	F_z	F	F_y	F_z	F
Both lower	F_x	0.46 *	−0.26	−0.26	0.41 *	0.45 *	0.47 *
	F_y	-	0.13	0.11	-	0.81 *	0.79 *
	F_z	-	-	0.99 *	-	-	0.99 *
Right lower	F_x	0.25	−0.46 *	−0.46 *	0.15	0.35	0.47 *
	F_y	-	−0.04	−0.09	-	0.81 *	0.74 *
	F_z	-	-	0.98 *	-	-	0.97 *
Left lower	F_x	0.42	0.04	0.06	0.59 *	0.86 *	0.85 *
	F_y	-	0.27	0.31	-	0.78 *	0.78 *
	F_z	-	-	0.99 *	-	-	0.99 *

* statistically significant, $p < 0.05$.

The resultant impact force in the turning kicks was significantly ($p < 0.05$) affected by the height of athletes and did not depend on body mass; however, for the side kicks, there was a significant ($p < 0.05$) weak correlation between age and impact force (Table 4).

Table 4. Spearman correlation coefficients between strength indices for selected kicks and age and somatic elements.

Force (F)	Age	Body Mass	Height
Turning kick	0.18	0.26	−0.49 *
Side kick	0.35 *	0.28	−0.06

* statistically significant, $p < 0.05$.

4. Discussion

The resultant impact force in the side kicks was significantly higher ($p < 0.05$) than in the turning kicks. The impact force values in this study were higher than the results in other studies [5,16,17]. Moreover, previous studies did not specify whether the analysis conducted concerned the mean, peak, or another impact force value, and this is the first study to investigate the resultant impact force in taekwon-do kicks, which could lead to different results [5,16]. The results revealed that the resultant impact force in the side kicks peaked later than in the turning kicks. This indicates that, although the force curve rises slower than the turning kick force curve, the force is applied over a longer period and peaks higher; there could be a link between contact time and the amount of force. On the other hand, the turning kick reaches the maximum value within a shorter contact time (Figure 2). A shorter contact time could indicate that the kick was executed in a shorter time; however, to the authors' knowledge, no research has investigated the relationship between contact time with the target and the duration of kick execution. The greater force of the side kick could be related to a greater effective mass; it has been demonstrated that there is more effective mass in a side kick (37.6%) than in a turning kick (34.4%) [15]. However, to the authors' knowledge, there is limited research in this area.

Regarding the second aim (whether there are significant differences in the impact forces between, and across, the left and right leg), the results revealed that side kicks performed with the right leg produced a significantly higher F_x than side kicks performed with the left leg (Table 1). Despite this, there were no significant differences between the right and left leg in the resultant impact force. This suggests that there were no significant differences in the overall impact force between the right and left leg. As there were no significant differences in the resultant impact force, this suggests that there was a relatively even development of the left and right legs in the athletes studied. This is consistent with traditional taekwon-do training methodologies, where exercises are typically performed equally on both sides of the body. Furthermore, a study indicated that improvements in the skill and performance of the non-dominant and dominant limb are accompanied by beneficial changes in certain brain structures [24]. Thus, activating symmetrical parts of the human body increases the health dimension of training in this martial art. In addition, from a utilitarian perspective, both limbs can be used with a similar probability of success in, for example, self-defence.

The results demonstrated that the resultant impact force in both kicks depends mainly on F_z. This makes sense in terms of the kick since the Z-axis was the main direction of the movement of the foot during impact. This suggests that F_z could be the main axis in which to study impact force; this result demonstrates that future research on impact force in taekwon-do side kicks and turning kicks should focus on the F_z of the impact force. Furthermore, as force is a component of other biomechanical variables such as power, other biomechanical variables related to force should be investigated.

There was a significant moderate positive correlation between F_y and F_z for turning kicks with the right leg, with no significant differences between F_x and F for left turning kicks. This could suggest that there is a difference in force distribution and, therefore, in motor control between the two limbs, despite the resultant impact force remaining statistically indifferent in overall force capture. By contrast, the resultant impact force of the side kick was F_x and F_y. This could be due to the direction of movement of the entire body towards the target, as the side kick rises towards the target and comes across to the target, resulting in high F_x and F_y. The significant correlation between the resultant impact force and F_y suggests that the participants kicked up at the target rather than straight towards it, meaning the height of the chamber position was lower than the height of the target. Furthermore, the significant correlation between the resultant impact force and F_x suggests that the heel was behind the knee, rather than in front of the knee. To the authors' knowledge, this is the first study to investigate the impact force in taekwon-do kicks within the X, Y, and Z axes. Future research should investigate the impact force in the X, Y, and Z axes to add to the results of this study.

This was the first study to conduct a three-dimensional analysis of the impact force in taekwon-do turning kicks and side kicks; however, a limitation of this study was that it only investigated male athletes. Biomechanical studies on athletic manoeuvres have found that females have different kinematics that subject them to higher forces per body weight during impact [10,18,25–28]; future research should investigate the impact forces in turning kicks and side kicks in female athletes, which could help inform future research, as well as practical implications for instructors. Furthermore, although impact forces were quantified and analysed in this study, this study did not investigate how the impact forces were generated; future research should investigate which joints generate and dissipate force, which allows for the impact forces to be produced, and this would further the knowledge in the field.

The practical aim of this study may be to make recommendations for coaches and practitioners in order to optimise the technical execution of techniques and improve training methods. A limitation of this study was the use of a static and constrained target and not a large number of subjects. Consequently, caution should be exercised when generalising these results. However, given the existing limitations of the scientific literature on the biomechanics of taekwon-do, the results of this study may provide valuable insights, informing future research and supporting further interdisciplinary exploration.

5. Conclusions

In conclusion, side kicks produced significantly greater resultant impact force than turning kicks. There were no significant differences in the resultant impact force between the left and right legs in both side kicks and turning kicks. In practice, this knowledge makes it possible to verify and recommend the implementation of the technique of both kicks.

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

Data Availability Statement: Restrictions apply to the availability of these data. The data presented in this study are available on request and after appropriate IRB approvals.

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Article

The Impact of Effective Mass on the Strength of Side and Turning Kick in Taekwon-Do Male Practitioners

Tomasz Góra [1], Dariusz Mosler [1,*], Robert Podstawski [2] and Jacek Wąsik [1,*]

[1] Institute of Physical Culture Sciences, Jan Dlugosz University in Częstochowa, 42-200 Częstochowa, Poland; t.gora@ujd.edu.pl
[2] Department of Physiotherapy, University of Warmia and Mazury in Olsztyn, 10-720 Olsztyn, Poland; podstawskirobert@gmail.com
* Correspondence: d.mosler@ujd.edu.pl (D.M.); j.wasik@ujd.edu.pl (J.W.)

Abstract: Background: One of the elements of improving the striking power of combat sports athletes is the ability to use their body mass in an efficient manner; this can improve movement technique and thus increase combat effectiveness. Therefore, the aim of this study was to gain knowledge about the influence of the effective mass obtained on the strength of turning and side kicks in the context of lateralization. Material and methods: The study involved four adult taekwon-do ITF (International Taekwon-do Federation) competitors. Acceleration and force data were obtained by mounting a wireless IMU sensor manufactured by Noraxon, which was synchronized with a force plate. Results: The median force pressure values amounted to 2661.53 N for the turning kick and 4596.15 N for the side kick, with foot acceleration of 150.56 m/s^2 and 74.34 m/s^2, respectively. The calculated median effective mass for the turning kick was 20.12%, and for the side kick, it was 73.09% of the total body mass. The conducted analysis indicates a lack of statistically significant differences between the right and left leg in the obtained kinetic variable values ($p > 0.05$). Conclusions: Our research suggests that the side kick achieves, on average, higher force values than the turning kick. The noted correlation between the three variables informs us that the greater the effective mass, the greater the force pressure and the smaller the foot acceleration, which is consistent with other studies. The lack of lateralization in the limbs performing the kicks is consistent with another study.

Keywords: turning kick; side kick; roundhouse kick; taekwon-do; effective mass; strength kicks

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1. Introduction

Strength is a fundamental element of many sports disciplines. It is a key factor influencing efficiency, the ability to generate power, and overall athletic performance. Its significance is noticeable in various sports contexts [1–4]. It depends on a number of factors, including distance, speed, and the involvement of the right body segments in the movement [1,2]. Determining the impact force for a uniformly shaped block of mass is a simple product of the mass and its acceleration [3]. In such a situation, the effective mass is simply equal to the mass of the whole body. However, the mass of a human being is not homogeneous. It consists of many moving segments, which include bones, muscles, tendons, ligaments, etc. Moreover, after an impact, they can deform, reducing the force of the impact [4]. Therefore, one of the elements of improving the striking power of combat sports athletes is their ability to use their body mass in an efficient manner; this can improve movement technique and thus increase combat effectiveness [5,6]. This mass is often referred to as "effective mass". In the case of boxing, judo, or taekwon-do, effective mass is a key element in combat. Boxers, for example, utilize their body mass by shifting weight from one leg to the other, which allows them to generate greater striking force [7]. In judo, effective mass is utilized for throws and incapacitating maneuvers. Understanding how to use the opponent's body mass and manipulate it is crucial in the techniques of throws [5]. In the case of kicks in taekwon-do, body mass is used to generate force in the kicks. By properly utilizing body mass and hip rotation, the force of a kick can be increased. It is suggested that the more body segments an athlete can engage in a movement, the greater the potential effective use of mass [8]. Interestingly, there is no linear correlation between effective mass and the total body mass of an athlete [9]. This suggests that well-trained and experienced martial arts competitors can achieve a higher effective mass through proper muscle contraction just before contact with the target [10]. Moreover, achieving the appropriate value of effective mass is crucial, as maximum speed or acceleration alone cannot guarantee high force values behind a strike [11]. From physics, we know that force is directly proportional to both mass and acceleration [12,13]. However, the maximum striking force in combat sports depends on many factors, including the distance, speed of the limb, and proper coordination of the kinematic chain during the strike [14–16].

Technological advancements have significantly influenced biomechanical studies in taekwon-do, particularly using load cells and force platforms, along with advanced motion measurement systems featuring accelerometer arrays. This technology has been critical in dissecting the dynamics of taekwon-do techniques, providing invaluable insights into the forces and movements involved [17]. The application of force platforms in taekwon-do biomechanics is essential for accurately measuring motion parameters and the forces exerted during various taekwon-do moves, enhancing our understanding of the mechanics behind these movements. This understanding is crucial for refining techniques and improving training methodologies. Accelerometers, or inertial measurement units (IMU), play a pivotal role in measuring accelerations and velocity changes, thereby offering a deeper analysis of taekwon-do's dynamic movements [18]. In biomechanical research on taekwon-do, combining force plates with motion analysis systems, such as stereophotogrammetric methods with cameras or IMU units, is common. Synchronizing these devices is key to minimizing measurement errors and accurately capturing all variables at specific moments in taekwon-do techniques [19].

The turning kick and side kick are among the most commonly used in the taekwon-do ITF (International Taekwon-do Federation, since we will be focusing on this martial art) [20]. The fundamental difference between these two techniques is the direction of the strike. In a turning kick, the foot moves in an arc along the body's axis, while in a side kick, the foot is moved sideways towards the opponent [21,22].

Determining the effective mass in these strikes is important for training practice and preparation for combat. Effective mass, a term often used interchangeably with "inertial mass," refers to the portion of an athlete's body mass that effectively contributes to the force of a strike. This mass is not a static measure, but is dynamically influenced by several biomechanical factors, including muscle stiffness, co-contraction, and the kinetic chain involved in the movement. A critical aspect of effective mass is its dependence on the biomechanical alignment and muscular activation at the moment of impact. When a fighter executes a strike, not all body mass contributes equally to the impact. The effective mass is predominantly determined by the mass of the body segments in motion and their velocity, but, significantly, it is also influenced by the stiffness of the muscles and joints involved [23]. Muscles that are actively contracted at the moment of impact can increase the effective mass of the striking limb, thereby enhancing the force delivered [8]. Furthermore, the concept of joint stiffness is integral to understanding effective mass. Increased joint stiffness through muscle co-contraction can lead to a higher transfer of force. This biomechanical strategy is often observed in skilled fighters, who can adeptly modulate their joint stiffness to maximize the impact force. It is not only about the mass, but about how effectively this mass is used in the context of a combat sport movement. The kinetic chain, which refers to the sequence of movements in different body parts leading up to a strike, also plays a critical role in the effective mass. Efficient kinetic chain sequencing can augment the effective mass involved in a strike. For instance, a punch that properly harnesses the sequential movement from the legs through the torso to the arm and fist can deliver a more potent force than a punch that relies solely on the arm's movement.

The dynamics equations used to determine effective mass in combat sports [9,23,24] are based on simple models of the principle of conservation of momentum. Measurements of effective mass and estimates calculated from regression equations [25] confirm that the studied athletes presented higher effective masses than their estimated hand masses, confirming what has been suggested by other researchers [16]. Moreover, with such a measurement, effective mass can vary depending on the mass of the object being struck. Investigating momentum transfer in combat sports uncovers critical biomechanical dynamics crucial for athletes' performance and safety. Lenetsky et al. [26] tackled the less studied concept of effective mass in punch dynamics, showing that existing theoretical models do not fully account for the complexities of real-world impacts. This gap highlights the need for more nuanced research to improve training and reduce injuries. Therefore, we decided to determine the effective mass differently than before, relying on the classical relationship of Newton's second principle of dynamics:

$$\text{Effective mass} = \frac{\text{Force pressure}}{\text{Foot acceleration}}$$

The appropriately chosen effective mass in taekwon-do is an extremely important element of training, affecting the effectiveness of kicks. However, it requires an understanding of the biomechanics of movement and the recognition of the impact of various variables. Therefore, the aim of these studies was to gain knowledge about the influence of the obtained effective mass on the strength of the turning and side kick in the context of lateralization. In this regard, the following research questions were posed: What is the effective mass in the side and turning kicks, and which of these kicks achieve higher values of this variable? Can we observe the phenomenon of lateralization, and how does the correlation between effective mass, kick force, and foot acceleration shape up?

Answers to these questions can help coaches and competitors in optimizing training and their potential to increase the effectiveness of kicks in practice. This could contribute to the application of the unused technical potential of competitors.

2. Materials and Methods

2.1. Participants

Four male taekwon-do ITF (International Taekwon-do Federation) trainees (age: 28.5 $\pm$ 6.5 years; body mass: 77.5 $\pm$ 6.1 kg; height: 180.0 $\pm$1.4 cm) participated in this study. The conditions for inclusion in the study group were being male, 18 years old or older, holding a 1st Dan (black belt) or higher, and active participation in sports competition at the national level for at least 4 years.

2.2. Equipment

To assess the impact force, a force plate was used as the target. It was padded with a training shield to protect the participants from hitting the force plate directly and mounted onto a stable structure (AMTI, model MC12-2K, 2000 series, Watertown, MA, USA). The force plate dimensions were 305 mm $\times$ 406 mm $\times$ 79 mm. The force plate was synchronized in time and space to Noraxon (MR 3.18, Scotssdale, AZ, United States). Acceleration data were obtained by mounting a wireless IMU sensor, Ultium, manufactured by Noraxon, which was synchronized with the force plate. The sampling rate of the IMU sensors was 2000 Hz. The sensors were equipped with acceleration-only attachments, allowing for measurements up to 4000 g. The sensor was attached to a side of the foot, near the lateral malleolus.

2.3. Protocol

Data were collected at the Center for Human Movement Analysis, Jan Dlugosz University of Humanities and Sciences, Częstochowa [27]. Participants performed a self-selected

10 min warm-up. After the warm-up, participants performed side kicks (yop chagi) to the target five times with their right leg, starting in sport stance. In taekwon-do, the turning kick is described as focusing on the kinetic and kinematic aspects. Kinematically, it involves a rapid rotation of the body around the vertical axis, initiated by hip rotation and followed by a sequential movement of the body segments, leading to the extension of the leg towards the target. The kicking leg's motion includes flexion at the knee followed by a rapid extension. Kinetically, this kick generates significant angular momentum and force. The force is transferred from the ground through the supporting leg, while the hip, knee, and ankle joints of the kicking leg contribute to the speed and power of the kick [28].

After a one-minute rest, the participants performed a turning kick (dollyo chagi) five times from sport stance to the target with their right leg. In biomechanics, the "yop chagi" or side kick in taekwon-do is a complex movement involving several key biomechanical principles. It starts with the practitioner rotating their body and lifting the knee of the kicking leg towards the target, aligning the hip. The kick is executed by rapidly extending the leg, with the foot ideally making contact using the heel or the blade of the foot. This motion primarily involves the muscles of the hip, thigh, and lower leg. Kinematically, it is about the coordination and alignment of body segments to maximize force and reach. Kinetically, it involves generating force through the leg muscles, transferring it through the body to the target [29].

Then, the same procedure was repeated for the left leg for all participants. Participants were asked to kick with maximum effort to achieve the highest impact force they could, with no time constraints to execute the kicks (Figure 1).

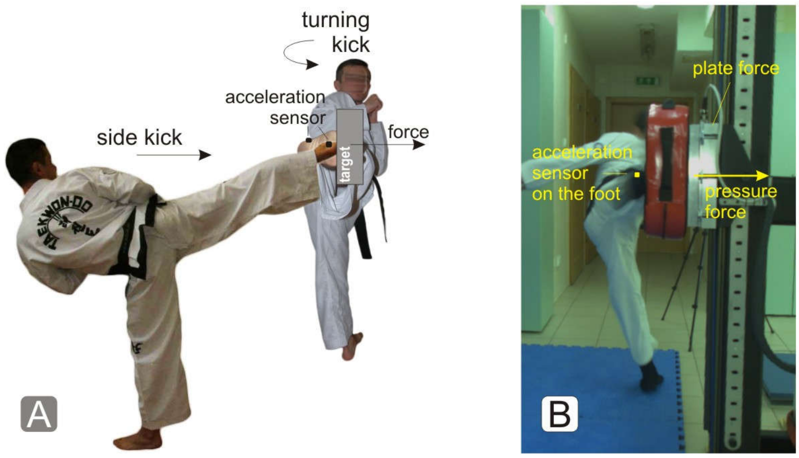

Figure 1. Visualization of kick and overall setup environment, including force plate covered with training shield and acceleration sensor attached to the foot: (**A**) positioning of the athlete according to the type of kick to the target of the strike; and (**B**) the setup of the force plate, padded with a training shield and mounted to a stable vertical structure, with the participant performing a turning kick.

Data acquisition entailed recording five strikes for each technique per participant. Initially, the data were exported from the measurement software (Noraxon MR 3.18 with Myomotion module) into the Excel (Microsoft 365 version, WA, United States) *.slk format and subsequently converted to the *.xlsx format for enhanced processing. The maximum force was ascertained using a Python (version 3.12) script, utilizing the scipy library and the findpeaks function to identify the peak force values. The script was launched through Jupyter Lab (version 4.0.11) and executed for each Excel file separately. After collecting the data, i.e., the values of maximum force pressure on the platform and changes in foot acceleration, they were exported to Excel (Microsoft Office Professional Plus 2010) for organization according to the type of kick and the left or right leg. In this way, data for 80 measurement positions (4 people × 5 trials × 2 types of kicks × 2 legs) were collected.

The code was composed of uploading data with pandas, converting raw data from milligs to m/s^2, and peak detection. As data were collected for five strikes per file, the code detected events (strikes) around the maximum value of force for a specific strike, then detected the values of acceleration of each marker at the time value of maximum force. Code is provided in the github repository (https://github.com/Dareczin/tkd_force_acceleration_detection).

2.4. Statistical Analysis

After analyzing the data, they were exported to Statistica 13 software (TIBCO software, Santa Clara, CA, United States). Due to the lack of normal distribution of the data, as verified by the Shapiro–Wilk test, further analyses of differences between groups were conducted using the Mann–Whitney U test. Descriptive statistics were based on the median and the upper and lower quartiles, and additionally, the mean and standard deviation were given. Statistical significance was set at a level of $p < 0.05$. The sample size, estimated using G*Power software (version 3.1.9.2; Kiel University, Kiel, Germany) [30], returned a minimum of 70 measurement positions for $\alpha = 0.05$, effect size f = 0.9, and $\beta = 0.95$.

3. Results

In Table 1, the registered force pressure and foot acceleration, as well as the calculated values of effective mass in kg and % of total mass, are compiled according to the type of kick and whether the right or left leg was used. The median force pressure values amounted to 2661.53 N for the turning kick and 4596.15 N for the side kick, with foot acceleration of 150.56 m/s^2 and 74.34 m/s^2, respectively. The calculated median effective mass for the turning kick was 20.12%, and for the side kick, it was 73.09% of the total body mass. The conducted analysis indicated a lack of statistically significant differences between the right and left leg in the obtained kinetic variable values ($p > 0.05$). Figure 2 presents the medians of force pressure (side kick: F = 4596.15 N and turning kick: F= 2661.53 N; $Z = -5.25$; $p < 0.001$) and the calculated values of the competitors' effective mass for the turning kick at 14.69 kg (20.12%) and for the side kick at 54.56 kg (73%) ($Z = -7.43$; $p < 0.001$). Table 2 includes a summary of the Spearman correlation coefficients of the analyzed variables. It shows that the side kick positively correlated with effective mass ($r = 0.84$; $p < 0.05$) and force pressure ($r = 0.59$; $p < 0.05$), while the turning kick negatively correlated with foot acceleration ($r = -0.84$; $p < 0.05$). Furthermore, the greater the effective mass, the greater the force pressure ($r = -0.74$; $p < 0.05$) and the smaller the foot acceleration ($r = -0.87$; $p < 0.05$).

Table 1. Average values of selected kinetic indicators during the execution of turning kicks and side kicks with the left and right leg.

Kick Type	Indicator	Leg	Mean	SD	Median	Lower Quartile	Upper Quartile	Z	*p*
Turning kick	Force pressure [N]	Right	2820.28	596.21	2793.905	2432.915	3078.750	1.296	0.194
		Left	2475.59	623.09	2602.770	2353.070	2733.020		
		Total	2636.93	628.54	2661.535	2413.320	2913.720	-	
	Foot acceleration [m/s^2]	Right	170.38	45.23	150.064	137.946	201.576	0.214	0.830
		Left	180.96	62.40	152.966	120.845	225.101		
		Total	176.01	54.72	150.566	127.860	217.252	-	
	Effective mass [kg]	Right	17.59	6.14	16.324	13.459	18.923	1.120	0.262
		Left	15.46	6.79	13.237	11.816	20.911		
		Total	16.46	6.51	14.696	12.404	19.054	-	
	Effective mass [%]	Right	22.80	8.76	20.832	16.560	25.390	0.843	0.398
		Left	20.17	10.01	16.518	14.020	29.044		
		Total	21.40	9.43	20.126	14.562	25.749	-	

Table 1. *Cont.*

Kick Type	Indicator	Leg	Mean	SD	Median	Lower Quartile	Upper Quartile	Z	*p*
Side kick	Force pressure [N]	Right	4551.55	1363.99	4321.310	3449.290	5820.810	0.131	0.895
		Left	4319.84	1390.00	4828.220	3213.875	5525.125		
		Total	4438.52	1364.45	4596.155	3449.290	5562.930	-	
	Foot acceleration [$m/s^{2.5}$]	Right	68.93	24.69	79.489	54.156	89.214	0.307	0.758
		Left	72.58	20.54	71.934	50.911	89.311		
		Total	70.71	22.55	74.337	53.163	89.214	-	
	Effective mass [kg]	Right	77.72	46.75	52.473	45.851	80.360	−0.014	0.988
		Left	60.66	18.43	54.561	45.762	75.318		
		Total	69.40	36.45	54.561	45.851	76.906	-	
	Effective mass [%]	Right	101.96	67.22	66.538	52.736	103.292	−0.540	0.588
		Left	78.89	22.52	74.752	61.841	93.164		
		Total	90.71	51.34	73.097	56.088	94.765	-	

Statistical significance: $p < 0.05$.

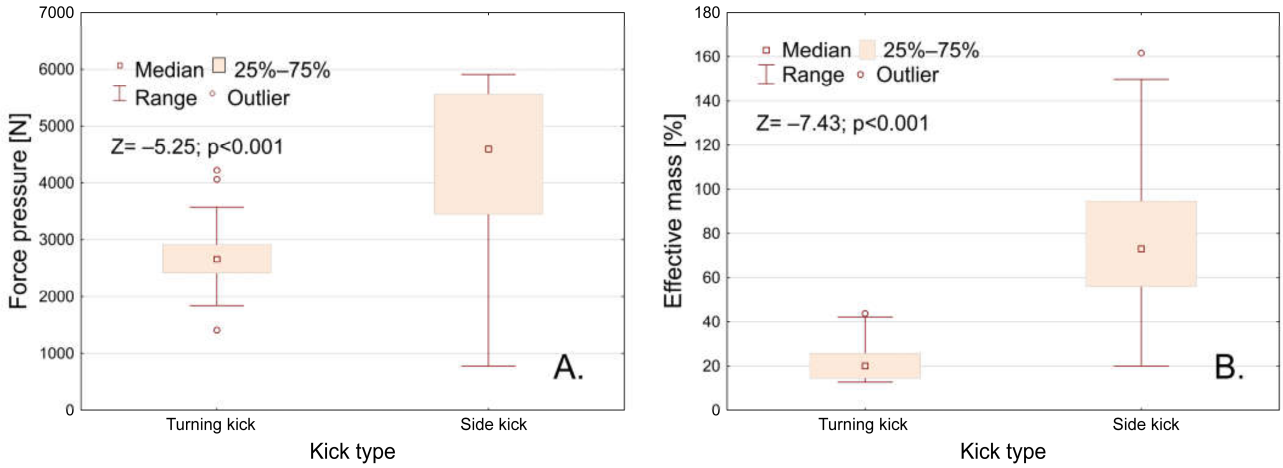

Figure 2. Force pressure (**A**) and effective mass (**B**) for turning kick and side kick.

Table 2. Spearman correlation matrix.

Indicator	Leg	Force Pressure	Foot Acceleration	Effective Mass	Body Mass
Kick type	0.00	0.59 *	−0.84 *	0.84 *	0.01
Leg		−0.11	−0.03	−0.04	−0.12
Force pressure			−0.37 *	0.74 *	0.15
Foot acceleration				−0.87 *	0.22 *
Effective mass					−0.13

* Statistical significance: $p < 0.05$.

4. Discussion

From the conducted analyses, it emerged that the average force of the side kick was 4596 N, significantly greater than the turning kick's force of 2661 N. Other studies have suggested that the turning kick achieves a force ranging from 1800 N [31] to 6400 N [32]. Unfortunately, there are not many studies recording the force of kicks in taekwon-do. In the review of Vagner et al. [33], the reported values of roundhouse kicks were much lower, ranging from 1200–1800 N. A study by Thibordeeand and Prasartwuth [34] had even lower values of up to 200 N. A study of side kicks by Lee et al. [35] also obtained lower values of around 1300 N. Differences in the study designs can be attributed to various factors, such as the chosen targets, their size, the distance of participants from these targets, and the height of the targets. These elements must be considered when comparing force values across different studies. The challenges in reproducing these studies arise from the variability in technique execution; the non-standardization of distances; and the heterogeneous nature of the equipment, like shields or dummies, in some of the mentioned studies. As the study of this subject is more or less 15 years old with the current setup capabilities, our study used a fixed column that did not move. This might be a reason why we obtained higher values of force compared to other studies, considering the lack of force loss upon impact.

These factors contribute to the difficulty of establishing a single, objective indicator of total force values as a reliable predictor of performance across different assessment facilities. However, these very settings, which complicate direct force measurement, might also be seen as variables influencing the acceleration and velocity of a kick, with the target acting as a dependent variable. In this context, the concept of "effective mass" could provide a viable approach to determining a benchmark for assessing the effectiveness of a kick. By focusing on the kinetic aspects of the movement, such as the speed and momentum of the kick in relation to the target, a more consistent and objective measure of performance could be established, potentially offering a more accurate representation of an athlete's skill and effectiveness.

The estimated effective mass of the competitors for the side kick was 73%, and for the turning kick, 20% of the total body mass of the competitors. However, this requires confirmation. Our measurements indicate that the analyzed kicks positively correlate with effective mass and force pressure. This is consistent with current knowledge and the available scientific literature on sports and taekwon-do, where a relationship has been found in the ability of athletes to increase striking force as a result of increasing body mass [36–38]. However, it has been noted that beginner competitors mainly use their body mass to generate large striking forces, overestimating its significance [15]. This suggests that the level of athlete advancement may influence the ability to balance the center of gravity and the specific movement technique to achieve greater striking force. Consequently, perhaps the technical skills of competitors could be recognized based on the relationship between kick force and effective mass. Additionally, it has been noted that the starting position and body alignment relative to the target also influence the force of the kick [39], which was not considered in our measurements. In considering the differences between linear and circular motion in martial arts, the distinction between the turning kick and the side kick is crucial. The turning kick involves a whip-like motion with body rotation around the supporting leg, generating force through the rotational action of the core muscles and the kicking leg. For effective force transfer in the sagittal plane of the opponent, a martial artist typically approaches at an angle ranging from 45 to 90 degrees, which affects the possibility of transferring body mass effectively. Conversely, the side kick is characterized by its linear motion and direct approach toward the target, allowing for a more straightforward transfer of body mass towards the opponent or target. However, the choice of technique is not solely determined by force. Technical and tactical considerations, such as the duration of the kick, its executability under specific combat conditions, and the duration of contact with the target, also play significant roles in deciding which technique to employ next. From a utilitarian perspective, this study suggests that the side kick tends to be stronger, utilizing a higher percentage of body mass, and thus requires a lower level of skill for effective execution. This makes it a recommended technique in emergency situations, like breaking through doors or barriers for escape, due to its straightforward application and potent force transfer.

Generally, our studies show a correlation between three variables, informing us that a greater effective mass results in greater force pressure and lower foot acceleration. No significant differences were noted between the right and left leg in the average values of force, acceleration, or effective mass while performing both turning kicks and side kicks. Perhaps the effect of lateralization will reveal itself with a larger research group. However, this is consistent with studies showing that, among ITF taekwon-do competitors, no significant differences can be observed between maximum speed and movement time during the execution of selected kicks with the right or left leg [40].

It was registered that the foot acceleration was greater for the turning kick. This correlation was also demonstrated by the calculated correlation coefficients. Therefore, it can be assumed that the studied kicks have different kinetic specifics. The side kick is slower to execute, but achieves greater striking force as opposed to the turning kick [41,42]. Studies show that in combat sports, competitors most often use the turning kick in fights [20,43]. This indicates that high striking force alone is not the only determinant of effectiveness in combat. However, in a situation where one does not need to worry about the opponent's reaction and the value of generated force is the main priority, utilizing the side kick may be a better solution.

Certainly, a limitation of the results is the small size of the study group. Despite these limitations, it is undeniable that this study expands the knowledge about the biomechanical dependencies of executing kicks in martial arts, and fills the gaps concerning research on effective mass in taekwon-do. Of course, in the pursuit of perfection, further research is necessary to determine the value of the effective mass of different strikes and, more precisely, its impact on taekwon-do competitors in real combat, which will help us to understand how variables influence moments of high performance. It represents a certain segment of the issue; the results and considerations presented here can serve as a reference point for other researchers and may pave the way for further exploration.

5. Conclusions

This study has uncovered significant insights into the biomechanics of taekwon-do kicks, particularly focusing on the side (dollyo chagi) and turning (yop chagi) kicks. Our key findings include that the median force pressure values for the turning kick and side kick are 2661.53 N and 4596.15 N, respectively, with foot acceleration at 150.56 m/s^2 for the turning kick and 74.34 m/s^2 for the side kick. The calculated median effective mass was 20.12% of the total body mass for the turning kick and 73.09% for the side kick. These results demonstrate a substantial difference in the force generated between the two kicks, highlighting the impact of effective mass and acceleration on kicking force.

The practical implications of these results for taekwon-do athletes and coaches are substantial. They suggest that training regimes could be optimized by focusing on techniques that enhance effective mass and acceleration to maximize the force of kicks. This could lead to more effective strategies in both training and competition.

In conclusion, this research significantly contributes to the understanding of physical dynamics in martial arts, offering valuable insights for both theoretical knowledge and practical application in sports science and martial arts training.

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Data Availability Statement: The data presented in this study are available upon request and after appropriate IRB approvals. The data are not publicly available due to privacy.

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Analysis of Combat in Sport JU-JITSU during the World Championships in Fighting Formula

Tadeusz Ambroży [1], Łukasz Rydzik [1,*], Wojciech Wąsacz [1], Zbigniew Małodobry [2], Wojciech J. Cynarski [3], Dorota Ambroży [1] and Andrzej Kędra [1,*]

1 Institute of Sports Sciences, University of Physical Education, 31-571 Kraków, Poland; tadek@ambrozy.pl (T.A.); dorota.ambrozy@awf.krakow.pl (D.A.)
2 Podhale State Vocational University in Nowy Targ, 34-400 Nowy Targ, Poland; maloz@vp.pl
3 Institute of Physical Culture Studies, College of Medical Sciences, University of Rzeszow, 35-959 Rzeszów, Poland; ela_cyn@wp.pl
* Correspondence: lukasz.rydzik@awf.krakow.pl (Ł.R.); aakedra@poczta.onet.pl (A.K.)

Abstract: Background: The observation and specialized analysis of confrontations in combat sports are fundamental for making corrections in training programs as well as for modifying individual technical–tactical profiles of athletes in such activities. These actions comprehensively assess the course of sports activities and ultimately inspire and guide the type of training in academies and sports clubs. The aim of the study was a general and detailed analysis of sport fighting in JU-JITSU during a top-tier tournament, in the fighting formula for the entire competition and for each weight category. Methods: The research material consisted of multimedia recordings of sports fights taken during the World JU-JITSU Championships in the fighting formula, Wroclaw 2016. A total of 229 tournament fights were analyzed in seven weight categories. For the purpose of evaluating the structure of the fight, a retrospective analysis of the recorded empirical material was conducted, and technical–tactical preparation (TTII) indicators were calculated, both in a global tournament context and for individual weight categories. Results: Of the 229 matches, more than half were decided by the advantage of technical points (58.52%) within the regulatory fight time, while in 74 clashes, victory was declared by Full Ippon (32.31%) before the designated fight time. Activity and attack effectiveness, as well as the number of technical points, were highest in the first part of the fight. Significant variations were observed in terms of activity, attack effectiveness, and point gains for all parts of the clash, and for effectiveness in the weight categories compared to the second part. The most frequently occurring penalty was the minor shido penalty, while the offense was the lack of fighting in the second part of the duel. The total fight time was 256 s, of which 144 s were effective fighting, and 112 s were breaks. Conclusions: The analysis of sports fight observations revealed that the majority of fights ended with a technical point advantage win (58.52%), with notable activity and attack effectiveness in part I. Middleweight fighters were most active early on, while heavyweight categories dominated later phases. Attack efficiency varied across weight categories. Penalties were predominantly minor (shido), and the total fight time included 144 s of effective fighting and 112 s of breaks.

Keywords: combat sports; fight analysis; technical–tactical indicators; sport Ju-Jitsu

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1. Introduction

Ju-Jitsu is an ancient Japanese martial art derived from brutal hand-to-hand combat [1]. Historically, it is the "ancestor" of many martial arts disciplines, and it was the basis for the development of Judo and Aikido, among others [2]. The philosophy of Ju-Jitsu is multidimensional and assumes the comprehensive development of a person's physical and psychological aspects, in areas such as motor skills, psychology, technical–tactical, and utility [3].

In the sporting dimension, Ju-Jitsu as direct combat in the fighting formula is a cross-sectional and complete martial arts discipline, showcasing a rich range of technical–tactical training [4]. Specialized combat techniques are used in the fight, including various strikes with the upper limbs, kicks with the lower limbs, throws, takedowns, limb locks, chokes, and restraining positions. The goal of the competition is to dominate the opponent by ending the match before time (Full Ippon) or by technical point advantage [5]. The competition takes place on three levels (3 parts of the match). The fight starts from a standing position where competitors exchange strikes and kicks (Part I). When it comes to grappling, they struggle to bring each other to the ground through throws and takedowns (Part II). Ground combat using holds, chokes, and joint locks is also allowed (Part III) [5]. Competitors compete in traditional attire (judogi) and protectors, divided into weight categories according to IJJF (International Ju-Jitsu Federation) regulations [5].

Thematic literature suggests that the largest share in the preparation profile of martial arts athletes is technical–tactical (31.3%) and physical (structural–functional 28.4%), with theoretical preparation (25.5%) and psychological (14.8%) taking a smaller share [2]. Scientific observation and subsequent retrospective, detailed analysis of confrontations in martial arts contain multi-dimensional stimuli. These measures enable a technical–tactical diagnosis of training trends of a given nation, as well as recognizing the individual or group characteristics of competitors' competitive activities (differentiation by weight category, level of sports achievements, or discipline formula) [6,7]. Such measures comprehensively assess the course of sporting activities and ultimately inspire and determine the type of training in sports clubs [8]. This type of scientific activity and its impact on the broad understanding of the optimization of the training process can be observed in many martial arts disciplines [9–11].

Therefore, the issue of technical–tactical preparation seems to be highly relevant in the case of Ju-Jitsu (fighting formula), with a cross-sectional profile of the combat plan. Previous scientific reports precisely analyzed the time and material structure of the conduct of the fight [12] and its significance for elite athletes and coaches [13,14]. The effectiveness of techniques that occur in the first part of the fight was also studied [15,16]. Analyzing the Ju-Jitsu fights at the Junior World Championships in Bucharest in 2013, the most frequently used techniques in the various parts of the fight were demonstrated [13–15]. In the research by Ambroży and co-authors in 2021, technical–tactical indicators were used to assess the entire clash without dividing it into individual parts of the fight. Moreover, based on empirical observation, it was noticed that, in the first part, the confrontation of fighters in the fighting formula resembles standing, striking, and kicking martial arts (Karate, Kickboxing), while in the second and third parts, the fight is similar to Judo [17]. Based on the mentioned literature and player–coach empiricism, in assessing sport Ju-Jitsu confrontations, it is necessary to analyze in detail such elements as the material and time structure of sports fighting. Due to the cross-sectional nature of the clash (standing, grappling, ground), success is determined by comprehensive technical–tactical preparation, the effectiveness of the performed techniques, and mistakes made by the opponent [11,18]. The condition for planning an effective training program aimed at achieving sports mastery is a precise analysis of the fight structure with the recognition of the requirements it imposes on athletes [19,20]. Moreover, according to Bocioaca, the factor that decides victory in an evenly matched duel between rivals with similar motor and technical profiles is the fight tactics [21]. Therefore, achieving sports mastery is possible thanks to proper technical–tactical preparation [22].

Hence, the question arises, what specific aspects of technique and tactics should be developed and improved in sport Ju-Jitsu to optimally support the realization of training and competition goals? The complexity of the training system for technical–tactical differentiation in the various parts of the fight poses a great challenge for coaches and athletes in this discipline. In available domestic and foreign literature, a deficit of scientific studies was identified, taking into account the comprehensive problems of the technical–tactical sphere for top-level competitions. The aim of this study was to provide a general and detailed analysis of Ju-Jitsu sports fighting during the World Championships, in the fighting formula for all competitions, with particular emphasis on technical–tactical efficiency, and taking into account individual weight categories. The results of this study should determine the desired direction of action for theorists and practitioners to improve the quality of coaching control and thus further development of this discipline. The novelty of this study is the use of PPT indicators with division into individual parts of the fight. This is important for the training process in Ju-Jitsu because the technical and motor structures of the individual parts differ.

2. Materials and Methods

2.1. Participants and Events

The research material consists of multimedia recordings of sports fights taken during the Ju-Jitsu Seniors World Championship (fighting formula), which took place in Wroclaw on 25 and 26 November 2016. A total of 132 athletes from 49 countries participated, representing the top of world Ju-Jitsu. The athletes fought 229 matches in different weight categories (Table 1). The competition was conducted according to IJJF (International Ju-Jitsu Federation) rules.

Table 1. Summary of weight categories, number of athletes, and matches.

Weight Category	Number of Athletes	Number of Fights
56 kg	10	15
62 kg	23	41
69 kg	24	43
77 kg	22	39
85 kg	29	53
94 kg	13	21
+94 kg	11	17
Total	132	229

2.2. Research Design

Details of the experimental program are presented in Figure 1.

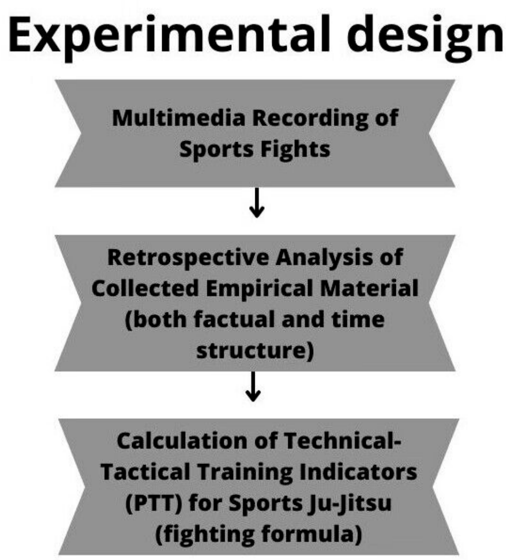

Figure 1. Experimental design.

2.3. Research Procedures

Four specialized Sony HDR-PJ6203 digital cameras (Sony, Tokyo, Japan) were used for video recording, covering the entire fighting area where the sports matches were held.

The camera setup allowed for continuous observation of the fighting athletes, referees, and the scoreboard. All matches from the elimination part to the medal rounds were recorded. Cameras were active from the start of the elimination matches to the end of the final matches. Full matches were recorded, including all breaks that occurred during their duration. Breaks in the competition due to the schedule were not recorded. Actions in the technical–tactical sphere were noted on a specialized observation sheet. A team of four Ju-Jitsu sports experts (three master class coaches and one internationally qualified referee) conducted a retrospective analysis of the recorded empirical material.

To profile the specific course of competition in Ju-Jitsu and its individual fighting parts and weight categories, both factual and time structures were analyzed.

In assessing the factual structure, offensive actions were analyzed both qualitatively and quantitatively. The type of match conclusion (before time vs. technical points advantage), type of attack (effective vs. ineffective), referee score (Wazaari—1 point; Ippon—2 or 3 points), and penalties (Shido, Chui, Hansoku-make) were noted at different parts of the fight (Part I: Atemi-waza—striking while standing, Keri-waza—kicks; Part II: Nage-waza—throws, takedowns, and groundwork; Part III: Ne-waza—groundwork involving holds, chokes, and joint locks). The percentage share and averages of selected parameters in the fight were then calculated.

For the time structure analysis, each match was divided into three active–passive segments. Using a stopwatch with an accuracy up to 1/100th of a second, the following times were measured:

1. Total Time (entire duration of the fight, including breaks)—measured from the referee's Hajime command (start of the fight) to the Matte command (signaling the end of the fight).
2. Break Time (breaks occurring between efforts in the fight)—measured from the Matte command (interrupting the competition) to Hajime (resumption of the match).
3. Effective Fight Time (difference between total time and breaks)—measured from the Hajime command (start or resumption of the match) to Matte (pause or end of the competition).

2.4. Analysis of the Fight: Technical–Tactical Training Indicators (TTITTI)

The motivation for determining the model technical–tactical profile in sports Ju-Jitsu, based on observed activity in fights and using the specialized formulas presented below, was to calculate indicators characterizing the level of technical–tactical training. In scientific research, this strategy is often used in combat sports to assist coaching control and optimize the broad understanding of the training process [23].

1. Attack Effectiveness in the First Part of the Fight
   SaF1= ((n1 × 1) + (n2 × 2))/N
   n1—number of attacks assessed as Waza-ari (1 point)
   n2—number of attacks assessed as Ippon (2 points)
   1, 2—point values for successful attacks
   N—total number of observed fights

2. Attack Effectiveness in the Second Part of the Fight
   SaF2 = ((n1 × 1) + (n2× 2))/N
   n1—number of attacks assessed as Waza-ari (1 point)
   n2—number of attacks assessed as Ippon (2 points)
   1, 2—point values for successful attacks
   N—total number of observed fights

3. Attack Effectiveness in the Third Part of the Fight
   SaF3 = ((n1 × 1) + (n2 × 2) + (n3 × 3))/N
   N1—number of attacks assessed as Waza-ari (1 point)
   n2—number of attacks assessed as Ippon (2 points)
   n3—number of attacks assessed as Ippon (3 points)

1, 2, 3—point values for successful attacks
N—total number of observed fights

4. Attack Efficiency in the First Part of the Fight
EaF1 = (number of successful attacks/total number of attacks) × 100

5. Attack Efficiency in the Second Part of the Fight
EaF2 = (number of successful attacks/total number of attacks) × 100

6. Attack Efficiency in the Third Part of the Fight
EaF3 = (number of successful attacks/total number of attacks) × 100

7. Attack Activity in the First Part of the Fight
AaF1 = (∑a)/n
∑a—sum of attacks
n—number of fought matches

8. Attack Activity in the Second Part of the Fight
AaF2 = (∑a)/n
∑a—sum of attacks
n—number of fought matches

9. Attack Activity in the Third Part of the Fight
AaF3 = (∑a)/n
∑a—sum of attacks
n—number of fought matches

10. Referee Penalty Effectiveness Indicator
Sk = ((k1 × 1) + (k2 × 2))/N
k1—minor penalty "shido" (1 point)
k2—moderate penalty "chui" (2 points)
1, 2—point values for penalties
N—total number of observed fights

2.5. Statistical Analysis

Statistical analysis of the collected data was conducted using Statistica software by StatSoft (version 13.1, StatSoft, Kraków, Poland). The following basic descriptive statistics were calculated: arithmetic mean, median, minimum and maximum values, the level of the first and third quartiles, standard deviation, and the coefficient of variation. To evaluate the significance of the differences between the variables, non-parametric Mann–Whitney U-Test and Kruskal–Wallis ANOVA were used, fulfilling the requirements of the nature of the variables being studied, which were verified using the Shapiro–Wilk test.

3. Results

The surveyed group of 132 competitors had a total of 229 sporting bouts. It was shown that in JU-JITSU, over half of the confrontations (58.52%) ended with a victory due to a technical points advantage within the full duration of the regulation bout time, i.e., 134 bouts. Of the observed fights, 95 (41.49%) ended before time, of which 74 (32.31%) were won by Full Ippon, while in 21 (9.17%), victory by one of the competitors was announced by the referees due to injury or refusal to continue the fight.

As can be seen in Table 2, the highest activity and effectiveness of attack were observed in Part I of the fight. Attack effectiveness took place in Part II of the fight and was associated with successfully transitioning the confrontation to the ground level. Detailed values of technical–tactical training indicators for all competitors participating in the World JU-JITSU Championships, Wrocław 2016, are presented in Table 2.

Table 2. Basic Descriptive Statistics of Activity, Effectiveness, and Efficiency of Attack in Different Parts of the Fight.

Indicator	N	$\bar{x}$	Me	Min	Max	Q_1	Q_3	SD	V
Activity Part I	132	9.80	9.71	1	20	7.67	11.71	3.30	33.71
Activity Part II	132	1.57	1.50	0	4	1.00	2.00	0.92	58.51
Activity Part III	132	0.59	0.50	0	2	0.00	1.00	0.53	89.15
Effectiveness Part I	132	6.17	6.13	0	13	4.13	7.88	2.91	47.19
Effectiveness Part II	132	1.04	1.00	0	4	0.33	1.60	0.83	79.98
Effectiveness Part III	132	0.33	0.00	0	2	0.00	0.67	0.45	138.75
Efficiency Part I	132	46.21	46.33	0	77.41	39.34	52.86	13.49	29.19
Efficiency Part II	121	48.43	50.00	0	100.00	28.57	72.73	29.55	61.01
Efficiency Part III	98	46.50	50.00	0	100.00	0.00	75.00	35.92	77.26

N, number of subjects; x, arithmetic mean; Me, median; Min, minimum value; Max, maximum value; Q_1, lower quartile; Q_3, upper quartile; SD, standard deviation; V, coefficient of variation.

From the conducted comparative analyses, it appears that the average values of activity and effectiveness of the attack show significant variations in different parts of the fight. This trend was not observed in the case of attack efficiency, where the averages of individual parts are similar (Tables 2 and 3).

Table 3. Comparative Summary of Technical–Tactical Indicators in Three Parts of the Fight (Mann–Whitney U Test).

Indicator	*p*
Activity Part I vs. Activity Part II	0.0000 *
Activity Part II vs. Activity Part III	0.0000 *
Activity Part I vs. Activity Part III	0.0000 *
Effectiveness Part I vs. Effectiveness Part II	0.0002 *
Effectiveness Part II vs. Effectiveness Part III	0.0000 *
Effectiveness Part I vs. Effectiveness Part III	0.0000 *
Efficiency Part I vs. Efficiency Part II	0.7411
Efficiency Part II vs. Efficiency Part III	0.6586
Efficiency Part I vs. Efficiency Part III	0.8806

* $p < 0.05$.

In the assessment of technical–tactical performance in individual weight categories, the highest average activity value for Part I was recorded in the up to 77 kg category, while for Parts II and III, it was recorded in the up to 85 kg category. The lowest values for Parts I and II were recorded in the heaviest weight category, above 94 kg, while for activity in Part III, it was recorded in the up to 62 kg category (Table 4).

Table 4. Basic Descriptive Statistics of Attack Activity in the Three Parts of the Fight, Divided by Weight Categories.

Indicator		56 kg	62 kg	69 kg	77 kg	85 kg	94 kg	+94 kg	Total
Activity Part I	$\bar{x}$	9.28	9.78	9.52	10.68	10.04	9.86	8.45	9.80
	N	10	24	24	22	29	12	11	132
	SD	2.92	3.70	3.21	3.26	3.00	3.91	3.40	3.30
	Min	3.50	2.50	6.00	5.50	5.00	4.00	1.00	1.00
	Max	14.00	15.00	18.67	20.00	16.14	16.50	13.33	20.00
	Q_1	8.00	7.00	7.58	9.00	8.25	7.00	7.00	7.67
	Me	9.75	10.25	8.71	10.90	10.00	9.60	8.00	9.71
	Q_3	10.67	12.70	10.83	11.67	11.25	11.75	11.25	11.71

Table 4. *Cont.*

Indicator		56 kg	62 kg	69 kg	77 kg	85 kg	94 kg	+94 kg	Total
Activity Part II	$\bar{x}$	1.42	1.27	1.49	1.81	1.87	1.69	1.16	1.57
	N	10	24	24	22	29	12	11	132
	SD	0.63	1.00	0.98	0.88	0.66	1.28	0.86	0.92
	Min	0.50	0.00	0.00	0.00	0.50	0.00	0.00	0.00
	Max	2.33	3.50	3.67	3.50	3.50	4.00	2.00	4.00
	Q_1	1.00	0.45	1.00	1.33	1.50	0.50	0.00	1.00
	Me	1.42	1.00	1.27	1.78	2.00	1.83	1.50	1.50
	Q_3	1.67	1.83	1.75	2.33	2.25	2.50	2.00	2.00
Activity Part III	$\bar{x}$	0.59	0.50	0.51	0.59	0.70	0.63	0.68	0.59
	N	10	24	24	22	29	12	11	132
	SD	0.58	0.49	0.48	0.62	0.44	0.46	0.78	0.53
	Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Max	1.67	1.80	1.50	2.00	1.60	1.60	2.00	2.00
	Q_1	0.00	0.00	0.00	0.00	0.33	0.34	0.00	0.00
	Me	0.50	0.50	0.37	0.33	0.67	0.58	0.50	0.50
	Q_3	1.00	0.71	0.71	1.00	1.00	1.00	1.67	1.00

Regarding the effectiveness of the attack in Part I, the highest indicators were observed in the lowest weight category, up to 56 kg. In contrast, higher effectiveness in the fight is characterized by heavier competitors, i.e., up to 85 kg in Part II and above 94 kg in Part III. The lowest effectiveness was recorded in the above 94 kg category for Part I, up to 69 kg for Part II, and 77 kg for Part III (Table 5).

Table 5. Basic Descriptive Statistics of Attack Effectiveness in the Three Parts of the Fight, Divided by Weight Categories.

Indicator		56 kg	62 kg	69 kg	77 kg	85 kg	94 kg	+94 kg	Total
Effectiveness Part I	$\bar{x}$	7.28	6.45	5.09	6.65	6.59	6.14	4.90	6.17
	N	10	24	24	22	29	12	11	132
	SD	3.03	3.13	2.37	3.16	2.68	3.17	2.86	2.91
	Min	2.00	1.00	1.00	2.00	2.00	0.00	0.00	0.00
	Max	12.00	13.00	12.00	13.00	13.00	11.25	8.00	13.00
	Q_1	5.00	4.75	3.83	4.33	5.00	3.86	3.50	4.13
	Me	7.50	6.00	4.42	6.58	7.00	6.67	5.33	6.13
	Q_3	8.00	8.63	6.58	8.20	8.50	8.04	7.50	7.88
Effectiveness Part II	$\bar{x}$	1.21	1.05	0.80	0.90	1.32	0.99	0.98	1.04
	N	10	24	24	22	29	12	11	132
	SD	0.98	0.80	0.68	0.77	0.92	0.99	0.72	0.83
	Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Max	3.33	2.67	2.00	2.80	4.00	3.25	2.00	4.00
	Q_1	0.50	0.33	0.00	0.20	0.67	0.17	0.00	0.33
	Me	1.00	1.23	0.88	0.88	1.00	0.75	1.00	1.00
	Q_3	1.50	1.71	1.27	1.50	2.00	1.55	1.67	1.60
Effectiveness Part III	$\bar{x}$	0.42	0.35	0.23	0.21	0.37	0.22	0.62	0.33
	N	10	24	24	22	29	12	11	132
	SD	0.49	0.55	0.33	0.39	0.43	0.25	0.66	0.45
	Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Max	1.33	2.00	1.00	1.40	1.50	0.67	1.67	2.00
	Q_1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Me	0.25	0.00	0.00	0.00	0.33	0.14	0.50	0.00
	Q_3	0.67	0.58	0.50	0.20	0.67	0.45	1.33	0.67

The highest values of attack efficiency in Parts II and III were shown by competitors in the above 94 kg category. The opposite trend was observed in Part I, where the highest indicators were recorded in the lowest weight category, up to 56 kg. The least efficiency characterized the up to 69 kg category (Part I) and the up to 77 kg category (Parts II and III) (Table 6).

Table 6. Basic Descriptive Statistics of Attack Efficiency in the Three Parts of the Fight, Divided by Weight Categories.

Indicator		56 kg	62 kg	69 kg	77 kg	85 kg	94 kg	+94 kg	Total
Efficiency Part I	$\bar{x}$	58.79	50.46	39.67	43.92	49.16	42.92	40.15	46.21
	N	10	24	24	22	29	12	11	132
	SD	11.68	10.06	10.93	11.08	9.78	14.97	24.23	13.49
	Min	39.29	33.33	13.33	21.43	30.77	0	0	0
	Max	77.42	71.43	65.00	71.11	71.15	58.00	76.19	77.42
	Q_1	53.85	40.83	33.10	40.00	42.11	40.53	30.00	39.34
	Me	57.52	50.00	40.28	44.09	48.48	47.81	43.59	50.00
	Q_3	68.33	58.46	46.62	51.22	54.84	50.00	48.89	52.86
Efficiency Part II	x	50.10	61.72	41.38	37.36	51.00	39.10	62.04	48.43
	N	10	21	23	21	29	9	8	121
	SD	27.26	30.34	33.19	28.29	28.43	19.11	21.07	29.55
	Min	0.00	0.00	0.00	0.00	0.00	20.00	33.33	0.00
	Max	85.7	100.0	100.0	100.0	100.0	72.7	100.0	100.0
	Q_1	33.33	40.00	0.00	20.00	28.57	25.00	47.32	28.57
	Me	50.00	62.5	42.86	33.33	50.00	33.33	63.33	50.00
	Q_3	80.00	83.33	75.00	50.00	75.00	44.44	70.83	72.73
Efficiency Part III	$\bar{x}$	55.71	44.17	48.01	26.81	49.78	52.92	65.28	46.50
	N	7	16	17	16	26	10	6	98
	SD	45.41	32.03	41.88	34.85	36.31	26.36	20.99	35.92
	Min	0.00	0.00	0.00	0.00	0.00	25.00	40.00	0.00
	Max	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Q_1	0.00	16.67	0.00	0.00	25.00	33.33	50.00	0.00
	Me	50.00	50.00	50.00	8.33	50.00	50.00	63.33	50.00
	Q_3	100.00	58.30	80.00	47.20	80.00	50.00	75.00	75.00

Comparative analyses found no significant differences in technical–tactical performance (TTP) in relation to the compared weight categories. The exception was the attack efficiency in Part I, where significant variation was noted (Table 7).

Table 7. Comparative Summary of Technical–Tactical Indicators for the Three Parts of the Fight with Weight Categories (ANOVA KW Test).

Indicator	*p*
Activity Part I	0.6860
Activity Part II	0.1260
Activity Part III	0.8350
Effectiveness Part I	0.2181
Effectiveness Part II	0.3901
Effectiveness Part III	0.1921
Efficiency Part I	0.0008 *
Efficiency Part II	0.0643
Efficiency Part III	0.2320
Effectiveness of Referee Penalties	0.8401

* $p < 0.05$.

It was observed that out of 229 matches, 132 competitors scored a total of 6747 technical points. Statistical analysis showed that competitors most frequently scored points in the first part of the fight, and least frequently in Part III (Table 8). Additionally, the number of points scored in each part differed significantly in statistical terms ($p = 0.0000$).

Table 8. Descriptive Statistics of the Total Points Scored in Parts I, II, and III, and the Total Points from All Three Parts.

Indicator	N	$\bar{x}$	Me	Min	Max	Q_1	Q_3	SD	V
Total Points Part I	132	23.2	20	0	91	10	32.5	16.7	71.8
Total Points Part II	132	5.3	4	0	27	2	8	5.0	94.1
Total Points Part III	132	2.3	2	0	20	0	3.5	3.2	135.7
Total Points from All Three Parts	132	30.8	26.5	0	107	13	42	21.3	69.0

In all weight categories, the most points were scored in Part I of the fight (56 kg = 85%, 62 kg = 80%, 69 kg = 77%, 77 kg = 84%, 85 kg = 77%, 94 kg = 78%, +94 kg = 72%). The fewest points were scored in Part III (56 kg = 5%, 62 kg = 7%, 69 kg = 10%, 77 kg = 4%, 85 kg = 9%, 94 kg = 8%, +94 kg = 14%). In all weight categories, the total points scored in the fight ranged from 80% to 51%. The effectiveness of referee penalties for the entire competition was an average level of 1.16 ± 0.84 points. The highest values for the effectiveness of referee penalties were noted in the 62 kg category, while the lowest values were recorded in the above 94 kg category (Table 9).

Table 9. Effectiveness of Referee Penalties Divided by Weight Categories.

		56 kg	62 kg	69 kg	77 kg	85 kg	94 kg	+94 kg	Total
Effectiveness of Referee Penalties	$\bar{x}$	1.19	1.36	1.09	1.05	1.11	1.32	1.00	1.16
	N	10	24	24	22	29	12	11	132
	SD	1.00	1.12	0.75	0.62	0.86	0.77	0.61	0.84
	Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Max	3.50	4.00	3.33	2.00	3.00	3.00	2.00	4.00
	Q_1	0.33	0.50	0.50	0.60	0.50	0.88	0.50	0.50
	Me	1.00	1.17	1.00	1.00	1.00	1.33	1.00	1.00
	Q_3	1.60	2.00	1.42	1.50	1.50	1.73	1.50	1.55

The total average match time was 256 s and ranged between 55 and 432.5 s. Of this, the effective fight time was 144 s, while the break time amounted to 112 s (Table 10).

Table 10. Descriptive Statistics of the Total, Effective, and Break Times for the Entire Group of Competitors.

Fight Time	N	$\bar{x}$	Me	Min	Max	Q_1	Q_3	SD	V
Total Time	132	256	256	55	432.5	225	296	61	24
Break Time	132	112	111	5	263.5	83	138	43	38
Effective Time	132	144	146	50	216	129	165	28	19

4. Discussion

The aim of our study was to characterize Ju-Jitsu sports fighting in the "fighting" formula for all participants in the championship tournament, both globally for the entire competition as well as by individual weight category. In our research, a significant number of Ju-Jitsu bouts ended early due to a Full Ippon (32.31%), although more than half of the tournament confrontations were decided by a technical point advantage (58.52%). Winning before time is the highest form of advantage over an opponent and provides the most satisfaction and glory to the winner. However, when two similarly trained opponents face off and the fight is closely contested, the outcome is often decided by technical points. Based on empirical observation and competitive-coaching experience, one can distinguish fighters who try to impose their style from the first second of the fight, aiming for a quick end, and those who control their opponent for the prescribed duration of the fight, aiming for a points advantage. This is dictated by the individual fighting model and the structural–functional profile of the competitor [24]. This may suggest to coaches a profile for specialized combat preparation of athletes for subsequent championship-level competitions. In qualitative terms, a warrior should strive to resolve the confrontation early but should also be mentally, volitionally, and endurance-ready to fight the full distance.

Attack activity, according to the original assumptions of combat sports theory, is the sum of executed technical–tactical actions [25]. An example of high activity among fighting competitors is the analysis of kickboxing bouts, which reaches the highest values compared with other indicators [26]. We observed a similar trend in our research, where the attack activity index was highest in the first part of the fight but significantly decreased in the second and third parts. This is a consequence of fighting tactics and the structure of the bout, in which competitors aim to achieve the largest point advantage by dominating the first part of the fight. Striking combat in a standing position is characterized by a high frequency of blows, which is confirmed by numerous analyses of boxing and kickboxing bouts [18,27], the specifics of which correspond to the first part of a Ju-Jitsu bout. A similar trend was observed in terms of attack effectiveness (the ratio of effective techniques to the total number of observed bouts), which was highest in Part I of the duel. This proves that as the activity index for attacks increases, its effectiveness proportionally rises in Part I of the fight. Significant variations in the level of activity and effectiveness in different parts of the fight were shown, further emphasizing the importance of the striking–standing aspect of Ju-Jitsu. The fight begins in this plane and mastering its intricacies is essential for practitioners of this sport to achieve success. In our championship tournament research, the level of fighting in Parts II and III showed significantly lower indicator values compared to strikes. There is a suggestion to enrich training programs focused on increased activity and effectiveness in these parts of the fight. Effective takedowns provide technical points and enable ground fighting, thereby exploiting the possibilities offered by this aspect of combat. Effective Part III techniques have high point values, which may decide the final result [11]. Analysis of weight categories showed that the highest activity in the first part of the fight was in the athletes weighing up to 77 kg, while in the second and third parts of the fight, the highest activity was in the category of athletes weighing up to 85 kg. On the other hand, the lowest activity in the first and second parts was recorded in the heaviest weight category—+94 kg—while in the third part, the lowest activity was recorded in the category of athletes weighing up to 62 kg. Attack effectiveness was highest in the category up to 56 kg in the first part, in the category up to 85 kg in the second part, and in the +94 kg category in the third part. The lowest performance was observed in the +94 kg category in the first part, in the up to 69 kg category in the second part, and in the up to 77 kg category in the third part. Reports from the combat sports community indicate that athletes in heavier-weight divisions throw fewer strikes compared with those in lighter-weight categories; this is associated with structural and functional potential [28]. Our research results partially confirm this, particularly in terms of activity in the first and second parts of the fight and the effectiveness of the first part in the heaviest athletes. Generally, the observed trend of variations in indicators for a given category was not straightforward, meaning it was not directly proportional (higher indicator values vs. higher body mass) or inversely proportional (higher indicator values vs. lower body mass). Qualitatively, the nature of the three-dimensional combat in JU-JITSU (stand-up striking and grappling, as well as ground fighting) and the associated broad concept of specialization in fighting style with the individual preferences of the studied athletes in the sports competition could explain this phenomenon.

The effectiveness index characterizes the quantitative ratio of effective attacks to all executed attacks. Therefore, its high values may coexist with low fighter activity [25]. The average value of attack effectiveness in our study was 47.05% across all parts during the entire championship. Similar trends were observed in each part of the fight. However, when weight categories were considered, the heaviest division, i.e., +94 kg, led globally. In contrast, for Part I, lighter weight classes up to 56 kg and 62 kg showed effectiveness advantages. Lighter fighters are characterized by higher speed, agility, and stamina [29], which may have translated into higher effectiveness in these weight categories. Interestingly, this index is dominated by the heaviest category, +94 kg, in Parts II and III. Heavier weight classes are characterized by a higher level of muscular strength, which may favor takedowns and ground fighting, thus affecting the effectiveness index [30]. In summary, the comparative analysis of our research revealed no significant differences in technical–tactical performance across the compared weight categories. An exception was found in the effectiveness of the attack in the first part of the fight, where significant variations were observed with respect to weight categories. Our research analysis showed that fighters score the most technical points during the first part of the fight. This is a consequence of the high activity and effectiveness indices observed in this plane of combat. High striking–standing activity in our studies led to higher strike effectiveness and a greater number of technical points. This is associated with the dynamics of the competition, which takes place in a standing position and structurally resembles kickboxing [18]. Individual technical actions or their combinations are characterized by high execution speed, less complex movement structure, and simpler starting positions compared with techniques in Parts II and III of the fight.

An important tactical aspect of the fight is the referee's penalties, given for exceeding the rules, as they provide points to the opponent [5]. Rydzik et al., in their observational studies, identified violations during kickboxing fights, showing that athletes most commonly commit two illegal actions during a match [31]. The effectiveness of referee penalties for the entire competition, based on their research, was at a moderate level of 1.16 points; this varied by weight category. The observed discrepancy may arise from differing knowledge of the rules and the ability to practically apply them under pressure during tournament fights. It could also be due to chance, as Ju-Jitsu fights are characterized by high dynamics.

In their research, the most common penalty was the minor penalty "shido," which affected 89% of athletes, followed by a medium penalty "chui" (39%). Balci and Ceylan proved that the penalty "shido" significantly affects the technique and tactics of athletes, and indirectly affects the outcomes of JUDO competitions [32]. Molina et al. demonstrated that receiving a "shido" is directly associated with the outcome of the JUDO competition, increasing the likelihood of loss [33].

In top-level competitions, only 2% of athletes were disqualified (Hansoku-Make), indicating a good understanding of the regulations and the ability to adhere to them in order to avoid the harshest penalty, which results in immediate defeat [5].

Regarding violations, the majority of athletes (83%) were found to be lacking in Part II of the fight. This could be justified by the structure of the match and the tactical actions of the athletes, who avoid fighting in Part II due to its effectiveness in terms of point scoring or a lack of competence in this area [34]. Sequentially, based on the level of participation, athletes committed violations such as uncontrolled strikes, lack of fighting in Part I, strikes after a clinch, lack of fighting in Part III, and holding the head. It is recommended that comprehensive training practice content that shapes and improves knowledge, views, and practical functioning be introduced into the sphere of regulation compliance and tournament atmosphere. This type of action requires the organization of refereed, simulated sparring during training sessions. During the referee's ruling on effective techniques (scored) and regulatory violations, it is recommended that the sparring be paused for a detailed analysis and assessment of the executed action by all trainees.

To become accustomed to the tournament atmosphere, which is different from the training environment, it is recommended that a designated fighting area, a referee, and an audience made up of all trainees and possibly visiting guests be organized during training.

Previous studies showed that periods of intense effort and breaks were observed in Ju-Jitsu sports fights. The total fight time ranged from 55 to 432.5 s, with an average time of 256 s. This result indicates a large discrepancy in the total fight time. Various factors influenced this observation. The shortening of the struggle time was due to fights ending before time due to achieving three Ippons in different parts of the bout, or due to injury or disqualification. The extended time was due to breaks caused by bodily injuries, regulatory requirements, or tactical procedures (e.g., adjusting the athlete's attire). On the other hand, the effective fighting time was much shorter, averaging 144 s. Effective fighting is a reflection of the athlete's offensive capability, which may influence the outcome of the bout [35].

An innovative value of the conducted analysis is the introduction of an assessment based on technical–tactical indicators, in individual parts of the fight, which provides the possibility of a comprehensive and precise evaluation of the athletes' actions in hand-to-hand combat during sports competitions. This type of action constitutes a credible identification of the baseline situation and provides a foundation for potential targeted training intervention.

Limitations of the Study

Our research had certain limitations. Specifically, we only examined elite-level tournament athletes. In future comparative studies, it is recommended that the sample be expanded to include athletes of national championship or local tournament status for more comprehensive comparisons. Another limitation was the lack of consent to expand the scope of research during the competitions, which precluded the assessment of adaptive effort parameters and the psychological potential of the athletes. To capture a multi-dimensional clinical context, it is advisable to broaden the diagnostic approach to include measurements such as blood lactate concentration, stress levels, motivation, aggression, and mental attitude, and to explore their associations with technical–tactical preparation.

Furthermore, for a thorough understanding of the multi-dimensional clinical context, future research should aim to identify model characteristics of medalists at this level of competition. Additionally, it should be possible to differentiate and analyze, in detail, the sub-skills of technical abilities in different parts of the fight in future studies.

5. Conclusions

Analysis and evaluation of results from the conducted observations allowed for the following conclusions:

1. It was shown that over half of the sports fights (58.52%) ended in a win through technical point advantage within the full timeframe of the bout, whereas 32.31% of fights ended with a Full Ippon victory.
2. The highest level of activity and attack effectiveness was observed in Part I of the fight, whereas the lowest was observed in Part III; furthermore, significant variations were shown across different parts of the fight. Middleweight fighters displayed the highest activity in the first part of the fight, while heavyweight categories dominated in the remaining parts of the bout.
3. The level of attack effectiveness throughout the competition showed similar values in each part of the fight, except for weight categories in Part I, where the highest values were recorded in the light categories. The values for the medium and heavy categories were similar.
4. Athletes in the heavier weight category displayed higher levels of effectiveness and attack efficiency in Parts II and III, whereas the opposite trend was observed for the lightest weight categories in Part I.
5. The highest level of technical points scored was recorded in Part I of the fight, and significant variations were again noted across the parts.
6. Athletes were most frequently penalized with a minor penalty called shido; only 2% received a disqualification (hansoku make), with the most frequent violation being a lack of fighting in Part II.
7. The total fight time was 256 s, of which 144 s were effective fighting and 112 s were breaks.

Practical Application

The study shows that effective JU-JITSU competition requires comprehensive motor, technical–tactical, and mental preparation. Athletes should focus on striking skills to gain technical points and on mastering throws and takedowns for potential high-point gains in later parts of the fights. Simulated sparring is advised to get accustomed to tournament conditions. Strength-speed and endurance-strength exercises, such as interval and circuit training, are recommended for conditioning. The use of Technical–Tactical Indicators (TTI) can optimize training by allowing diagnosis and intervention in various aspects of fighting, benefiting not just JU-JITSU but also other combat sports.

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Article

Physical and Morphological Differences between Young Elite Taekwondo and Karate Players

Alejandro Martínez-Rodríguez [1,2], Fernando Alacid [3,*], Bernardo J. Cuestas-Calero [2], Piotr Matłosz [4] and Daniel López-Plaza [5]

1 Department of Analytical Chemistry, Nutrition and Food Science, University of Alicante, Alicante Institute for Health and Biomedical Research (ISABIAL), 03690 Alicante, Spain; amartinezrodriguez@ua.es
2 European Institute of Exercise and Health, 03204 Alicante, Spain
3 Department of Education, Health Research Center, University of Almeria, 04120 Almeria, Spain
4 Institute of Physical Culture Sciences, Medical College of Rzeszow University, University of Rzeszow, 35-310 Rzeszow, Poland; pmatlosz@ur.edu.pl
5 International Chair of Sport Medicine, UCAM Catholic University of Murcia, 30107 Murcia, Spain; dlplaza@ucam.edu
* Correspondence: falacid@ual.es; Tel.: +34-950-21-40-00

Abstract: The different nature of taekwondo and karate actions involves sport-specific actions with different physical demands and a typical morphological profile. The aims of the current investigation were to compare body composition and strength factors between young karate and taekwondo players and to investigate the body proportionality of each discipline. Twenty-five young taekwondo fighters (18 boys and 7 girls) and twenty-eight karate athletes (19 boys and 9 girls) volunteered for the study. A battery of anthropometric measurements were obtained for each individual (heights, weight, girths, lengths, and sum of skinfolds). Upper-body and lower-body strength were determined using the handgrip test and counter-movement jump test, respectively. In boys, significantly greater Σ 6 skinfold, wrist, and maximum thigh girth measurements were observed in taekwondo athletes ($p < 0.05$; $d > 0.59$), while karate competitors revealed larger muscle mass values ($p < 0.05$). Nevertheless, girls only showed significant differences with respect to anterior-posterior chest breadth, age at peak height velocity (APHV), and head girth ($p < 0.05$). Proportionality analysis revealed that both sexes presented lower skinfold thicknesses and breadths than the normal population. Therefore, in both disciplines, similar profiles were determined, but young karate athletes seemed to exhibit a tendency towards a more robust and compact profile with greater body strength.

Keywords: martial arts; body composition; strength; proportionality

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1. Introduction

Body composition is an important determinant of athletes' performance, especially in individual sports such as taekwondo and karate [1–3]. Over the last decades, investigations regarding the relationship between certain anthropometry attributes and performance have increased [4–6]. In martial arts, individual anthropometric parameters and somatotype components can not only be used to identify the representative morphological profile of an athlete but also for talent identification purposes or the assessment of training programs' efficacy [7,8]. Taekwondo emphasizes lower body actions using kicks and dynamic footwork [1], while karate focuses on powerful strikes and upper body techniques [3,9]. Despite technical differences, common anthropometric attributes might be observed in athletes of both disciplines.

Typically, martial arts competitors exhibit higher values of body fat percentage, triceps, biceps, and abdominal skinfolds compared to individual sports athletes [7]. However, da Silva et al. [10] determined a negative association between total fat mass, body fat percentage, and karate-specific aerobic tests. Since martial arts players are often classified according to their body mass to minimize differences between competitors, maintaining a body weight relatively close to their fighting class via the control of body fat is paramount [8,11,12]. Furthermore, high lean body mass and arm circumference values have been identified as other determinants of optimal performance in mixed martial arts [8].

Previous studies have reported strong associations between fitness attributes and individual performance [13,14]. Although the level of overall physical fitness may be determined using field tests, specific assessments, especially with respect to power and strength, have allowed the identification of more accurate determinants for performance in martial arts [1,15]. The quick and powerful actions executed in taekwondo and karate require high muscular strength demands. Most successful martial arts players have typically exhibited greater force production in the upper and lower body and also greater anaerobic tolerance [9,12,16,17].

During puberty, the maximum development of physical attributes such as strength or aerobic power occurs around the age at peak height velocity (APHV). Furthermore, at this stage, physical fitness and morphological changes are highly dependent on biological maturity [18]. This process is usually very different from one individual to another in terms of tempo and timing, resulting in opponents of the same chronological age but uneven biological age. In recent years, the influence of age and developmental periods on performance has become a central topic in sports research [14,18]. Particularly in martial arts, where young athletes undergo rapid physiological and morphological changes, understanding these changes is pivotal [1–3].

Only a few studies have investigated the differences in morphology, strength, and power between taekwondo and karate players [9]. In addition, the influence of biological maturation on performance determinants in young martial arts competitors has never been taken into consideration. All these determinants might provide a more complete athlete profile for talent identification purposes from young ages in both disciplines. The current investigation might help bridge the literature's gap by investigating the differences in body composition and upper and lower body strength between young elite karate and taekwondo competitors. By focusing on this age group, the findings of the present research study might contribute valuable insights into their specific training needs and developmental trajectories. It is hypothesized that karate athletes could reveal greater upper body strength, dimensions, and muscle mass compared to taekwondo competitors. Therefore, the aims of the current investigation were to analyze the morphological and strength differences between young karate and taekwondo players and to compare their body proportionality to the normal population.

2. Materials and Methods

2.1. Participants

A total of 53 participants volunteered for the present investigation: 37 boys (18 taekwondo and 19 karate competitors) and 16 girls (7 taekwondo players and 9 karate players). The participant inclusion criteria for this study required the following: (a) training on a regular basis between 3 and 5 days per week; (b) training at least 1.5 h per day; (c) having training experience of more than 2 years; and (d) competing at the national level in the last year. Before the beginning of the investigation, a signed written informed consent form was required from the participants and their parents or legal guardians. In addition, any participant under pharmacological treatment or injury recovery was excluded from any assessment. Written informed consent was obtained from parents/guardians and participants according to the Helsinki Declaration, and the study's procedures were approved by the University Ethical Committee before the beginning of the test (No. UA-2019-04-09).

2.2. Procedures

A battery of anthropometric and physical fitness tests were performed on two separate days. Participants were required to maintain their normal pre-training diet and avoid caffeine ingestion and intense training sessions 24 h before testing. Anthropometric assessments were completed early in the morning to avoid any potential changes in body composition. Before the beginning of the physical fitness test, clear instructions with respect to proper tests procedures and a supervised warm-up were provided for all participants. Warm-up comprised 5 min of multidirectional running and joint mobility activities followed by 5 min familiarization with the materials and procedures of each test.

2.3. Anthropometric Measurement

All measurements were performed by a certified level 2 anthropometrist following the procedures and methods described by the International Society for the Advancement of Kinanthropometry (ISAK). Before the beginning of each testing session, all instruments were calibrated to prevent any potential measurement error. For the determination of heights (cm) and direct lengths (cm), a GPM anthropometer (Siber-Hegner, Zürich, Switzerland) was used, girths (cm) were measured using Lufkin W606PM (Lufkin, TX, USA), a metallic non-extensible tape, and the sum of 6 and 8 skinfolds (mm) was obtained using a Harpenden calliper (British Indicators, Surrey, UK). Each parameter was measured two or three times depending on whether the difference between the first two measurements was larger than 5% for the skinfolds and 1% for the other parameters. Fat mass percentages were estimated following the procedures defined by Slaughter et al. [19], whereas muscle mass percentages were determined using the equation of Poortmans et al. [20] for adolescents. To obtain the Z-scores of each parameter, the equation of the Phantom Stratagem defined by Ross and Marfell-Jones [21] was used. Test–retest reliability was examined using the intra-class correlation coefficient (ICC) and the coefficient of variation (CV), with values of 0.88 and 3.8%, respectively.

2.4. Maturity

Biological maturity was obtained using the procedures described by Mirwald et al. [18] and the age at peak height velocity (APHV) of the athletes relative to their current chronological age. Since APHV was considered a maturational benchmark reference (0 value) that is representative of the maximum stature development, the difference between APHV and chronological age was considered the maturity offset value. Thus, negative values indicated the years remaining until APHV, whereas positive values denoted the years past after APHV.

2.5. Physical Fitness Tests

For the determination of hand grip strength, a dynamometer, TKK 5105 (Takei Scientific Instruments Co., Ltd., Tokyo, Japan), was used. At maximum effort, participants performed a hand grip for at least 3 s while sitting in a chair with the elbow angled at 90° [22] under the supervision and encouragement of an instructor. The best of three attempts with each hand was considered for subsequent analysis. Three minutes of rest was provided to all competitors between efforts.

The countermovement jump test (CMJ) was used to examine lower body power according to the recommendations described by Temfemo et al. [23]. Before the jump, a countermovement until approximately 90° of knee flexion was permitted for participants. The athlete's contact time (s) and jump height (m) were registered using a Bosco platform (Bosco System, Barcelona, Spain). Only the best of three attempts with 3 min rest in between was taken into consideration for posterior analysis.

2.6. Statistical Analysis

All statistical analyses were performed using the Statistical Package for the Social Sciences v24.0 (SPSS Inc., Chicago, IL, USA). Measures of homogeneity and spread were described as mean ± SD. The Kolmogorov–Smirnov test and the Levene's test were used to investigate the hypotheses of normality and the homogeneity of variance, respectively. The difference between the mean values of different groups was examined using a *t*-test for independent samples, or the Mann–Whitney nonparametric test was used when the normality assumption of the data was rejected. The level of statistical significance was set up at $p < 0.05$. The effect size of the observed differences was analyzed using Cohen's d, and it was considered small when values ranged between 0.2 and 0.5, moderate when values ranged between 0.5 and 0.8, and large when the effect was >0.8 [24]. The calculation of statistical power ranged from 0.03 to 0.81 and from 0.04 to 0.94 for boys and girls, respectively.

3. Results

Table 1 summarizes the differences in anthropometric parameters, maturity status, and upper and lower body strength between male taekwondo and karate players. Significantly higher morphological values were identified in taekwondo players in terms of Σ 6 skinfold, wrist and maximum thigh girth measurements and also with respect to femur breadth and leg length ($p < 0.05$; $d > 0.59$). Conversely, the karatekas revealed superior MM% and anterior-posterior chest breadth than taekwondo players, with moderate effect sizes ($d > 0.7$).

Table 1. Differences in anthropometric parameters, maturity status, and upper and lower body strength between male taekwondo and karate players.

	Taekwondo		Karate			
	Mean ± SD	**95% CI**	**Mean ± SD**	**95% CI**	***p* Value**	**Cohen's *d***
Age (years)	14.02 ± 1.58	13.23–14.80	13.62 ± 1.86	12.72–14.51	0.48	0.23
APHV (years)	13.85 ± 0.56	13.57–14.13	13.77 ± 0.81	13.38–14.16	0.74	0.11
Maturity	0.14 ± 1.47	−0.59–0.87	−0.17 ± 1.67	−0.98–0.63	0.55	0.2
Weight (Kg)	57.52 ± 13.70	50.70–64.33	50.41 ± 9.25	45.95–54.87	0.07	0.61
Height cm)	164.77 ± 10.85	159.38–170.17	159.94 ± 9.90	155.17–164.71	0.17	0.47
Sitting height (cm)	84.81 ± 5.80	81.93–87.70	84.33 ± 7.44	80.75–87.92	0.83	0.07
Arm span (cm)	162.31 ± 21.46	151.64–172.98	162.24 ± 11.07	156.90–167.57	0.99	0
Σ 6 skinfolds (mm)	80.00 ± 36.02	62.09–97.91	61.08 ± 27.58	47.79–74.37	**0.04**	0.59
Σ 8 skinfolds (mm)	101.44 ± 48.94	77.10–125.78	77.33 ± 35.51	60.22–94.45	0.09	0.56
FM percentage (%)	19.87 ± 8.74	15.52–24.21	15.95 ± 6.98	12.59–19.32	0.14	0.49
MM percentage (%)	46.34 ± 2.33	45.18–47.50	47.74 ± 1.51	47.01–48.47	**0.04**	0.71
Right hand grip (kg)	21.74 ± 10.94	16.30–27.18	26.22 ± 10.89	20.80–31.63	0.23	0.41
Left hand grip (kg)	19.62 ± 10.84	14.23–25.01	23.03 ± 9.58	18.27–27.80	0.32	0.33
CMJ (cm)	28.80 ± 7.28	24.60–33.00	31.55 ± 7.04	28.16–34.94	0.28	0.38
Medial calf skinfold (mm)	14.15 ± 6.53	10.91–17.40	10.61 ± 5.13	8.13–13.08	0.07	0.6
Head girth (cm)	55.27 ± 1.43	54.56–55.98	54.56 ± 1.25	53.96–55.16	0.12	0.53
Relaxed arm girth (cm)	26.02 ± 4.23	23.92–28.13	24.58 ± 2.44	23.41–25.76	0.21	0.42
Flexed and tensed arm girth (cm)	28.59 ± 4.41	26.40–30.79	26.47 ± 2.58	25.23–27.71	0.08	0.59
Corrected arm girth (cm)	24.98 ± 4.28	22.85–27.11	23.41 ± 3.06	21.93–24.89	0.21	0.42
Forearm girth (cm)	24.02 ± 2.48	22.79–25.26	23.43 ± 1.93	22.50–24.35	0.42	0.27
Wrist girth (cm)	16.18 ± 1.48	15.44–16.92	15.19 ± 1.13	14.64–15.73	**0.03**	0.75
Chest girth (cm)	81.40 ± 9.21	76.82–85.98	79.99 ± 7.45	76.40–83.58	0.61	0.17
Waist girth (cm)	71.17 ± 7.77	67.31–75.03	67.95 ± 5.26	65.42–70.49	0.15	0.48
Hip girth (cm)	87.02 ± 9.84	82.12–91.91	83.46 ± 5.68	80.73–86.20	0.18	0.44
Max thigh girth (cm)	55.05 ± 7.26	51.44–58.66	49.52 ± 4.23	47.48–51.55	**0.01**	0.93
Thigh girth (cm)	47.56 ± 6.87	44.15–50.98	45.82 ± 3.38	44.19–47.44	0.33	0.32
Medial calf girth (cm)	34.02 ± 3.37	32.35–35.70	33.83 ± 6.19	30.85–36.82	0.91	0.04
Corrected thigh girth (cm)	29.58 ± 2.99	28.09–31.06	30.50 ± 5.69	27.76–33.25	0.54	0.2
Ankle girth (cm)	22.76 ± 2.18	21.67–23.84	21.73 ± 1.38	21.07–22.40	0.1	0.56
Leg length (cm)	79.96 ± 6.35	76.80–83.11	75.61 ± 5.99	72.72–78.49	**0.04**	0.71
Anterior-posterior chest breadth (cm)	14.52 ± 1.59	13.73–15.31	16.32 ± 3.11	14.82–17.82	**0.03**	0.73
Humerus breadth (cm)	6.69 ± 0.55	6.42–6.96	6.47 ± 0.38	6.29–6.66	0.17	0.46
Wrist breadth (cm)	5.29 ± 0.40	5.09–5.49	5.15 ± 0.36	4.98–5.33	0.29	0.36
Femur breadth (cm)	9.83 ± 0.71	9.48–10.18	9.26 ± 0.45	9.04–9.48	**0.01**	0.97
Ankle breadth (cm)	7.05 ± 0.63	6.74–7.36	6.98 ± 0.38	6.80–7.16	0.66	0.14
Hand breadth (cm)	7.43 ± 0.75	7.05–7.80	7.04 ± 0.57	6.77–7.31	0.08	0.58

CI: Confidence interval. Bold—significant difference ($p < 0.05$).

The comparison of anthropometric parameters, biological maturity, and the upper and lower body strength of female karate and taekwondo competitors is presented in Table 2. No significant differences were identified between disciplines except for maturity and head girth, observing significantly higher values and large effect sizes in taekwondo competitors ($p < 0.05$; $d > 1$). In addition, greater anterior-posterior chest breadth (cm) was determined in karate players ($p < 0.001$; $d = 1.87$).

Table 2. Differences in anthropometric parameters, maturity status, and upper and lower body strength between female taekwondo and karate players.

	Taekwondo		Karate			
	Mean ± SD	95% CI	Mean ± SD	95% CI	*p* Value	Cohen's *d*
Age (years)	13.40 ± 1.48	12.03–14.77	12.20 ± 1.09	11.36–13.04	0.08	0.92
APHV (years)	12.13 ± 0.31	11.84–12.42	11.78 ± 0.32	11.54–12.02	**0.04**	1.11
Maturity	1.24 ± 1.52	−0.16–2.65	0.39 ± 1.02	−0.40–1.18	0.2	0.66
Weight (Kg)	53.34 ± 11.63	42.59–64.10	46.42 ± 10.12	38.65–54.20	0.22	0.63
Height cm)	159.93 ± 12.80	148.09–171.77	153.57 ± 7.15	148.07–159.06	0.23	0.61
Sitting height (cm)	83.26 ± 6.29	77.44–89.08	84.10 ± 6.68	78.96–89.24	0.8	0.13
Arm span (cm)	162.34 ± 12.87	150.44–174.25	154.97 ± 7.77	148.99–160.94	0.18	0.69
Σ 6 skinfolds (mm)	85.43 ± 25.58	77.60–139.83	76.89 ± 27.62	55.65–98.12	0.54	0.32
Σ 8 skinfolds (mm)	108.71 ± 33.65	15.95–27.81	98.39 ± 38.40	68.87–127.91	0.58	0.29
FM percentage (%)	21.88 ± 6.42	37.57–41.04	21.13 ± 5.48	16.92–25.34	0.8	0.13
MM percentage (%)	39.30 ± 1.88	16.74–32.49	40.52 ± 3.44	37.87–43.16	0.42	0.44
Right hand grip (kg)	24.61 ± 8.52	15.40–28.12	18.91 ± 5.43	14.74–23.09	0.12	0.8
Left hand grip (kg)	21.76 ± 6.88	19.60–40.21	16.99 ± 6.35	12.10–21.87	0.17	0.72
CMJ (cm)	29.91 ± 9.82	24.60–33.00	26.08 ± 3.99	21.12–31.04	0.44	0.51
Head girth (cm)	55.21 ± 1.27	21.94–27.72	53.17 ± 1.59	51.94–54.39	**0.01**	1.42
Relaxed arm girth (cm)	24.83 ± 3.13	23.62–28.73	23.96 ± 3.77	21.06–26.86	0.63	0.25
Flexed and tensed arm girth (cm)	26.17 ± 2.76	20.15–24.43	24.64 ± 3.54	21.92–27.37	0.36	0.48
Corrected arm girth (cm)	22.29 ± 2.31	20.48–24.12	20.70 ± 2.53	18.75–22.65	0.22	0.66
Forearm girth (cm)	22.30 ± 1.97	13.66–15.74	21.99 ± 2.37	20.16–23.81	0.78	0.14
Wrist girth (cm)	14.70 ± 1.13	73.08–85.75	14.86 ± 0.87	14.19–15.52	0.76	0.15
Chest girth (cm)	79.41 ± 6.85	61.29–69.85	77.41 ± 8.07	71.21–83.61	0.61	0.27
Waist girth (cm)	65.57 ± 4.63	78.15–94.48	65.52 ± 6.96	60.17–70.87	0.99	0.01
Hip girth (cm)	86.31 ± 8.83	48.65–63.35	85.30 ± 8.46	78.79–91.81	0.82	0.12
Max thigh girth (cm)	56.00 ± 7.94	42.11–51.41	50.19 ± 6.78	44.98–55.40	0.14	0.79
Thigh girth (cm)	46.76 ± 5.03	30.45–35.66	44.52 ± 5.73	40.12–48.93	0.43	0.41
Medial calf girth (cm)	33.06 ± 2.82	25.98–30.62	34.22 ± 7.33	28.58–39.85	0.7	0.21
Corrected thigh girth (cm)	28.30 ± 2.51	19.89–23.06	29.91 ± 7.22	24.35–35.46	0.59	0.3
Ankle girth (cm)	21.47 ± 1.72	11.64–14.28	21.26 ± 1.26	20.29–22.22	0.78	0.14
Leg length (cm)	76.67 ± 7.20	70.01–83.33	69.47 ± 6.92	64.15–74.79	0.06	1.02
Anterior-posterior chest breadth (cm)	12.96 ± 1.43	5.65–6.35	15.93 ± 1.74	14.60–17.27	**<0.001**	1.87
Humerus breadth (cm)	6.00 ± 0.38	4.61–5.59	6.04 ± 0.29	5.82–6.27	0.79	0.13
Wrist breadth (cm)	5.10 ± 0.53	8.33–9.52	4.93 ± 0.50	4.55–5.32	0.53	0.32
Femur breadth (cm)	8.93 ± 0.64	5.60–6.80	8.64 ± 0.66	8.14–9.15	0.4	0.44
Ankle breadth (cm)	6.20 ± 0.65	12.78–16.36	6.53 ± 0.43	6.20–6.86	0.24	0.61
Hand breadth (cm)	6.86 ± 0.41	61.77–109.09	7.09 ± 0.39	6.79–7.39	0.27	0.58

CI: Confidence interval. Bold—significant difference ($p < 0.05$).

Figure 1 shows the anthropometric Z-Scores of males and females according to discipline. Boys exhibited lower skinfold thickness and breadths than the normal population in both karate and taekwondo. Similarly, the analysis of proportionality in girls revealed lower skinfolds and girths in the lower body, especially in karate players.

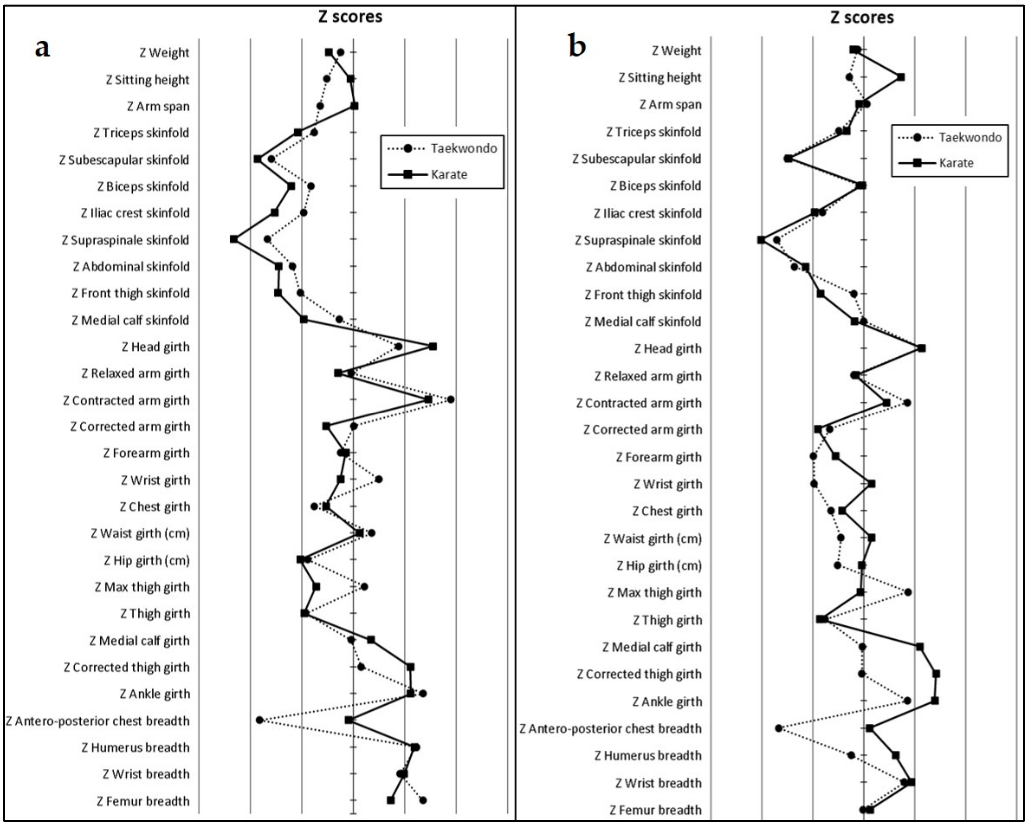

Figure 1. Anthropometric Z-Scores of males (**a**) and females (**b**).

4. Discussion

The purpose of the current study was to investigate the differences in body composition and in upper and lower body strength between young elite karate and taekwondo competitors. The main finding of this research was the significantly greater upper body dimensions of karatekas, especially with respect to muscle mass and chest girths in both boys and girls. Additionally, analyses of proportionality revealed leaner and more robust morphotypes as the typical anthropometric profile of karate and taekwondo players with respect to both sexes compared to the normal population. Since this is the first study to compare and analyze proportionality in successful mixed martial arts players, these data might provide normative data on morphological and strength determinants for talent identification purposes at young ages.

Before delving into comparisons, it is crucial to individually understand the morphological and physical characteristics of each type of fighter. Karatekas traditionally have exhibited greater muscle mass and chest girths, and this is attributed to the involvement of both upper and lower body sections in offensive and defensive actions. Drawing parallels with prior research studies, the findings of the current study further cement the theory posited by Kim and Nam [2] where morphological attributes heavily influence martial art styles. Taking into consideration that categories in martial arts are based on weight, maintaining a relatively low body mass via the minimization of fat mass is crucial to compete in the desired category [1]. However, performance can be affected if the power-to-weight ratio is altered by muscle mass reduction [25]. Previous research studies have reported significantly lower fat mass in international taekwondo players than in recreational taekwondo players [2,16,26], and greater muscularity in senior than junior athletes has been reported [1]. Similarly, more successful junior competitors also exhibited lower levels of adiposity than those obtained in the present study, ranging from 12% to 18% [27] using the anthropometric method [18]. However, further studies in young taekwondo players have reported contradictory results, perhaps as a result of the different methods used for estimations [1,2]. In boys, the determination of the physical profile of karate players obtained in the current research revealed a more compact and leaner morphotype than taekwondo competitors, while the comparison in girls only revealed a similar tendency. These findings are in agreement with prior investigations in young karate players, observing fat mass values of 10–12% and mesomorphic levels from 3.5 to 5 [3,17,28].

Strength and power assessments revealed no significant differences between the disciplines examined in the current study. Nevertheless, karate competitors showed a meaningful tendency towards greater hand grip values than taekwondo players. A possible explanation is related to the fact that the main technical actions in taekwondo are performed by the lower body, while upper body motion is limited to defensive and balance movements [1,15]. Conversely, in karate, both body sections are equally involved in the execution of offensive and defensive actions [3]. High demands of muscular power in the lower body are determinants in both disciplines but especially in taekwondo where powerful kicks and jumps are paramount in the pursuit of an optimal performance [1,9,12]. This fact might explain their higher morphological values in aspects such as leg length and femur breadth observed here. Previous research studies reported similar values that ranged between 22 and 50 cm in CMJ tests in junior categories [1,16]. Surprisingly, in the current investigation, CMJ analyses in boys revealed no significant differences between groups, while taekwondo girls exhibited a tendency towards larger values (d = 0.55). By understanding these particularities, the stark differences observed between these two groups and those reported in the present study might seem reasonable. However, the findings obtained here with respect to physical fitness and morphological development should be treated with caution when carrying out comparisons relative to other athletes of different ethnic origins or geographical conditions because they might influence the biological maturity process.

Traditionally, there are certain morphological attributes that characterize typical athlete profiles relative to a sport, playing position, or even a specialist role within a discipline [6]. The examination of proportionality revealed similar predispositions in both sports and sexes. Values below 0 were identified in almost all evaluated skinfolds, resulting in body composition profiles with low levels of fat mass. These findings are in agreement with previous research studies that identified lean and robust athletes among the most successful competitors [2,7,8,28]. Additionally, the large corrected and contracted girths observed in this investigation also confirm the typical leaner profile associated with martial arts competitors [2,8,28]. In fact, athletes in both sports are typically classified as 'ectomorphic mesomorph' according to conventional descriptors [2,28]. The only noticeable difference observed between disciplines is the lower upper body girths exhibited by taekwondo players, especially with respect to girls. The secondary role of the upper body in taekwondo actions is possibly related to the lower dimensions of forearm, wrist, and chest girths not only in karate competitors but also in the normal population. Since proportionality allows the interpretation of body dimensions based on the normal population, these findings might provide normative data for talent identification purposes.

Regarding limitations, due to the restricted number of participants recruited in the current study, the final results were treated with some caution. Nevertheless, the high athletic and performance levels of athletes reduced the total number of potential candidates for the investigation. In addition, the Z-scores presented here were based on normal population data. The values of senior elite athletes are necessary to better understand the evolution of morphological characteristics from young ages and to monitor young athletes who exhibit body composition determinants that are associated with optimal successful performances later in senior categories. The implications of these results are profound, especially when formulating training regimens for young martial artists. The balance between muscle mass and agility, for instance, has always been a topic of debate, and our findings tilt the scales slightly towards the significance of discipline-specific training.

5. Conclusions

To the best of our knowledge, this is the first study to investigate not only body proportionality but also strength values of young elite male and female martial artists. Summarizing the critical insights, this study not only uncovers the distinct morphological profiles of young elite karate and taekwondo competitors but also underscores the impact of age and developmental periods on these attributes. These findings shed light on the importance of discipline-specific morphological characteristics, particularly the greater upper body dimensions in karatekas and the leg emphasis in taekwondo practitioners. From a practical standpoint, trainers and coaches can leverage this knowledge to tailor training programs, emphasizing areas of weakness and capitalizing on the inherent strengths of the athletes, thereby ensuring optimized performance in competitions.

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Data Availability Statement: All data presented in the current study are available upon request.

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When and How a Judo Contest Ends: Analysis of Scores, Penalties, Rounds and Temporal Units in 2018, 2019 and 2021 World Championships

Xurxo Dopico-Calvo [1], Xián Mayo [2,*], Luis Santos [1,3,*], Eduardo Carballeira [1], Jožef Šimenko [4], Bayram Ceylan [5], Iván Clavel [1] and Eliseo Iglesias-Soler [1]

1 Performance and Health Group, Department of Physical Education and Sport, University of A Coruna, 15179 A Coruña, Spain
2 Observatory of Healthy and Active Living of Spain Active Foundation, Centre for Sport Studies, King Juan Carlos University, 28942 Madrid, Spain
3 Department of Physical Education and Sport, University of León, 24071 León, Spain
4 School of Life and Medical Sciences, University of Hertfordshire, Hatfield AL10 9EU, UK
5 Department of Coaching Education, Faculty of Sport Sciences, Kastamonu University, Kastamonu 37150, Türkiye
* Correspondence: xian.mayo@urjc.es (X.M.); lsanr@unileon.es (L.S.)

Abstract: The main aim of this study was to analyse the relationship between how contests end (scores or penalties), the temporal units and the competition rounds regarding when the contest end in the 2018, 2019 and 2021 Judo World Championships. A total of 2340 contests involving 2244 elite judo athletes (1343 men and 901 women) were analysed. Pearson's chi-squared (χ^2) was implemented to analyse the association between variables, and the standardised residuals were used to analyse its interpretation; the strength of the associations was reported as Cramer's V. Shapiro–Wilk and Kolmogorov–Smirnov were implemented to test the normality of the length of golden score (GS) sequences, and Kruskal–Wallis was applied for analysing GS sequences by championships. Mann–Whitney U was also implemented if a significant effect was detected. The level of significance was set at 0.05. The results were as follows: (1) Most contests ended before the accomplishment of the regular time (BRT), and they were won by *ippon*. (2) During BRT, the defeated accumulated more *shido* than the winner, while the opposite happened in contests finishing at the regular time (FRT). (3) Contests ending in the first and third minutes decreased, while contests ending in the second and fourth minutes increased; a longer length of the GS period was observed for women compared with men. (4) BRT contests were overrepresented in rounds 1 and 2, while extended time contests (EXT) in repechage, semi-final, bronze and final were overrepresented. (5) There were fewer *waza-ari* than expected during the preliminary rounds and more in the final rounds. The current study reveals cornerstone information that could be used to improve the training programs of elite judo athletes.

Keywords: performance analysis; combat sports; rule; temporal unit; phase; stage; golden score

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1. Introduction

As a combat sport, judo has a different range of scores leading to winning a contest, while penalties do not score but may also lead to winning a contest. Thus, a contest may end immediately when one judo athlete scores an *ippon* (I), accumulates two *waza-ari* (*waza-ari-awasete-ippon*, WW) or accumulates three penalties (three *shido*, SH3). In addition, a contest finishes at the end of regular time if there is only one *waza-ari* (W) scored.

The different ways to obtain a score (*how a contest ends*, HwCE) and win a judo contest determine the end of the combat at diverse time points during the contest (*when the contest ends*, WhCE), i.e., finishing before the accomplishment of the regular time (BRT), finishing at the regular time (FRT) or finishing in extended time (EXT). The judo rules establish a golden score period (GS, after more than four minutes) when judo athletes are tied by scores (no score or W for each athlete) at the end of the regular time. During the GS period, there is a slight modification of the way to win because a W would be enough to determine the end of the contest and would give the victory to the scoring athlete. Furthermore, during the regular time, if any of the judo athletes received one or two *shido*, this would not modify the scoreboard, and in the case of a tie, just the extended time would be applied, and the penalties would be retained. During the GS, if a possible new *shido* would be received by any of the athletes, it would be summed up to the three *shido*, which would lead to the end of the contest. Therefore, and considering the criteria regarding HwCE, it is of great importance to determine at what time points the highest scores are achieved (I, WW, W or SH3) because it establishes WhCE on the three different possibilities in which the judo contest might end, i.e., BRT, FRT and EXT.

New judo rules from 2018 might change the ways of developing and ending the contest [1]. The International Judo Federation (IJF) has implemented rule changes trying to promote a more dynamic and positive judo [2–7] and to reduce the duration of competitions to attract more viewers by decreasing the direct effect of penalties on the contest outcomes [4,8]. Thus, the duration and distribution of BRT, FRT and EXT contests influence training planning and programming. At the same time, it will affect strategic and tactical motor behaviours. This is because the chances of winning and losing depend directly on the score required to end the contest, the accumulated *shido* and possible time left to the end of the contest and the possibility to extend the contests until a GS is achieved. Nevertheless, efforts to analyse the distribution and changes of WhCE are scarce and incomplete. In this regard, studies have considered the contest duration as a continuous variable, without considering that the key behaviours to obtain a win are not weighted equally depending on if the contest ends at BRT, FRT or EXT [3,9,10]. Research analysing judo performance behaviours [1,11–13] also reported a dissimilar distribution regarding when a contest ends, BRT being the most represented stage of the contest (65%), followed by EXT (20.3%) and FRT (14.7%) [14]. In this regard, ignoring the categorisation of contests as BRT, FRT and EXT and their impact on strategic and tactical behaviours may lead to wrong practical implementation, negatively influencing coaches' and judo athletes' decisions when planning, programming and executing specific judo training. In this regard, WhCE analysis may stimulate specific fighting behaviours depending on if the contest might be far or close to the end of the regular time or when the contest is EXT.

Regarding penalties, IJF are trying to discourage judo athletes from performing certain behaviours by additionally punishing specific actions and reducing the number of *shido* available before being disqualified and thus reducing the number of contests reaching GS [10]. Regarding the total penalties received, prior studies indicated that the loser receives more penalties than the winner [6,15] with an analysis in temporal terms leading to a possible misinterpretation of the findings suggesting wrong particular patterns.

This study aimed to analyse the relationship between WhCE (i.e., BRT, FRT and EXT) also taking into account temporal units, HwCE (i.e., I, WW, W and SH3) and the penalties considering the sex category of the athletes and the round (e.g., preliminary vs. final rounds; PR and FR, respectively) as potential variables affecting WhCE and HwCE during three World Championships (WC18, WC19 and WC21). We hypothesised that (1) most of the contests will finish BRT and by I. (2) In addition, the defeated will accumulate more *shido* but only on certain WhCE. (3) Last, with new rules, WhCE and HwCE will be affected with longer contests ending in W and SH3.

2. Materials and Methods

2.1. Design

This was a cross-sectional observational study, extracted from an open-access website between 15 December 2021 and 15 January 2022, analysing both the men and women categories of three World Judo Championships, the World Judo Championships of Bakú 2018 (WC18, https://www.ijf.org/competition/1591/contests), Tokyo 2019 (WC19, https:

//www.ijf.org/competition/1751/contests) and Budapest 2021 (WC21, https://www.ijf.org/competition/2239/contests), which were performed under new competition rules changed in 2018. Deeming that the analysed data were attained from an open-access website in secondary form and not generated by experimentation, there were no ethical issues in examining or interpreting them [16]. Additionally, the personal identification or nationalities of the athletes whose contests were assessed were not specified.

2.2. Procedures

A total of 2370 contests involving 2244 judo athletes (1343 men and 901 women) were considered in the present study. A total of 2340 contests were finally analysed since 30 contests were excluded due to *fusen-gachi* (failing to appear), *kiken-gachi* (abandonment or injury) and *hansoku-make* (direct defeat by grave infringement). This study used an ad hoc tool designed to observe and collect data using the program Lince PLUS version 1.3.2. [17,18].

Three possibilities were defined regarding WhCE to carry out the data analysis of the present study: (a) contests ending before the accomplishment of the regular time of 4 m (BRT), and thus the scoreboard being determined by I, WW or SH3; (b) contests finishing at the regular time of 4 m (FRT) and the scoreboard always being W; and (c) contests finishing during the extended time of golden score period (EXT), in which an additional time is needed until an I, a second W (i.e., WW) during a tie or a first W is scored or an SH3 is penalised. Regarding HwCE, the scores and penalties leading to the finish of the contest were analysed (i.e., I, W, WW and SH3).

The accumulation and distribution of *shido* between judo athletes in every contest were also analysed considering if the winner or the defeated was more penalised or if the judo athletes were tied at zero, one or two shido at the end of the contest.

Temporal units (TUs) were established dividing the contest into different periods of time according to previous research by Dopico-Calvo et al. [19]: TU1, from 0 to 59 s; TU2, from 60 to 119 s; TU3, from 120 to 179 s; TU4, from 180 to 239 s; TU-FRT, for contests ending at the second 240 (except if these types of contests expressed a continuation derived from an immobilisation or *osae-komi-waza*); and TU-GS, corresponding to EXT contests. In addition, the duration of the extended times of the EXT were also recorded in seconds for further analyses.

Finally, the competition rounds were also registered and analysed in two different ways (separately, from round 1 to the final round (FL), and recoded into two variables, PR and FR). The variables used in the study are summarised in Table 1.

Table 1. Variables of the study and their abbreviations.

Variable	Abbreviation	Description
World Judo Championship Baku 2018	WC18	
World Judo Championship Tokyo 2019	WC19	
World Judo Championship Budapest 2021	WC21	
When the contest ends	WhCE	
Before the accomplishment of the regular time	BRT	Contests that end before the regular time (less than 4 m)
Finishing at the regular time of 4 min	FRT	Contests that end into the regular time (4 m)
Extended time–golden score	EXT	Contests with extended time and golden score (more than 4 m)
How the contest ends (scores and penalties)	HwCE	

Table 1. *Cont.*

Variable	Abbreviation	Description
Ippon	I	
Waza-ari	W	
Waza-ari-awasete-ippon (double *waza-ari)*	WW	
Shido 3	SH3	
Accumulation and distribution of *shido* in a contest		
Winner		Contests where the athlete who wins ends with more *shido*
Defeated		Contests where the athlete who defeats ends with more *shido*
Tied at zero *shido*		Contests ending without penalties
Tied at one *shido*		Contests ending tie at one *shido*
Tied at two *shido*		Contests ending tie at two *shido*
Temporal unit	TU	Time phase in which a contest was divided
	TU1	First temporal unit: from 0 to 59 s
	TU2	Second temporal unit: from 60 to 119 s
	TU3	Third temporal unit: from 120 to 179 s
	TU4	Fourth temporal unit: from 180 to 239 s
	TU-FRT	Temporal unit at the end of the 4 m of regular time
	TU-GS	Temporal unit of the extended time or golden score
Round		Rounds, by sex category
Round 1	R1	First round
Round 2	R2	Second round
Round 3	R3	Third round
Round 4	R4	Fourth round
Quarter-final	QF	The winner goes to the semi-final, and the defeated goes to the repechage
Repechage	RP	The winner goes to the bronze, and the defeated is eliminated
Semi-final	SF	The winner goes to the final, and the defeated goes to the bronze
Bronze	BZ	The winners win the bronze medal (two medals), and the defeated are eliminated
Final	FL	The winner wins the gold medal, and the defeated wins the silver medal
Rounds recoded in two categories		
Preliminary rounds	PR	Grouping of R1, R2, R3 and R4
Final rounds	FR	Grouping of QF, RP, SF, BZ and FL

2.3. Data Analysis

The three championships mentioned before were considered for analysing the evolution of the variables of study (i.e., WC18, WC19 and WC21). All data referring to HwCE (i.e., scores and penalties that implied the end of the contest), the total number of *shido*, the temporal units (TU, i.e., periods of time in which the judo contest was divided for analysis), the rounds (R) and sex category were registered.

Scores and penalties (HwCE) were analysed considering WhCE (i.e., BRT, FRT and EXT contests) and the round of the championship.

The total number of *shido* in a contest was analysed considering (a) when one judo athlete accumulated more than the other, (b) when both athletes were tied in terms of *shido* (none, one or two) and (c) the accumulation of *shido* between a winner and defeated during a contest, while also considering when the contest ended (BRT, FRT and EXT).

Regarding TUs, frequency and percentage within BRT, FRT and EXT were analysed. BRT could finish in temporal units TU1, TU2, TU3 and TU4; FRT contests only could end in TU-FRT (4 m); and EXT contests only could finish in the golden score (i.e., >4 m). All the temporal units in which the contests might end were analysed.

Concerning the competition rounds, first, each round was analysed separately, i.e., round 1 (R1), round 2 (R2), round 3 (R3), round 4 (R4), quarter-final (QF), repechage (RP), semi-final (SF), bronze (BZ) and FL. Second, a complementary analysis in which the nine rounds were recoded into two variables was carried out for simplifying the interpretation of outcomes: PR, that is, R1, R2, R3 and R4, which were the initial rounds, and final rounds, FR, that is, QF, RP, SF, BZ and FL, in which the medals were disputed or passed on to contests that allowed athletes to go on to dispute the medals.

2.4. Statistical Analysis

The descriptive data were presented as absolute values and percentages. Most of the analysed variables were categorical, and only one variable, GS time, was quantitative.

Regarding the categorical variables, a one-sample Pearson's chi-squared (χ^2) test was implemented to analyse the hypothesis of a uniform distribution of the temporal units (TUs) in the whole sample of contests. Furthermore, Pearson's chi-squared (χ^2) was implemented to analyse the association between variables. When a significant association was detected, its interpretation was carried out considering standardised residuals (SRs, where residuals with values greater than 2 or lower than -2 were deemed significant):

$$\textit{standarised residual} = \frac{\text{observed}_{ij} - \text{model}_{ij}}{\sqrt{\text{model}_{ij}}}$$

where "observed" is the frequency corresponding to cell ij (i.e., row i; column j), and "model" is the expected frequency in that cell for independent variables [20].

When significant, the strength of associations was reported as Cramer's V (V). A Cramer's V value lower than 0.20 was considered as a small effect, a value within the range of 0.21–0.35 was considered as a medium effect and a value larger than 0.35 was considered as a larger effect [21].

The length of the GS sequences in the raw values and after the logarithmic transformation was tested for normality by the Shapiro–Wilk and Kolmogorov–Smirnov tests. Since the normality assumption was not verified, a Kruskal–Wallis one-way analysis of variance was applied for analysing GS sequences between championships; if a significant effect of championship was detected, the pairwise post hoc comparisons were performed by Mann–Whitney U. Finally, Mann–Whitney U was also performed to analyse the length of the GS sequences between men and women, including the championships all together.

All the statistical analyses were executed with SPSS 27 (IBM, Chicago, IL, USA). The level of significance was set at 0.05.

3. Results

3.1. WhCE (BRT, FRT and EXT) Considering the Championship

The chi-square test detected an association between WhCE and the championship analysed (p = 0.002; V = 0.060). The SR showed an overrepresentation of EXT contests in WC21 (SR = 2.2). When considering the sex of the judo athletes, the chi-square analysis showed an association between WhCE and championship for men (p = 0.009; V = 0.070) but not for women (p = 0.161; V = 0.059) (Table 2).

Table 2. Relation between WhCE (contests ending before the accomplishment of the regular time of 4 m (BRT), finishing at the regular time of 4 min (FRT) and finishing during the golden score period (EXT) and the championship analysed (WC18, WC19 and WC21) (n = 2340 contests).

	BRT	FRT	EXT	Total
WC18	n = 498	n = 129	n = 164	791
Percentage within WhCE	63.0%	16.3%	20.7%	100%
Percentage within championships	33.4%	37.5%	32.5%	33.8%
Men	n = 294	n = 76	n = 104	474
Percentage within WhCE	62.0%	16.0%	22.0%	100%
Percentage within championships	34.3%	35.7%	32.7%	34.2%
Women	n = 204	n = 53	n = 60	317
Percentage within WhCE	64.4%	16,7%	18.9%	100%
Percentage within championships	32.1%	40.5%	32.3%	33.3%
WC19	n = 587	n = 108	n = 165	860
Percentage within WhCE	68.2%	12.6%	19.2%	100%
Percentage within championships	39.3%	31.4%	32.8%	36.8%
Men	N = 345	N = 68	N = 105	518
Percentage within WhCE	66.6%	13.1%	20.3%	100%
Percentage within championships	40.3%	31.9%	33.0%	37.3%
Women	N = 242	N = 40	N = 60	342
Percentage within WhCE	70.8%	11.7%	17.5%	100%
Percentage within championships	38.1%	30.5%	32.3%	35.9%
WC21	n = 407	n = 107	n = 175	689
Percentage within WhCE	59.1%	15.5%	**25.4% ****	100%
Percentage within championships	27.3%	31.1%	**34.7% ****	29.4%
Men	n = 217	n = 69	n = 109	395
Percentage within WhCE	54.9%	17.5%	27.6%	100%
Percentage within championships	25.4%	32.4%	34.3%	28.5%
Women	n = 190	n = 38	n = 66	294
Percentage within WhCE	64.7%	12.9%	22.4%	100%
Percentage within championships	29.9%	29.0%	35.5%	30.8%
(WC18, WC19, WC21) TOTAL	n = 1492	n = 344	n = 504	2340
Percentage within WhCE	63.8%	14.7%	21.5%	100%
Men	n = 856	n = 213	n = 318	1387
Percentage within WhCE	61.7%	15.4%	22.9%	100%
Women	n = 636	n = 131	n = 186	953
Percentage within WhCE	66.8%	13.7%	19.5%	100%

** SRs with a value equal, or higher to 2. SRs = standardised residuals.

3.2. HwCE Considering the Championship

Considering all contests (n = 2340), the most common way to win was by I (46.2%), followed by W (22.6%), WW (17.7%) and SH3 (13.5%). The chi-square analysis showed an association between HwCE and the championship (p = 0.014; V = 0.058). Residuals showed an underrepresentation of W in WC19 (SR = −2.0). Differences in percentages were observed between championships. In WC18 (n = 791), 46.3% of the contests were won by I, 25% by W, 17.1% by WW and 11.6% by SH3. In WC19 (n = 860), 49.2% were won by I, 19.3% by W, 16.7% by WW and 14.8% by SH3. In WC21 (n = 689), 42.38% were won by I, 23.8% by W, 19.7% by WW and 14.1% by SH3.

When considering the judo athletes' sex, the chi-square also showed an association between the championship and HwCE for men (p =0.044; V = 0.068) but not for women (p = 0.325). Differences were also observed for men and women considering the championship. For men (n = 1387), in WC18 (n = 474), 48.5% of the contests were won by I, 24.9% by W, 14.8% by WW and 11.8% by SH3; in WC19 (n = 518), 49.6% were won by I, 19.5% by W, 15.1% by WW and 15.8% by SH3; and in WC21 (n = 395), 41.8% were won by I, 26.8% by W, 17.2% by WW and 14.2% by SH3. For women (n = 953), in WC18 (n = 317), 41.9% of the contests were won by I, 25.2% by W, 20.5% by WW and 11.4% by SH3; in WC19 (n = 342), 48.5% were won by I, 19.0% by W, 19.3% by WW and 13.2% by SH3; and in WC21 (n = 294), 43.2% were won by I, 19.7% by W, 23.1% by WW and 13.9% by SH3.

3.3. HwCE Considering the Championship by WhCE (BRT, FRT and EXT)

As FRT contests can only end by W, only the results from BRT and EXT contests are presented.

3.3.1. HwCE Considering the Championship during BRT Contests

Table 3 shows HwCE during BRT contests. The chi-square overall analysis showed an association between HwCE and the championship ($p = 0.009$; V = 0.067). Residuals show an overrepresentation of WW in WC21 (SR = 2.5). When considering sex, the chi-square analysis showed no association between HwCE and the championship neither for men ($p = 0.098$) nor for women ($p = 0.156$).

Table 3. Relation between how the contest ended (HwCE) and the championship (WC18, WC19 and WC21) in contests finishing before the accomplishment of the regular time (BRT) (n = 1492).

	I	WW	SH3	Total
WC18	n = 311	n = 127	n = 60	n = 498
Total (%)	62.45%	25.50%	12.05%	
BRT men (%)	65.99%	21.77%	12.24%	
BRT women (%)	57.35%	30.88%	11.76%	
WC19	n = 378	n = 132	n = 77	n = 587
Total (%)	64.40%	22.49%	13.12%	
BRT men (%)	65.51%	20.87%	13.62%	
BRT women (%)	62.81%	24.79%	12.40%	
WC21	n = 236	n = 132	n = 39	n = 407
Total (%)	57.99%	**32.43%** **	9.58%	
BRT men (%)	58.53%	30.41%	11.06%	
BRT women (%)	57.37%	34.74%	7.89%	
Overall	n = 925	n = 391	n = 176	n = 1492
Total (%)	62%	26.20%	11.8%	
BRT men (%)	63.90%	23.60%	12.50%	
BRT women (%)	59.43%	29.72%	10.85%	

** SRs with a value equal or higher to 2. SRs = standardised residuals.

3.3.2. HwCE considering the Championship during EXT Contests

Table 4 shows HwCE considering the championship during EXT contests. The chi-square analysis showed an association between HwCE and the championship ($p = 0.029$, V = 0.118). The residuals showed an underrepresentation of SH3 in WC18 (SR = −2.0). There was no association between variables for men ($p = 0.212$) or women ($p = 0.096$) when considering the sex.

3.3.3. WhCE (BRT, FRT and EXT) Considering the Distribution of Shido

Table 5 presents the relation between WhCE and the distribution of *shido*. There was an association between WhCE and the distribution of *shido* ($p < 0.001$; V = 0.318). For BRT, there was an overrepresentation of tied at zero *shido* and an underrepresentation of *shido* for the winning athlete and for tied at two *shido* (SR = 8.6, −3.9 and −5.5, respectively). For FRT, there was an overrepresentation of *shido* for the winner, tied at one *shido* and tied at one *shido* and two *shido* and an underrepresentation of *shido* for the defeating athlete and tied at zero *shido*. For EXT, there was an overrepresentation of *shido* for the defeating athlete and for being tied at two *shido* and an underrepresentation for being tied at zero *shido*.

Table 4. Relation between HwCE (I, W, WW or SH3) and the championship (WC18, WC19 and WC21) in contests finishing in the extended time of the golden score period (EXT) (n = 504).

	I	W	WW	SH3	Total
WC18	n = 55	n = 69	n = 8	n = 32	n = 164
Total (%)	33.54%	42.07%	4.88%	**19.51%** *	
EXT men (%)	34.62%	40.38%	5.77%	19.23%	
EXT women (%)	31.67%	45.00%	3.33%	20.00%	
WC19	n = 45	n = 58	n = 12	n = 50	n = 165
Total (%)	27.27%	35.15%	7.27%	30.30%	
EXT men (%)	29.52%	31.43%	5.71%	33.33%	
EXT women (%)	23.33%	41.67%	10.00%	25.00%	
WC21	n = 56	n = 57	n = 4	n = 58	n = 175
Total (%)	32.00%	32.57%	2.29%	33.14%	
EXT men (%)	34.86%	33.94%	1.83%	29.36%	
EXT women (%)	27.27%	30.30%	3.03%	39.39%	
Overall	n = 156	n = 184	n = 24	n = 140	n = 504
Total (%)	30.95%	36.51%	4.76%	27.78%	
EXT men (%)	33.02%	35.22%	4.40%	27.36%	
EXT women (%)	27.42%	38.71%	5.38%	28.49%	

* SRs with a value equal or higher to −2. SRs = standardised residuals.

Table 5. Relation between when a contest ended (WhCE: contests ending before the accomplishment of the regular time of 4 m (BRT), finishing at the regular time of 4 min (FRT) and finishing during the golden score period (EXT)) and the distribution of *shido* (n = 2340).

	Winner	Defeated	Tied at Zero *Shido*	Tied at One *Shido*	Tied at Two *Shido*
BRT	n = 181	n = 579	n = 551	n = 148	n = 33
Percentage within categories	12.1%	38.8%	36.9%	9.9%	2.2%
SR	**−3.9** *	−1.7	**8.6** **	−1.2	**−5.5** *
FRT	n = 132	n = 100	n = 21	n = 57	n = 34
Percentage within categories	38.4%	29.1%	6.1%	16.6%	9.9%
SR	**10.2** **	**−3.6** *	**−7.2** *	**3.2** **	**3.4** **
EXT	n = 67	n = 295	n = 28	n = 51	n = 63
Percentage within categories	13.3%	58.5%	5.6%	10.1%	12.5%
SR	−1.6	**5.9** **	**−8.9** *	−0.6	**6.6** **
Total	n = 380	n = 974	n = 600	n = 256	n = 130
Percentage within categories	16.2%	41.6%	25.6%	10.9%	5.6%

"Winner" indicates that the athlete winning ends with more *shido*, "defeated" indicates that the defeated athlete ended with more *shido*, "tied at zero *shido*" indicates contests ending without penalties, "tied at one *shido*" indicates contests ending tied at one *shido*, and "tied at two *shido*" indicates contests ending tied at two *shido*. * SRs with a value equal or higher to −2. ** SRs with a value equal or higher to 2. SRs = standardised residuals.

When considering the sex of the judo athletes, there was an association between variables (p = 0.024; V = 0.180). The residuals indicate an overrepresentation of tie at zero *shido* for women (SR = 2.5) and an underrepresentation of tie at zero *shido* for men (SR = −2.0).

3.4. Temporal Units (TUs) Considering the Championship

One sample chi-square test (n = 2340 contests) rejected the uniform distribution between temporal units (TU1, TU2, TU3, TU4, TU-FRT and TU-GS) in the whole sample of contests ($p < 0.00$; residuals = −132, 12, 22, 30, −46 and 114, respectively). In addition, one sample chi-square test by sex also rejected the uniform distribution in both men (n = 1387; $p < 0.001$; SR = −102.2, −3.2, 18.8, 17.8, −18.2 and 86.8, respectively) and women (n = 953; p = 0.004; SR = −29.8, 15.2, 3.2, 12.2, −27.8 and 27.2, respectively).

The chi-square overall analysis showed an association ($p < 0.001$; V = 0.082) between the TUs and the championship. In this regard, the SR indicated an overrepresentation of TU1 in WC19 and TU-GS in WC21 (SR = 2.3 and 2.2, respectively) and an underrepresentation of TU1 in WC21 (SR = −2.5). The chi-square analysis by sex also showed associations between TUs and the championship for women ($p = 0.009$; V = 0.111), with an overrepresentation of TU1-BRT in WC19 (SR = 2.3), and for men ($p = 0.05$; V = 0.081).

Finally, the data were also analysed regarding the duration of the extended time in EXT contests (n = 504). The Kruskal–Wallis test showed no significant differences between the length of the GS sequences and championships ($p = 0.309$; H = 2.347) (mean range: 250.8 in WC18, 265.7 in WC19 and 241.6 in WC21). When comparing the GS sequences and championships, but separately for men and women, the analysis showed no significant differences for women (n = 186; $p = 0.149$; H = 3.808) (mean range: 82.4 in WC18, 97.4 in WC19 and 100.0 in WC21) but significant differences for men (n = 318; $p = 0.03$; H = 7.028) (mean range: 169.7 in WC18, 169.0 in WC19 and 140.6 in WC21). An additional analysis was performed for men, and the Mann–Whitney test showed no significant differences between WC18 and WC19 (n = 209; $p = 0.885$) but significant differences between WC18 and WC21 (n = 213; $p = 0.026$; Z = −2.221) (mean range: 116.6 in WC19 and 97.8 in WC21) and between WC19 and WC21 (n = 214; $p = 0.019$; Z = −2.350) (mean range: 117.6 in WC19 and 97.7 in WC21), indicating, in both cases, that the length of the GS tended to be shorter in WC21 than in WC18 and WC19. The results are presented in Table 6.

Table 6. Golden score (GS) period analysis in temporal terms (seconds-s) by the championship (WC18, WC19 and WC21) and sex (men vs. women) (n = 2340).

	WC18		**WC19**		**WC21**		**Total**	
	N	**Mean ± SD**	**N**	**Mean ± SD**	**N**	**Mean ± SD**	**N**	**Mean ± SD**
Men	n = 104	100 ± 84.4	n = 105	96.8 ± 79	n = 109	76 ± 66.5	n = 318	90.7 ± 75.9
Women	n = 60	101 ± 88.3	n = 60	127.8 ± 101	n = 66	137.9 ± 127.3	n = 186	122.7 ± 108.1
Overall	n = 164	100.4 ± 83.1	n = 165	108.1 ± 88.6	n = 175	99.4 ± 98.5	n = 504	102.5 ± 90.4

Data are means ± standard deviation (SD).

When comparing GS sequences between men and women, including all the championships altogether, the Mann–Whitney test showed significant differences ($p = 0.003$; Z = −3.019) (mean range: 237.5 for men and 278.1 for women), indicating that the length of the GS tended to be longer for women than for men.

3.5. WhCE (BRT, FRT and EXT) and Temporal Units (TUs) Considering the Rounds

As can be observed in Table 7, the chi-square analysis showed an association between WhCE and rounds ($p < 0.001$; V = 0.160) for the whole sample and for both men ($p < 0.001$; V = 0.187) and women ($p = 0.001$; V = 0.161) separately.

To simplify the interpretation of these results, it was decided to group the rounds into two blocks, PR and FR, considering all the TUs. The chi-square overall analysis also showed an association ($p < 0.001$; V = 0.172) between variables (TUs and grouped rounds). The SR indicated an overrepresentation of TU-FRT and TU-GS in FR (SR = 3.1 and 4.8, respectively) and an underrepresentation of TU1, TU2, TU3 and TU-GS in PR rounds (SR = −3.3, −2.2, −2.6 and −2.4, respectively). As seen in Figure 1, the contest durations were longer in FR.

Results by sex also confirmed the association between TUs and grouped rounds, both for women ($p < 0.001$; V = 0.152) and for men ($p < 0.001$; V = 0.204). For women, the SR for the FR showed an overrepresentation of TU-GS and an underrepresentation of TU1-BRT (SR = 2.8 and −2.1, respectively). For men, the SR showed for the FR an overrepresentation of TU-FRT and TU-GS (SR = 3.2 and 4.2, respectively) and an underrepresentation of TU1-BRT and TU3-BRT (SR = −2.9 and −2.5, respectively).

Table 7. Relation between WhCE (BRT, FRT and EXT) and round for the whole sample and for men and women (n = 2340).

	R1	R2	R3	R4	QF	RP	SF	BZ	FL	Total (n)
BRT	n = 412	n = 573	n = 245	n = 45	n = 100	n = 32	n = 34	n = 33	n = 18	**1492**
Total %	2.6%	38.4%	16.4%	3.0%	6.7%	2.1%	2.3%	2.2%	1.2%	
SR	**2.7** **	**2.3** **	−1.1	−1.5	−0.7	−**2.7** *	−**2.6** *	−**2.7** *	−1.7	
Men %	26.4%	40.5%	17.2%	5.3%	5.0%	1.9%	1.5%	1.2%	1.1%	856
SR	1.9	**2.4** **	−0.8	−1.3	−1.2	−1.7	−**2.5** *	−**3.0** *	−1.1	
Women %	29.2%	35.5%	15.4%	-	9.0%	2.5%	3.3%	3.6%	1.4%	636
SR	1.8	0.7	−0.8	-	0.1	−**2.1** *	−1.2	−0.8	−1.3	
FRT	n = 67	n = 99	n = 70	n = 16	n = 32	n = 21	n = 14	n = 18	n = 7	**344**
Total %	19.48%	28.78%	20.35%	4.65%	9.30%	6.10%	4.07%	5.23%	2.03%	
SR	−1.8	−1.9	1.2	0.9	1.5	**2.7** **	0.5	1.7	0.3	
Men %	20.66%	24.88%	21.60%	7.51%	7.98%	6.10%	3.29%	5.63%	2.35%	213
SR	−0.8	−**2.6** *	1.1	0.7	1.1	**2.8** **	0.2	**2.3** **	1.0	
Women %	17.56%	35.11%	18.32%	-	11.45%	6.11%	5.34%	4.58%	1.53%	131
SR	−1.8	0.2	0.5	-	1.0	1.1	0.6	0.2	−0.5	
EXT	n = 88	n = 145	n = 98	n = 27	n = 36	n = 27	n = 35	n = 31	n = 17	**504**
Total %	17.46%	28.77%	19.44%	5.36%	7.14%	5.6%	6.94%	6.15%	3.37%	
SR	−**3.1** *	−**2.3** *	1.0	1.8	0	**2.4** **	**4.0** **	**3.2** **	**2.6** **	
Men %	16.67%	29.56%	19.18%	8.49%	7.55%	3.46%	6.92%	5.97%	2.20%	318
SR	−**2.4** *	−1.8	0.4	1.5	1.1	0.6	**4.0** **	**3.1** **	0	
Women %	18.82%	27.42%	19.89%	-	6.45%	8.60%	6.99%	6.45%	5.38%	186
SR	−1.8	−1.5	1.1	-	−1.1	**2.9** **	1.8	1.4	**2.9** **	
Total	24.23%	34.91%	17.65%	3.76%	7.18%	3.42%	3.55%	3.50%	1.79%	**2340**

* SRs with a value equal or higher to −2. ** SRs with a value equal or higher to 2. SRs = standardised residuals.

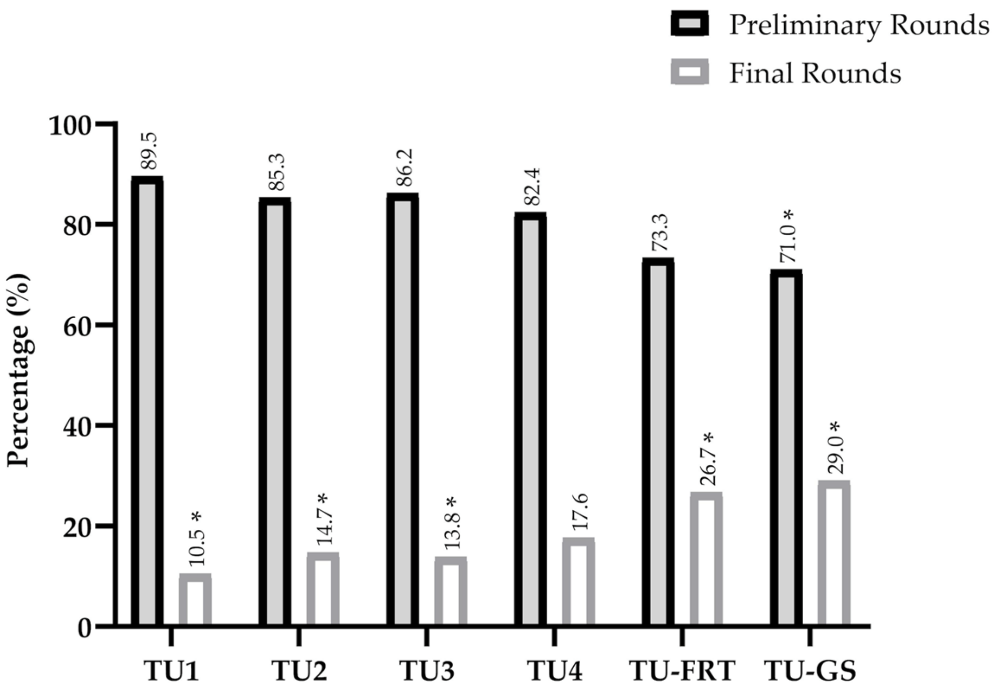

Figure 1. Descriptive analysis and associations between temporal units (TUs) and grouped rounds (preliminary and final rounds, PRs and FRs, respectively) (n = 2340). Asterisk highlights the variables leading to the most important contributions to the difference, according to the SR; SRs = standardised residuals.

3.6. HwCE and Grouped Rounds Considering WhCE (BRT, FRT and EXT)

Figure 2 shows the association between HwCE and the grouped rounds (PR and FR). In this regard, the chi-square analysis for the whole sample showed an association between HwCE and the rounds grouped ($p < 0.001$; V = 0.119). The SR showed an underrepresentation of W in PR (−2.2) and an overrepresentation of W in FR (4.5). When men (n = 1387; $p < 0.001$; V = 0.141) and women (n = 953; $p = 0.011$; V = 0.108) were analysed separately, an underrepresentation of W was observed during PR for men (−2.0), and an overrepresentation of W was observed during FR (4.2). For women, an overrepresentation of W was only observed during FR (2.3).

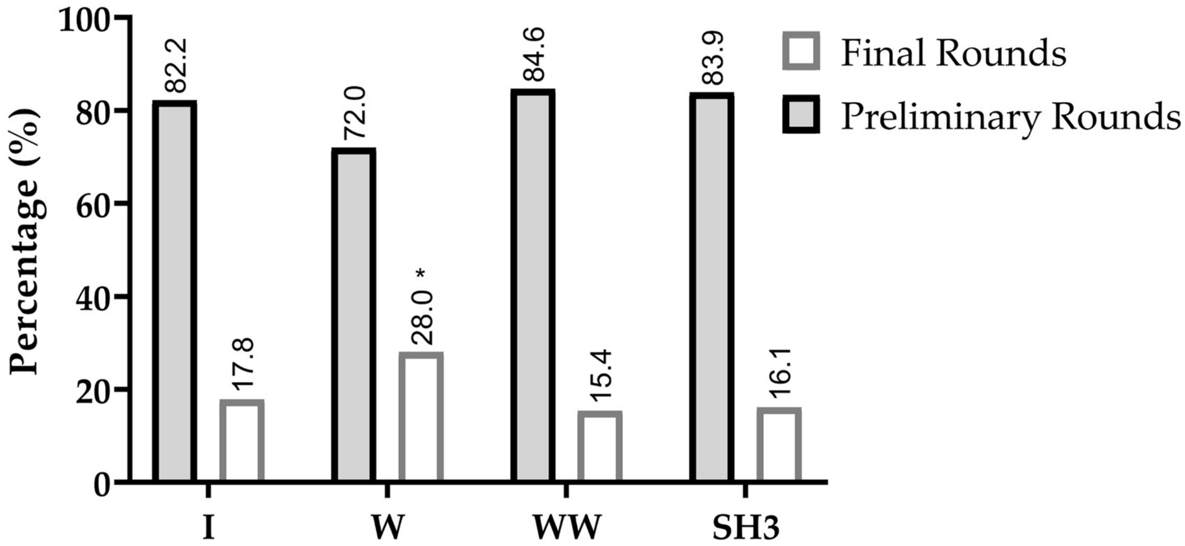

Figure 2. Relation between HwCE (I, WW, W and SH3) and grouped rounds (PR and FR) (n = 2340). * The variables leading to the most important contributions to difference, according to the to the SR; SRs = standardised residuals.

Further chi-square analyses considering WhCE separately (BRT, FRT or EXT) between HwCE and grouped rounds were performed. In BRT (n = 1492), an association between these variables was observed ($p = 0.017$; V = 0.074), with the SR indicating an underrepresentation of SH3 in FR (SR = −2.3). When sex categories were analysed separately, an association was observed for men (n = 856; $p = 0.019$; V = 0.096), with the SR showing an underrepresentation of SH3 in FR (−2.5), but not for women (n = 636; $p = 0.181$).

Finally, in EXT (n = 504), the chi-square analysis showed no association between variables for the whole sample ($p = 0.447$) or for men (n = 318; $p = 0.506$) and women (n = 186; $p = 0.883$) separately.

4. Discussion

In elite judo, most of the contests end BRT (<4 min) and by I. Regarding the accumulation of *shido*, during BRT, more contests ended with the winning athlete having fewer *shido* than the defeated athlete, while during FRT (4 min), more contests ended with the winner having more *shido* than the other judo athlete.

From WC18 to WC21, contests ending in the first and third minutes decreased, while contests ending in the second minute and fourth minute increased. The analysis of the TU-GS length in temporal terms (seconds) showed no significant differences from WC18 to WC21, while a longer length in EXT contests (>4 min) was observed for women compared with men. When considering the rounds, BRT contests were overrepresented in R1 and R2, while EXT were overrepresented during RP, SF, BZ and FL, indicating that WhCE depended on the round of the contest. During PR, there were fewer W, and during FR, there were more W than expected, indicating that HwCE was also modified during the rounds of the championship.

Our data showed that most of the contests ended BRT, followed by EXT and FRT. That was observed without regard to the championship analysed (WC18, WC19 or WC21) and for both men and women. Nevertheless, contests ending in EXT increased in WC21. Increases in contests ending in EXT were already found between the 2016 and 2020 Olympic cycles [22] and between 2018 and 2019 [14], suggesting a progressive but sustained increase in EXT contests in every new competitive year. Associations between the sex category and WhCE (BRT, FRT and EXT) were observed for men but not for women but without showing significant residuals.

Regarding HwCE, most contests ended by I, followed by W, WW and SH3. Changes with the year of the championship showed an increase in contests ending in W after WC19. When considering WhCE, BRT contests showed an increased percentage ending by WW during WC21, while EXT contests showed a reduced number of SH3 in WC18, suggesting an increased number of contests ending in SH3 after that. The differences in level between participants in a world championship or better training might explain why victory by I remains the most frequent HwCE. However, restrictions in scoring due to rule changes (for example, elimination of *yuko* score or not winning until three *shido* are penalised) has caused athletes to develop new strategies and tactical approaches to manage winning the contest [2–7]. A study comparing the effect of rule changes between the WC in Astana 2015 (WC15) and WC18 showed an increase in I in in the latter [23]. Nevertheless, another study comparing WC15 Astana versus WC17 Budapest did not find changes between championships [10]. The same findings were reported between WC12 London and Olympic Championship Rio 2016, showing that the rules changes did not effectively increase the number of I and W scores [3]. Another study analysed the Paris Grand Slam 2016 in comparison with 2017, finding an increase in W and a decrease in the total number of *shido* with a constant prevalence of I for men [24]. For women, the results were similar except for maintaining the total number of *shido* [24]. However, rule changes and a different analysis without considering WhCE (i.e., BRT, FRT and EXT contests) such as Calmet et al. [10] does not allow for more insight in this comparison. In addition, the results of the present study were consistent with those of other studies indicating an increase in winning by SH3 in EXT [13]. Similar levels of performance among judo athletes might be leading to a greater difficulty in scoring I, while causing it to be easier to score W (or even WW) since the change of rules eliminated *yuko*, and many old *yuko* would be scored as a W by the new rules.

When considering the accumulation of *shido* considering WhCE, results showed that during BRT, the most frequent result in a contest was tied at zero *shido*, and the least frequent was a tie at two *shido*. In this regard, more contests ended with the winning athlete having fewer *shido* than the defeated. During FRT, contests ending with the winner having more penalties than the other judo athlete were the most frequent results, followed by the defeated having more penalties. In that particular order, being tied with one *shido*, at two *shido* and at zero *shido* were less frequent in comparison. The interpretation of FRT contests suggests that winning by W and managing penalties until time runs out was the most frequent scenario. This finding consolidates the hypothesis of Kajmovic et al. [4], who claimed that in certain situations, the athlete could be "saving" penalties for the final period of the contest, reinforcing the hypothesis of a differentiated behaviour of the athlete in FRT contests. Last, EXT showed that the defeated judo athlete accumulated more penalties, as expected. The rest of the possibilities were reduced in frequency.

Contrary to the literature, the judo athlete winning and having more or fewer *shido* depended on WhCE, disagreeing with previous studies' findings [6,15]. This points out the importance of analysing BRT, FRT and EXT contests while studying judo contests since it has a direct implication in strategic planning and tactical execution that coaches and athletes must consider. This includes increasing work time in situations where a result must be maintained, stimulating behaviours where it is more difficult to receive fewer penalties (e.g., throwing techniques where there is less risk of being blocked, grips where there is no risk of being penalised, etc.). Considering the sex category, results showed that men systematically integrated *shido* as a tactical or strategic behaviour in a contest, while for women, this cannot be pointed out following the association observed in the FRT contests and tied at zero *shido*. This suggests that *shido* managing is still an element to include systematically in women's training. Scientific attention to *shido* management is increasing due to the interest in better understanding the dynamics of penalties in winning as they are an essential part of how a judo contest is won [8,15].

This entire scoring and penalty system is continuously affected by the constant modifications of the rules, so general criticism is reported as changes do not attend scientific findings to inform decisions [4–6,8,10,11,15,23–25]. A reflective and scientific process has already been recommended to be implemented before additional modifications are introduced to the sport [25], in which the findings of this study might enlighten a deeper understanding of the issue.

The overall analysis of TUs showed that from WC18 to WC21, contests ending in the first minute (TU1-BRT) and in the third minute (TU3-BRT) decreased, and contests ending in the second minute (TU2-BRT) and fourth minute (TU4-BRT) increased. These results were similar for women and men, except that the percentage of TU2-BRT also decreased for men. Therefore, an increase in contests with longer duration was confirmed, also while analysing women and men separately. The interpretation of our findings suggests that changes in the performance levels of judo athletes, particularly for women, together with rule changes, are causing increases in the duration of the contests, allowing athletes to face longer efforts in better conditions to maintain conditional needs.

The analysis of the TU-GS length (seconds) showed no significant differences from WC18 to WC21 (only for men when both sexes were analysed separately). Some studies have found a longer duration of the contest between 2013 and 2017 due to the change in rules [26]. It was also explained by the reduction from 5 m to 4 m of regular time since the length of GS increased by 3.6% despite the reduction of total regular time [26]. Other studies have found a lower total combat time in the 2016–2020 Olympic cycle than in the 2012–2016 Olympic cycle [22]. Nevertheless, those studies did not consider WhCE when comparing between BRT, FRT and EXT contests. When comparing sex categories including the three championships, a longer length of GS was observed for women, indicating their greater difficulty to score during the additional time. Our findings differed from another study in which no differences between the sex categories were reported [14].

The data were even clearer in the analysis carried out by grouping the competition rounds, similar to Adam et al. [12]. When grouping in PR and FR, there was an underrepresentation of TU1-BRT, TU2-BRT and TU3-BRT in PR and an overrepresentation of TU-FRT and TU-EXT contests in FR, indicating that the contests of higher performance level facilitated the appearance of longer contests. Despite differences in rules (e.g., *yuko* score and 5 m of regular time), the data were consistent with another study conducted at WC14 and WC15 [12]. When considering the sex categories, data of overrepresentation during TU-FRTs were not found for women, suggesting differences in managing the contest. The relationships between WhCE, TUs and rounds should be also taken into consideration in training. This is because the probabilities of ending in a particular BRT, FRT and EXT contest or TU while considering the round should also guide athletes' tactical and strategic decisions in their training and inform physiological needs, such as aerobic and/or anaerobic capacity or the capacity to maintain strength over time [27].

Last, and as was observed in a previous study [28], there was an overrepresentation of W during FR and an underrepresentation of W during PR, indicating that HwCE was modified during the championship and therefore should also inform tactical and strategic decisions since the chances on how the judo athlete is going to win or lose are going to change [12].

Considering all the evidence found, it should be noted that the contest duration was increasing while more contests ended during EXT. This incapacity to reduce contest duration and thus increase dynamism has already been shown in a previous study [26], suggesting IJF is not fulfilling its objectives of implementing a more positive judo. At the same time, more contests ended by WW, which was contrary to the spirit of judo in which I should be pursued.

The constant modification of the rules [5] and the data shown in this study also confirmed the statements of previous studies; if the rule changes implemented and analysed in 2013 [29], 2016 and 2017 [24] did not provide the desired effects during contests and in judo competition, the new changes implemented since WC18 also do not seem be oriented toward the right direction. One meaningful example of the path that actual judo is taking can be considered through the fact that in 2340 observed contests of the last three World Championships, the athletes who lost their contests only could score 128 W in total, i.e., judo athletes losing a contest only scored during the 0.05% of the contests. Therefore, these simple data should be taken into consideration to decide whether this is the sports model intended to be achieved and that judo is becoming, where the one who loses hardly has the option of scoring, with only a marginal percentage of chance. In addition, since *yuko* no longer exists, many throwing techniques that have been scored as W would actually have been *yuko* [23], so if W and I are similar, regarding the effect on the chances of winning a contest, and many W have the quality of the old *yuko*, can we assume that the last rule change as a whole has brought I closer to *yuko*, and thus, the quality of the sport of judo is diminishing?

It is possible that the modification of the rules (which also aimed to increase the dynamism and to reduce the duration of the contests) has not achieved either of the intended objectives since our data confirmed an opposite trend when verifying that in three World Championships, the percentage of contests that were decided in the GS increased, and the percentage of FRT contests remained constant (therefore, BRT contests decreased). Moreover, this attempt to reduce contest time by modifying the rules has been continuous for years, and its failure has already been shown in previous studies [5,14,26].

Extracting this valid and essential information should be the foundation that must guide future decisions regarding changing judo rules by the IJF as these changes substantially affect the planning, programming and execution of strategic and tactical behaviours and physical conditioning needs by coaches and judo athletes.

The results of the current study might be affected by the consequences of the worldwide epidemic of COVID-19. Therefore, the judo athletes could not develop their regular training programs to the full extent during the epidemic.

5. Conclusions

The formulated hypotheses were accepted. Most contests in elite judo were ended BRT, followed by EXT and FRT. Between WC18 and WC21, the number of EXT contests increased. Most contests were won by I, followed by W, WW and SH3. Between WC18 and WC21, the number of contests finishing by WW increased. Regarding the accumulation of *shido*, during BRT, more contests ended with the winning athlete having fewer *shido* than the defeated, while during FRT, more contests ended with the winner having more penalties than the other judo athlete. From WC18 to WC21, contests ending in the first and third minutes decreased, while contests ending in the second and fourth minutes increased. The analysis of the GS length in temporal terms (seconds) showed no significant differences from WC18 to WC21, while a longer length of GS was observed for women compared with men. When considering the rounds, BRT contests were overrepresented in R1 and R2, while EXT were overrepresented during RP, SF, BZ and FL, indicating that the WhCE depended on the round of the contest. There was an overrepresentation of W during FR, while an underrepresentation of W was observed during PR, indicating that HwCE was also modified during the championship.

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applied sciences

Article

Defining the Influence of Fatigue Protocol on Kinematic Parameters of Ippon Seoi Nage

Marko Cetinić, Vedran Dukarić *, Ivan Segedi, Tomislav Rupčić and Hrvoje Sertić

Faculty of Kinesiology, University of Zagreb, 10000 Zagreb, Croatia
* Correspondence: vedran.dukaric@kif.unizg.hr

Abstract: To achieve technical efficiency in a judo fight, it is necessary to know the technical details of each throw. The tempo of a judo fight is highly intense, and it is necessary for the competitor to be physically very well prepared. Considering the tempo, an important factor in the fight is the influence of fatigue, which can significantly affect the performance of a technique. The aim of this research is to determine the kinematic parameters and the influence of the fatigue protocol during the performance of ippon seoi nage (ISN) throw. The sample of participants consists of 30 young judokas (17.02 ± 0.91 year; 72.81 ± 6.52 kg; 178.60 ± 5.60 cm). The following variables were observed with Xsens Awinda kinematic system: the angle of the left shoulder (L_shou_A); the angle of the right shoulder (R_shou_A); the difference in the height of the pelvis in the tsukuri phase (Pel_tsu_H); the difference in the height of the pelvis in the kake phase (Pel_kake_H); hand velocity (Hand_V); head position (Head_pos). The participants performed three ISN throws before and after the fatigue protocol. A statistically significant difference (MANOVA) was found between the measurements ($F = 8.47$; $p = 0.00$). Additionally, observing the differences between individual variables (ANOVA), a significant difference was found in all measured variables, with a statistical significance of $p < 0.05$. This research presents key kinematic parameters that had not yet been observed in this manner. Furthermore, based on the established differences, it can be concluded that the participants significantly disrupt the performance of the ISN throw technique in situational, i.e., fight, conditions.

Keywords: hand throw; judo; kinematic analysis

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1. Introduction

Technical efficiency, in addition to conditioning, is an important factor for success in judo, a very complex sport of high intensity [1]. In order to overcome an opponent, a judoka must execute an offense technically correctly and quickly in order to score points and throw the opponent during a fight. Observing a fight structurally, by dividing it into a fight in a standing position and a fight in the parterre, most actions, offenses, and defenses take place in a standing position. Consequently, the highest points are achieved in a standing position by applying throwing techniques [2–5]. A large number of throwing techniques that a judoka can perform during a fight make this sport demanding and complex. However, research shows that certain throws are performed more often by judokas in fights. During a fight, after the kumikata, that is, grip fighting, the competitor tries to build a situation from which he will be able to launch an offense in order to overcome the opponent [6]. Since the tempo of the fight is highly intense, it is necessary for the competitor to be physically very well prepared. In situations where the fight between two judokas is tied, the result depends on who will be more affected by fatigue, while still being able to perform the throwing technique correctly [7,8]. Biomechanical analysis contributes to a better understanding of throwing techniques [9–14]. The aforementioned studies are focused on the analysis of throwing techniques by observing kinematic parameters, while a smaller number are focused on observing movement kinetics. This may be caused by the fact that it is currently very demanding to observe the elements of technique in situational conditions [12]. Furthermore, research focused on the study of kinematics (throwing techniques) has not yet proposed a biomechanical model, i.e., an ideal throwing model, or its modal values. There are multiple factors that contribute to this fact. One of the most important is that the assessment of the biomechanical characteristics of throwing techniques cannot be performed under real conditions. Instead, various systems have used, mainly cameras, markers, judo clothing (or lack of), and modified trainers under strictly controlled conditions [9–14]. Consequently, parameters that would contribute to a better understanding of judo throws cannot be detected or accurately measured. Given that judo consists of numerous elements, the need for a more exact definition of spatial and temporal parameters is becoming more and more important. The use of inertial sensors can make a significant contribution to observing a throwing technique [15]. The authors of [16] studied the uke's angular accelerations in the performance of the 'seoi nage' throw, while those of another study [17] determined the kinematic parameters of falls after the performance of the 'osoto gari' throw. In order for the tori to perform a successful throw, all phases must be completed precisely, quickly, and effectively. This creates the need to define the parameters or variables that most affect the effectiveness of a throw. Along with the correct performance of the throwing technique, an important factor in a fight is the influence of fatigue, which can significantly affect the performance of a technique. Research [18–20] confirms that fatigue significantly affects the performance of a technique of certain sports. Creatine kinase (CK) and lactate dehydrogenase (LDH) activities in plasma strongly reflect muscle injury, as proper biomarkers of muscle fibers disrupture. Furthermore, it was found that CK and LDH indicators increase significantly after a judo fight [21], and have a negative impact on motor abilities. Through segmental analysis of energy consumption, it was found that during the execution of the morote seoi nage throw, the lower extremities are activated the most, followed by the trunk and the upper extremities [22]. Fatigue due to the high intensity of the fight is an aggravating factor that can be alleviated by good conditioning preparation. The high demands of the fight require the judoka to apply a throwing technique when tired in order to either achieve a result or preserve the existing one, without receiving a penalty for inactivity, i.e., a shido. The definition of the parameters of individual elements of technique in judo, and the influence of different fatigue protocols that simulate situational conditions on these elements, need to be explained more clearly. It is also necessary to determine which factors change in the situational conditions of throwing. According to the authors of [23,24], ippon seoi nage (ISN) is one of the most frequently used throws in judo fights; therefore, it was selected as the focus of the here-presented research. This research aimed to determine the kinematic parameters and the influence of the fatigue protocol on the performance of ippon seoi nage throws.

2. Materials and Methods

2.1. Confirmation of the Ethics Committee

Prior to conducting the research, the participants were provided with detailed information about the measurement protocol, the benefits, and the risks of the research. Adult participants were asked to provide written consent for the testing procedure. For participants that were minors, their legal guardians provided consent for the measuring procedure and the use of personal data for scientific purposes. The research was approved by the Ethics Committee of the Faculty of Kinesiology, University of Zagreb, in accordance with the Declaration of Helsinki (Opinion No. 29/2021).

2.2. Participants

The sample of participants (Table 1) consisted of 30 youth judokas (17.02 ± 0.91 yr). With the use of G*power (v 3.1.9.2.) analysis, we calculated the total (N = 90) sample size (number of throws) required to conduct the study with error $p < 0.05$, statistical power of 0.8, effect size of 0.3, and with two measurements. The first inclusion criterion for the research was that participants must have at least a 3rd Kyu green belt degree and be actively competing. Regarding this criterion, participants had at least six years of active judo training and the following belt degrees: 3rd Kyu green belt (N = 5); 2nd Kyu blue belt (N = 9); 1st Kyu brown belt (N = 15), 1st dan black belt (N = 1). The second inclusion criterion for the study was health status (participants should not have had any musculoskeletal injuries in the past year). The participants were asked to avoid intensive activities two days prior to testing. Upon arrival, they were informed of the testing procedure, benefits, and risks during measurement. All judokas were right-handed and were throwing right ISN. Handedness was defined by the hand that is used for writing and is dominant in judo throws. Judokas were of different weight categories (60 kg-N = 1, 66 kg-N = 5, 73 kg-N = 12, 81 kg-N = 11, 90 kg-N = 1) and throws were performed with a uke from the same weight category. Based on previous experience of the participants and skilled performance of ISN, similar weight categories included in the research would not affect the presented results.

Table 1. Basic descriptive statistics of the participants (n = 30).

	N	Mean	Min	Max	St. Dev.
Weight (kg)	30	72.81	58.7	83.9	6.52
Height (cm)	30	178.6	169.6	190.6	5.6
Age (year)	30	17.02	15.11	18.6	0.91

2.3. Measurement Protocol

The measurement protocol begins with the definition of basic anthropometric characteristics and measurements necessary for the calibration of the kinematic system. The participant is then fitted with a kinematic suit, and the standardized warm-up protocol begins. The protocol consists of general preparatory exercises that include all parts of the body, ukemi waza (falls), and three methodical exercises: uchi komi, pushi gari, and nage komi (the studied throwing techniques). At the end of the warm-up, body and space calibration is carried out according to the previously defined protocol. The measurement and fatigue protocol were supervised by an expert laboratory researcher and the head of research. Testing was performed from 9–12 AM for 10 consecutive days (three participants per day) in the Judo hall at the Faculty of Kinesiology, University of Zagreb. Furthermore, the subject begins with the performance of ippon seoi nage (ISN) by throwing (Figure 1). Three consecutive throws are performed, with a pause between the throws lasting until the uke is raised and the starting position of the throw is taken. Upon completion of the initial set of throws, the tori performs the fatigue protocol. Immediately upon completion of the fatigue protocol, three consecutive ISN throws are again performed. The fatigue protocol consists of a 2 × 10-m shuttle run, at the end of which the participant performs two push-ups (Figure 1). This protocol is repeated for 10 cycles, and is used as measuring instrument to evaluate endurance in judo. After the 10th cycle, the examinee stands up and the test is ended. The total time required to perform the test is measured [25].

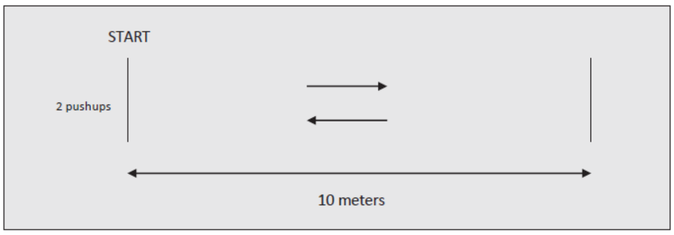
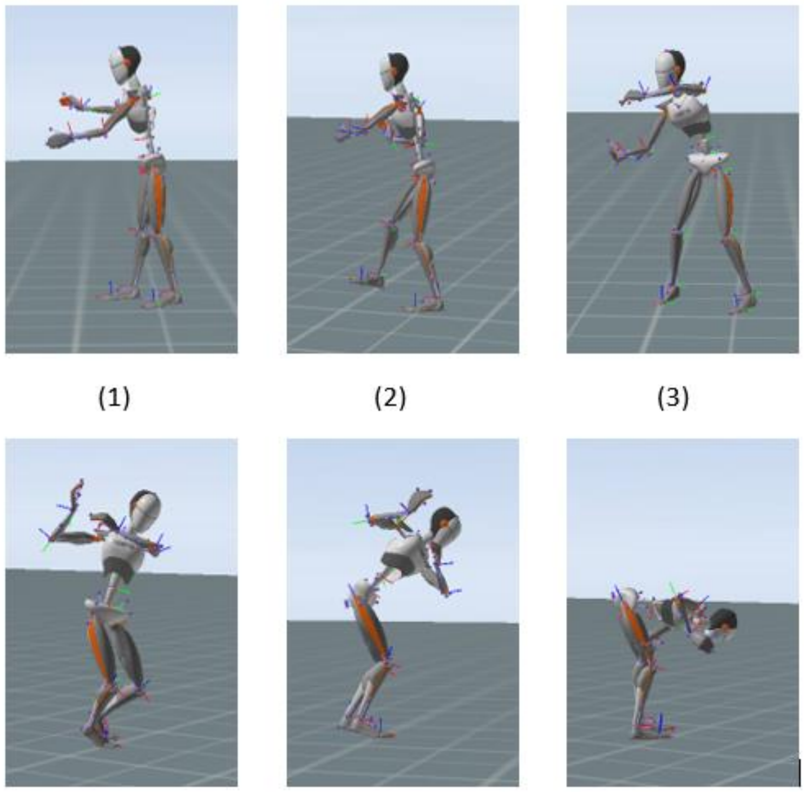


Figure 1. Specific endurance judo test [25].

The ISN throw was performed in place, without the uke's resistance (Figure 2). From the starting position (1), the tori moves forward with his foot. With both hands, he pulls the uke forward and up, breaking his balance (kuzushi, phase 1) (2). At the same time as he performs the kuzushi, the tori begins to perform the second phase of the tsukuri throw (3). Through the mae mawari sabaki movement, he turns his body 180 degrees and places it in the correct throwing position (tsukuri) (4). The final phase (5) of throwing (kake) follows, and it includes the uke's flight and the uke's control. The throw is finished (6) when the uke falls to the ground, while the tori must remain in a balanced position, and thus not fall forward (end of throw).



(1) (2) (3)

(4) (5) (6)

Figure 2. The performance of the ISN throw: (**1**) starting position; (**2**) kuzushi; (**3**) tsukuri; (**4**) tsukuri; (**5**) kake; (**6**) end of throw.

2.4. Materials

For the purposes of calibrating the system, i.e., the subjects and the measuring space, anthropometric characteristics were measured using a segmometer (Xsens MVN measuring tape), and a portable stadiometer (SECA 213). A TANITA scale (BC-545 n) was used to measure morphological characteristics (mass, fat tissue percentage, body mass index). Participants were instructed to stand barefoot on the scale with lower legs and thighs not touching. The skin and electrodes were precleared and dried before the measurement procedure [26]. The general measurement guidelines for bioelectrical impedance were followed [27]. A stopwatch (Witty Timer, Microgate, Bolzano, Italy) was used to measure the time required to perform the fatigue protocol, while a Polar H10 sensor connected to the Polar team application was used to measure the heart rate. The Xsens (Awinda, Enschede, Netherlands) kinematic system was used to observe the performance technique, i.e., the kinematic parameters of throwing (Xsens technologies BV, The Netherlands). Software package Xsens MVN ver. 2021.0. was used to process and analyze the measured parameters. Previous studies [28–30] confirm the reliability and validity (coefficient of multiple correlation > 0.96 for joint angle in flexion/extension) of the measurement system for observation and the possibility of its application in combat sports. Body and space calibration was carried out before the actual measurement procedure, according to a previously standardized protocol [31] provided by the manufacturer.

2.5. Variables

The kinematic parameters observed in the present research are the angle of the left shoulder (L_shou_A); the angle of the right shoulder (R_shou_A); the difference in the height of the pelvis in the tsukuri phase (Pel_tsu_H); the difference in the height of the pelvis in the kake phase (Pel_kake_H); hand velocity (Hand_V); head position (Head_pos). These variables were chosen as they present key factors in different phases of ISN throw.

Description of variables:

1. L_shou_A (°)—the phase of ejecting the uke from the balance position (abduction); the angle of the left shoulder represents the angle between the upper arm and the torso, which is achieved when pulling the uke's kimono sleeves in the kuzushi phase.
2. R_shou_A (°)—the phase of entering the throw and taking the optimal position for performing the throw (abduction): the angle of the right shoulder represents the angle between the upper arm and the tori's torso, which is present in the final phase of tsukuri, in which the right upper arm is placed under the uke's upper arm and ensures that the next phase of the throw is performed with complete control and high speed.
3. Pel_tsu_H (cm)—The difference in the height of the pelvis from the initial position to the final point of tsukuri, i.e., the moment when the pelvis is at its lowest point, and before the beginning of the upward lift, i.e., the beginning of the kake phase.
4. Pel_kake_H (cm)—the difference in the height of the pelvis from the lowest position in the tsukuri phase to the end of the throw (contact of the uke's body with the mat).
5. Hand_V (m/s)—maximum speed of the hand during the throwing phase.
6. Head_pos (cm)—the difference in the position of the head during the throwing phase (from the lowest position during the entry into the throw to the end of the throwing phase (kake))

2.6. Data Processing Methods

The Statistica v.14.0.0. (TIBCO software Inc.) software package was used for statistical data processing. The Shapiro–Wilk test was used to determine normality of distribution. Basic descriptive parameters (mean, minimum, maximum, and standard deviation) were calculated for all observed variables. Multivariate analysis (MANOVA) for repeated measures was used to determine difference between groups, and ANOVA for repeated measures was used to observe changes in variables. A total of 90 throws were observed before and after the fatigue protocol.

3. Results

The results of the basic descriptive indicators of ISN throwing before and after the fatigue protocol are presented in Table 2. During the implementation of the fatigue protocol, the average values of the heart rate (HR) were 188.17 ± 7.24 (Min = 177; Max = 202). The average results in the fatigue test were 86.16 s ± 5.26 s (Min = 78.70 s; Max = 100.91 s).

Table 3 shows the differences between the observed groups, that is, the kinematic parameters of the ISN throwing performance before and after the fatigue protocol. Significant differences were found between the observed groups (F = 8.47; p = 0.00). Considering the statistical significance of the differences, univariate analysis of variance was used to observe the differences between individual variables (Table 4). The statistical significance of the differences was determined in all the presented variables.

Table 2. Basic descriptive indicators of the observed kinematic parameters during the performance of the ISN throw.

	Protocol	N	Mean	Minimum	Maximum	St. Dev.
L_shou_A	Pre	90	29.92	3.36	57.23	14.02
	Post	90	19.76	−20.89	58.79	17.31
R_shou_A	Pre	90	44.89	14.68	88.21	16.81
	Post	90	37.65	13.04	76.24	15.10

Table 2. *Cont.*

	Protocol	N	Mean	Minimum	Maximum	St. Dev.
Pel_tsu_H	Pre	90	14.80	6.12	29.50	4.62
	Post	90	11.93	1.46	21.49	4.34
Pel_kake_H	Pre	90	12.60	−3.24	26.74	6.02
	Post	90	9.84	−2.58	22.72	5.21
Hand_V	Pre	90	3.37	1.91	5.47	0.88
	Post	90	2.45	0.55	5.82	1.30
Head_pos	Pre	90	65.02	25.79	84.44	10.94
	Post	90	68.87	39.10	104.07	13.25

Legend**:** **L_shou_A**—the angle of the left shoulder; **R_shou_A**—the angle of the right shoulder; **Pel_tsu_H**—difference in the height of the pelvis in the tsukuri phase; **Pel_kake_H**—difference in the height of the pelvis in the kake phase; **Hand_V**—hand velocity; **Head_pos**—head position.

Table 3. Results of MANOVA for repeated measures between the observed groups before and after the fatigue protocol.

	Test	Value	F	*p*	η^2
Group	Wilks	0.77	8.47	0.00 *	0.23

Legend: Value—Wilks' Lambda value; F—F value distribution; p—significance level; η^2—partial eta squared (measure of effect size). * Values are significant when $p < 0.05$.

Table 4. Results of ANOVA for repeated measurements for a single variable.

Dependent Variable	F	*p*
L_shou_A	18.73	0.00 *
R_shou_A	9.23	0.00 *
Pel_tsu_H	18.54	0.00 *
Pel_kake_H	10.76	0.00 *
Hand_V	30.85	0.00 *
Head_pos	4.52	0.03 *

Legend**:** **L_shou_A**—the angle of the left shoulder; **R_shou_A**—the angle of the right shoulder; **Pel_tsu_H**—difference in the height of the pelvis in the tsukuri phase; **Pel_kake_H**—difference in the height of the pelvis in the kake phase; **Hand_V**—hand velocity; **Head_pos**—head position. * Values are significant when $p < 0.05$.

4. Discussion

This research aimed to determine the influence of the fatigue protocol on the performance of ISN throws. The main findings of the presented research comprise the changes in kinematic parameters under fatigue conditions. As these conditions are similar to specific situations in judo combat, the stated results highlight the importance of understanding how fatigue conditions affect the performance of an ISN throw.

Ippon seoi nage is a throw that requires a significant level of connection, speed, timeliness, and technical excellence from the tori, in order to effectively apply it in situational conditions. Compared to other throws (osoto gari, harai goshi), in ISN performance, the influence of the tori's force on the uke is reduced, and more of the tori's own abilities, such as speed and explosive power, are applied in order to take the ideal position for throwing the uke [9]. Consequently, there are several studies on the kinematics of ippon seoi nage throwing. The goal of this research was to determine how fatigue protocol affects the observed performance parameters of ippon seoi nage throwing in all phases. By comparing HR values (188.17 b/min) with the results of a judo fight (174–185 b/min) [32], it can be concluded that the fatigue protocol made it possible to simulate conditions, i.e., fatigue manifested during a fight. The kinematic parameter data show that there is a statistically significant difference in all observed variables when performing the ISN throw before and after the fatigue protocol. Therefore, it can be concluded that the observed kinematic parameters are significantly affected in the simulation of situational conditions. Since, as with most previous studies [9,14,20–23], the throw was performed without the resistance of the uke, it can be assumed that with his resistance, it would be even more difficult to maintain the observed parameters at an optimal level. A judo fight in senior and junior competition lasts four minutes, during which both fighters are significantly exhausted. A fighter who, despite being exhausted, manages to perform throwing techniques at a technically higher level will certainly have a lower expenditure of energy and, at the same time, be at an advantage over his opponent. A drop in skill level leads to a whole series of difficulties in the kinematic chain responsible for throwing. The authors of [33] proved that fatigue due to a competitive judo fight affects the kimono grip strength in the right and left hand, as well as during simulated judo fights, i.e., during training. Since it is important not to lose control over the uke's kimono grip throughout all three phases of performing the ISN throwing technique, it is important to understand the connection between fatigue, a drop in the level of ability, and the disruption of kinematic parameters in the performance of throwing. Furthermore, poor execution of the throw under the situational conditions can lead to injury. According to previous research [34], in top-level judokas, the highest number of injuries occur in a standing position during the competition (78.0%), of which 22.3% are inflicted on the tori during throw performance. In the ISN throw, the majority of injuries relate to lower body extremities [35]. We state that highly trained judoka able to conduct the technically correct performance of the ISN have reduced risk of injury. Regarding muscle injury during competition, recent findings have shown that (MMA) fighters already present tissue injury and initiated inflammatory processes at the end of a competition [36,37]. Therefore, complex (metabolic) fatigue, such as complicated physiological status, during competition could also affect the mechanics required for the perfect application of the ISN throw in judo matches.

Kinematic parameters should not be viewed in isolation, but as an interconnected kinematic chain that leads to a successful throw. Disturbance or poorer performance in one part entails the need for compensatory actions in another part of the kinematic chain, and with it the overall reduced efficiency of the throw itself. The variable L_shou_A indicates the angle of the shoulder that occurs in the kuzushi phase, and is important because it disrupts the opponent's balance. A larger angle of the shoulder means a stronger action of the tori's left hand and, at the same time, raising the uke's COM to a higher level, which will enable the tori to be placed in a better position in the tsukuri phase. In this case, the values of the observed variables R_shou_a and Pel_tsu_H will be higher. This indicates the tori's lower position in the tsukuri phase and points precisely to the correct principle of performing the ISN throw. After the fatigue protocol, the angle of both shoulders in the observed variables decreases. In some participants, it decreased so much that they did not use their left hand at all in the initial phase of throwing when the uke's balance was disturbed. Since the uke does not resist, it can be assumed that in a fight without such an action, i.e., a quality kuzushi, the tori would not be able to perform a quality tsukuri. Consequently, such an attempt would end without the possibility of performing the final phase of the kake throw, or even with the performance of a counter throw by the opponent.

Observing the results of the L_shou_a variable before and after the fatigue protocol, it is evident that the differences between the minimum and maximum values are greater after the protocol, indicating that the differences between the subjects are increasing. It seems that some participants still managed to maintain the size of the angle of the shoulder at a slightly better level even in a state of exhaustion, which is exactly what training should achieve—technical excellence even in the zone of high physiological load in combat. Similar findings have been reported by Ishii et al. [14], who assert that there are differences between different groups of judokas in shoulder rotation, observing it as the angle between the axis of the uke's left and right shoulders and the axis of the tori's left and right shoulders in the kuzuhi and tsukuri phases.

Pel_tsu_H indicates how far the tori has descended under the uke at the end of the tsukuri phase. It was observed that the parameters change significantly after the fatigue protocol (F = 18.54; p = 0.00), but also that there is a large range in the participants from the minimum to the maximum result. Ishii et al. [14] observed that better trained judokas have a greater knee angle in the tsukuri phase than weaker judokas. The greater angle of the knee observed in that research is in direct positive correlation with the observed variable Pel_tsu_H, i.e., both indicate how much the tori has dropped below the COM uke in the tsukuri phase.

According to Melo et al. [38], when performing the ISN throw, the easiest way to perform it on a uke either taller than the tori or his height. A difference in the angle of left and right knee flexion was observed in the tori with a taller partner or one of the same height compared to a shorter uke. In this research, the participants were divided into pairs according to height and weight, and they performed the throw against each other. Certain results indicate a higher value of the pelvis in the kake phase compared to the tsukuri phase, which is a consequence of fatigue or compensation of the body segments (the throw is performed entirely by moving the body forward and swinging the arms). Similar results were obtained by Immamura et al. [9] where it was observed that the COM goes up or stays in the same position in the majority of participants, and in some it went down. According to Blais et al. [22], during a seoi naga throw in the tsukuri and kake phase, due to the heavy load, the legs and torso are most energetically involved, while the arms are dominant in throwing off balance and performing the throwing technique. These results are justified since the tori enters the crouching position and then lifts the uke out of the crouching position and throws him over himself using the strength of his trunk and arms. It was observed that before the fatigue protocol, the tori lowers his pelvis (Pel_tsu_H) and uses more the moment of lifting the uke with the hips off the floor (Pel_kake_H) and the hand speed (Hand_V). He also moves less into a forward bend (Head_pos), and thus is less rational, faster, and uses his body segments more efficiently, while remaining in a balanced position after the throw. The importance of the head position (Head_pos) during the throw defines how much the tori moves the upper part of the body into a forward bend, from the tsukuri phase to the kake phase, and whether he uses more body or hand influence when throwing the uke. ISN is a hand throw, and it is assumed that during the kake phase, the explosive power and speed of the arm and shoulder girdle muscles will be used more. This will be manifested in the parameters of the hand speed variable. It has been observed that some participants (Head_poss max.) use too much forward bend when throwing. This can lead to falling forward, which can give the uke an opportunity to turn the fight in his favor after the transition to the ground with a counterattack. Other authors [19,39,40] have studied the speed of the general center of gravity of the body and concluded that in the kuzushi and tsukuri phases, better judokas have a higher COM speed. However, they did not observe whether there is an influence of fatigue on their performance. Ishii et al. [23] also studied the joint speed in the kuzushi and tsukuri phases in from-the-spot throws between judokas of different quality. They found that there is a difference in the speed of the hip and ankle, but not in the speed of the shoulder and hand. In the present research, the speed of the hand was studied in each phase, and it was determined how fatigue affected this variable. It is interesting that there is a greater range in the studied velocity after the fatigue protocol with a greater minimum and maximum value. Some participants used their trunk to a greater extent by bending forward and less hand speed, while some used less forward bending and used their arms more for throwing. These differences confirm the assumption that better judokas manage to maintain the level of their technical efficiency at a higher level even in the fatigue phase.

As this research mainly focused on the influence of fatigue protocol, the limitations of the study relate to the lack of physiological parameters observed in testing procedure. Fatigue protocol could be implemented via a simulated judo fight with additional physiological parameters, such as blood lactate, to obtain even better insight into the associations between fatigue and technique performance in judo. Additionally, the fact that the tori performs throws without the uke's resistance is a limiting factor to achieving more exact conclusions about the kinematically ideal throwing performance. Additionally, observing these parameters between high-level and low-level judokas would provide more detailed insight into the differences in relation to the level of technical excellence.

5. Conclusions

The analysis of the technique of individual elements in judo is extremely important for a clearer understanding of spatial-temporal phenomena. Furthermore, fatigue is one of the factors that significantly affects throwing performance. The aim of this research was to determine the negative effects under the influence of the fatigue protocol. This research presents the key kinematic parameters that have not, until now, been measured in this manner. Additionally, by observing these variables, it can be concluded that the participants significantly violate the technique of performing ISN throws under situational or fighting conditions. Therefore, it is necessary to focus on the throwing performance in the training process under conditions of similar physiological load as in a competitive fight. Further research in the field of kinematic analysis and the influence of fatigue, and that also includes female judokas, is necessary to understand changes in technical performance. Certainly, future research should consider the study of throwing in motion, that is, simulated combat conditions that are dynamic with various changes in the direction of movement.

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

Data Availability Statement: Not applicable.

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Article

Contributions of Body Segments to the Toe Velocity during Taekwondo Roundhouse Kick

Taewoon Jung [1] and Hyoungjin Park [2,*]

1 Department of Physical Education, Yongin University, Yongin 17092, Korea
2 Department of Physical Education, Humanities & Arts, Korea Science Academy of KAIST, Busan 47162, Korea
* Correspondence: hjpark79@ksa.kaist.ac.kr

Abstract: The roundhouse kick is the most commonly executed kick in Taekwondo competitions. Because it is the fastest kick among kicking techniques and can easily change its motion on the basis of the opponent's motion, the roundhouse kick is suitable for scoring points. To explore the functional role of segmental movements during the roundhouse kick, this study aimed to investigate the effects of various footwork techniques on biomechanical contributions of body segments to toe velocity during roundhouse kicks. Ten elite Taekwondo athletes performed roundhouse kicks with different footwork positions. The contributions of body segments to the toe velocity were obtained through 3D motion analysis. Results were compared by repeated measures analysis of variance (ANOVA), and there were significant differences in the contributions of whole-body movement, trunk movement, trunk rotation, and toe velocity. It was concluded that in the minimum knee flexion (MKF) event, for all types of footwork, thigh rotation showed the most significant contribution (51–64.4%), followed by trunk rotation (16.7–29.9%) and whole-body movement (5.1–13.4%). However, in the impact event, the contribution of thigh rotation decreased, while the contribution of calf rotation increased significantly.

Keywords: motion analysis; biomechanics; combat sports; footwork

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1. Introduction

Taekwondo is a Korean martial art and sport practiced by approximately 80 million people worldwide [1]. During Taekwondo sparring matches, competitive Taekwondo athletes use kicking techniques more frequently than punches because kicking allows for a broader range of attacks [2–4]. The roundhouse kick is the most commonly used kicking technique in matches [5] because it can be easily changed according to the opponent's movements and is appropriate for scoring points in an unpredicted attack [6]. According to Pieter and Pieter [7], the roundhouse kick is the fastest kick, which could explain why roundhouse kicks are used the most in competitions. According to previous research, winners of the National Taekwondo competitions use more counterattacks [8]. Therefore, it is natural that Taekwondo athletes often use roundhouse kicks as a counterattack skill in response to their opponent's attack.

The roundhouse kick is executed by raising the kicking leg's knee in a chambered posture, rotating the hip, and extending the knee in a snapping-forward movement to attack the opponent [9]. The kicking leg delivers the kick, while the supporting leg bears the weight of the body and allows for hip pivoting. The trunk and the supporting leg are critical for stability and countermovement to maintain kick balance during kicking [6]. Characteristic Taekwondo stances with the lower extremities forward and back along the direction of attack can be switched back and forth during a sparring match [10]. Stepping back and forth is called footwork, and it has a significant impact on roundhouse kick performance during counterattack procedures [11]. When an opponent attacks from an open stance, the defender frequently counterattacks after taking a step back. If the attacker uses a long kick, the defense should take a longer step back to counterattack. Likewise, if the opponent uses a short kick, the defender should take a shorter step back [10]. Therefore, Taekwondo athletes should control the degree of step back according to the opponent's kick range in order to avoid giving clean hits to the opponent while also being able to execute fast roundhouse kicks as counterattacks [3].

The most critical factor in Taekwondo's fast kick is the contact velocity at the time of striking. In order to achieve maximum velocity, the cooperation of body segments is essential [12]. When the force, energy, velocity, etc. produced by the central body or the lower extremities are optimized and sequentially added or transmitted to the distal segment, the energy and velocity of the segment's end can be increased [13]. Even in Taekwondo kicks, the velocity of the foot segment is affected by the other adjacent body segments at the moment of striking the target [14]. Kim [15] concluded that the rational transfer of mechanical energy from the pelvis to the thigh, lower leg, and foot in the kicking leg is an essential factor in determining the impact force and the toe velocity at the time of striking. In this kinetic chain process, it is critical to explore each body segment's contribution to understand the possible influence of the segment's movement on roundhouse kick performance and practical training methods. Despite the roundhouse kick's intriguing dynamic properties and prevalence in Taekwondo, data on the comprehensive functional role of body segmental movements during the roundhouse kick are lacking.

Research on the roundhouse kick so far has investigated a diverse range of biomechanical variables, such as execution time [4,16,17], impact force [4,16,18], kicking velocity [17], and anticipation timing [19]. Researchers have also focused on the characteristics of participants: the skill level of the participants [20], the effect of fatigue [21], and weight category [22]. Furthermore, previous studies have explored the trial conditions, such as the effect of the backstep [3], the dominant leg [9,17], stance positions [22], kicking foot [23], and the effect of target variables [6,24,25]. However, scientific knowledge of the contribution to Taekwondo kicks is still quite limited. Furthermore, to date, no studies have included the footwork (back-step) or the contribution of the body segments in the analysis. Therefore, this study aimed to investigate the effects of various footwork techniques often used in games on the biomechanical contributions of body segments to toe velocity during Taekwondo roundhouse kick performances. The study was designed to provide answers to the following questions: 1. What is the contribution of the body segments to the toe velocity in Taekwondo roundhouse kicks without footwork? 2. How do different footwork (one-foot backstep) angles affect the contributions of the body segments to the toe velocity in the Taekwondo roundhouse kick? 3. How do different footwork (backstep with both feet) distances affect the contributions of body segments to the toe velocity in the Taekwondo roundhouse kick? 4. Is there a change in the toe velocity with different footwork techniques?

2. Materials and Methods

2.1. Subjects

In this study, ten male Taekwondo athletes participated. The participants' average body mass, height, age, and Taekwondo career years were 60.6 ± 3.7 kg (54.9–66.7 kg), 173.1 ± 4.3 cm (167.0–179.0 cm), 21.7 ± 0.5 years (21–22 years), and 8.91 ± 1.1 years (7–10 years), respectively. Furthermore, in the six months before the trial, all subjects were free of muscular severe or joint/ligament disorders. The study was approved by the university's institutional review board, and written informed consent was obtained from all participants. An a priori power analysis determined that to provide 99% power with an effect size of 2.59 at $a = 0.001$, ten participants were required to detect differences. The data used for the estimates were the results of the peak velocity in the transverse plane during a Taekwondo roundhouse kick reported in a study that was conducted by Estevan and colleagues on segment velocity [14].

2.2. Instrumentation

The positions of the reflective markers on the participant's extremities and trunk were captured using an MX-13 Vicon^{TM} motion capture system (Vicon, Ltd., Oxford, UK), which included 7 high-speed (250 Hz) cameras and MX control. On the basis of the direct linear transformation (DLT) approach [26], a calibration mount with 36 control points (1 m width, 2 m height, and 2 m length) was utilized for calibration. The kicking direction was employed as the sagittal axis (Y), the longitudinal axis (Z) was aligned vertically upward, and the transverse axis (X) was aligned left to right in the calibration frame.

Thirty-eight reflective markers with diameters of 14 mm were applied to particular body landmarks of the participants and the target for kinematic analysis. The 38 markers' three-dimensional coordinates were recreated using the Kwon3D program (Version 4.1, Visol, Seoul, Korea). A double-handed target mitt (All-Star®, Tae Hwa Sports, Seoul, Korea) was leveled to the participant's abdomen and tilted slightly for easy kick performance. One reflecting marker was placed on the target to determine the beginning of foot contact with the target. The 37 reflective markers were located at the following anatomical positions (Figure 1).

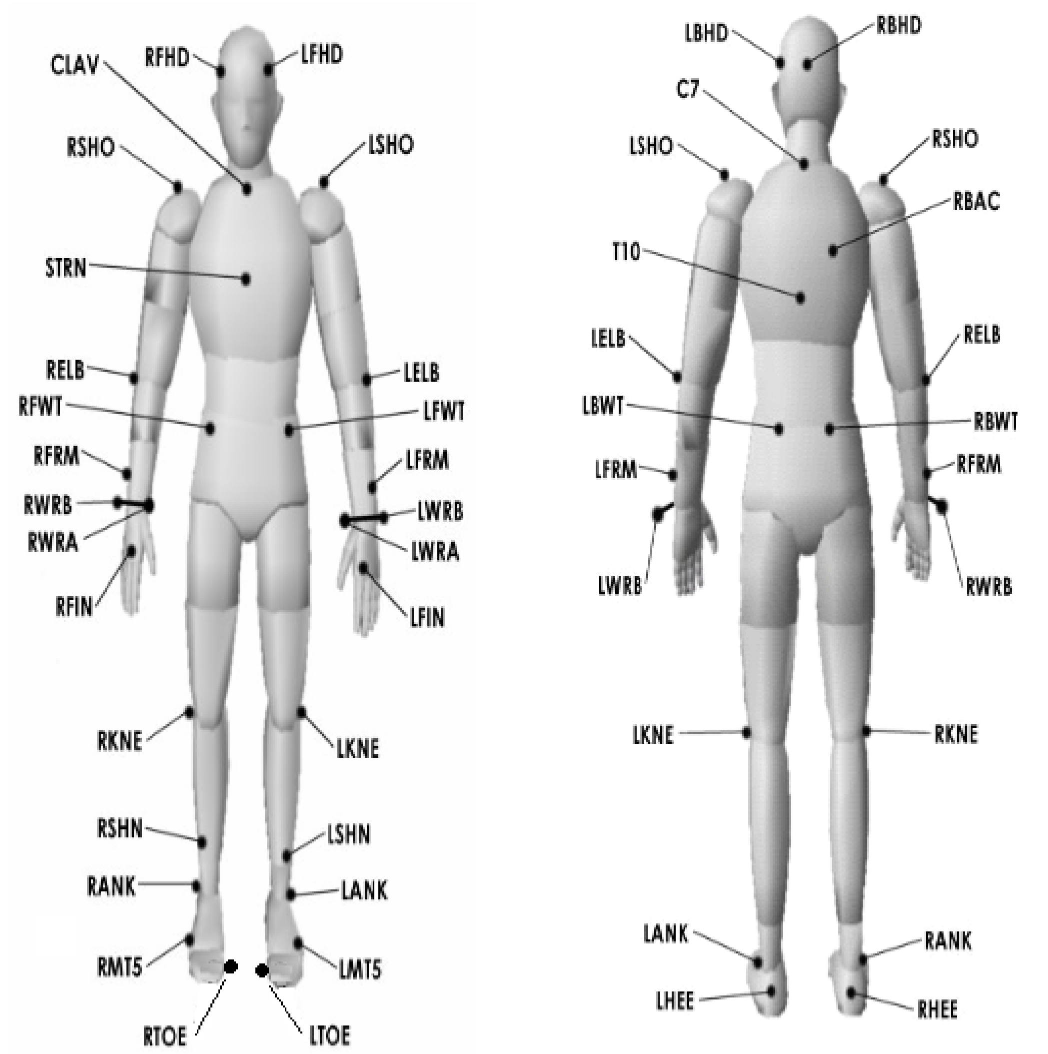

Figure 1. The locations of reflective markers.

2.3. Experimental Procedure

Warming up for the roundhouse kicks was allowed. After warming up, the participants performed their favorite stretching, stepping, and kicking. For the angle-change footwork, textured marks were placed on the ground for each angle so that participants could become familiar with each angle. All participants practiced until they were comfortable with the specific angles and lengths of the backsteps. The participants were then instructed to perform a kicking process that included footwork followed by a roundhouse kick to strike the target mitt as quickly as possible with a bare foot immediately after the flashing LED light. Five trials were conducted with a 5 min break before the subsequent trial's data collection.

2.4. Trial Conditions

2.4.1. The Roundhouse Kick without Footwork

As shown in Figure 2, all participants performed the roundhouse kick without footwork. All participants were right-footed; therefore, the left leg was the supporting leg, while the right was the kicking leg in the trials.

Figure 2. The roundhouse kick without backstep.

2.4.2. Roundhouse Kicks with Angle-Change Types of Footwork (One-Foot Backstep)

The participant's left foot became a pivot point in the one-foot backstep movement. Six conditions were used, as follows (Figure 3):

- the preferred backstep (PBS) roundhouse kick, in which the participants used their preferred angle;
- one-foot backstep roundhouse kicks at different angles (0°, 22°, 45°, 67°, and 90°).

The angles between the left foot and the x-axis clockwise were 0°, 22°, 45°, 67°, and 90°. The preferred target distance of each participant was used.

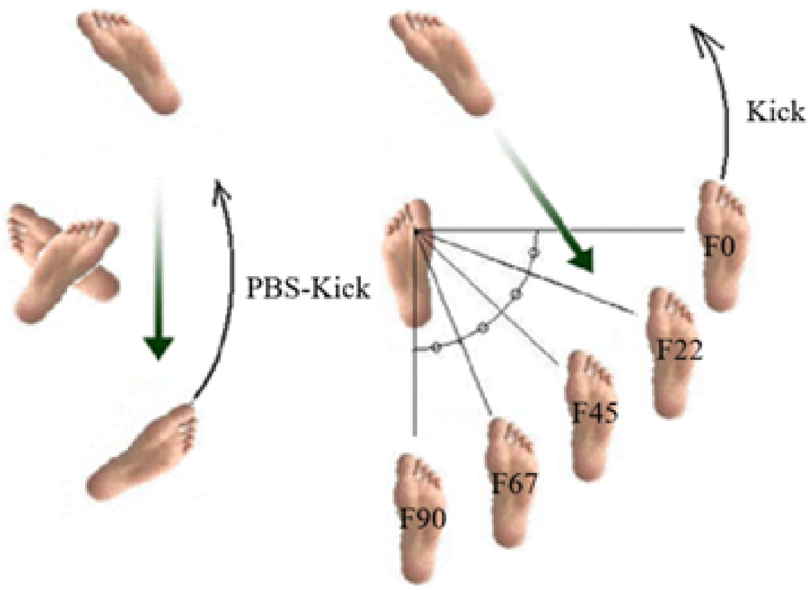

Figure 3. Angle-change types of footwork.

2.4.3. Roundhouse Kicks with Distance-Change Types of Footwork (Backstep with Both Feet)

Five conditions were used, as follows (Figure 4):

- a roundhouse kick with a preferred-distance backstep with both feet (PBS);
- a roundhouse kick with a short-distance backstep with both feet (SBS);
- a roundhouse kick with a long-distance backstep with both feet (LBS);
- a roundhouse kick with a short-distance double-backstep with both feet (SDBS);
- a roundhouse kick with a short-distance double-cross-backstep with both feet (SDCBS).

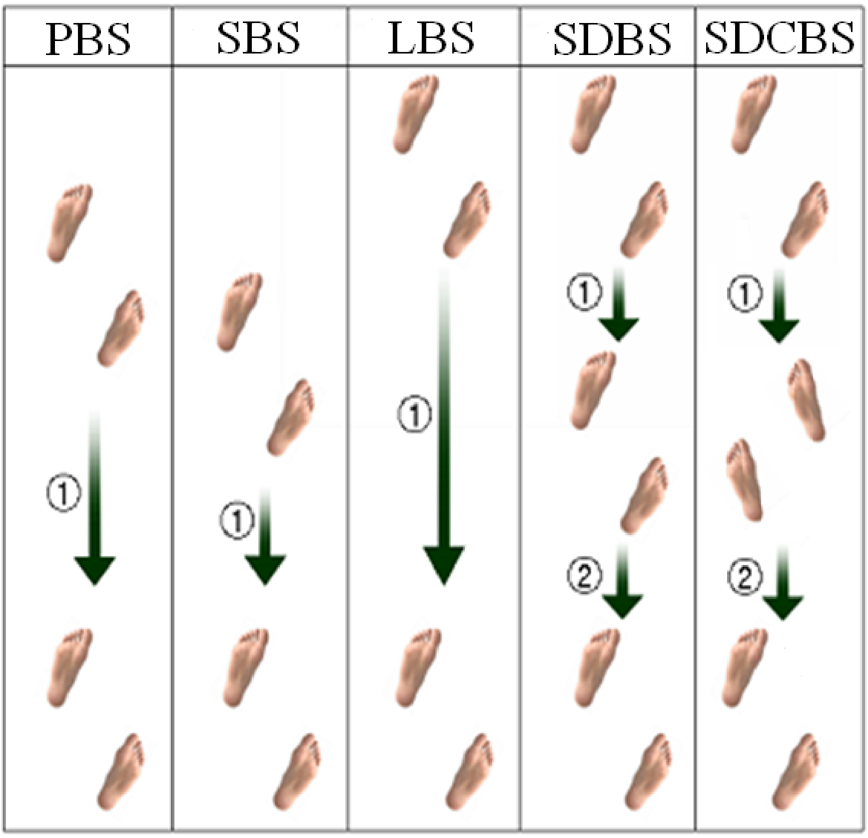

Figure 4. Distance-change types of footwork.

During the warm-up procedure, each participant performed the backstep movements five times. Then, the average distance of those backstep movements was calculated (PBS). The SBS distance was the average distance minus 30% of the average value; the LBS distance was the average distance plus 30% of the average value; the SDBS distance was two times that of the SBS; and the SDCBS was two times that of the SBS with the cross-backstep. Each participant's preferred distance from the target was used.

2.5. Data Reduction and Analysis

The signal, start, preparation, kick, minimum knee flexion (MKF), and impact were identified as a set of actual events to analyze data (Figure 5). The start (the start of the backstep motion) was visually determined using the movements of the right toe and heel markers. Preparation was described as the completion of the backstep and readiness to kick. The moment the kicking foot toe left the ground was defined as a kick. MKF was the moment when the kicking leg had the minimum knee flexion. The point when the marking on the target mitt began to move was considered the impact. At the MKF and impact events, the contribution of the body segments to toe velocity was calculated. For marker tracking, the best trial from each condition was chosen. Kwon3D software digitized motion capture data to find reflective markers. The reflective markers' 3D coordinates were generated using a DLT algorithm and smoothed with an 8 Hz low-pass 4th-order Butterworth filter.

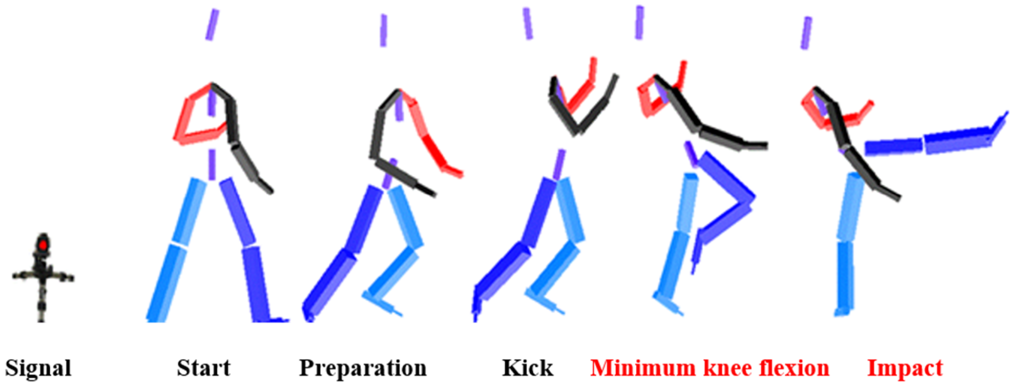

Figure 5. The events of the roundhouse kick.

The contribution was calculated by analyzing the effect of segments of the whole body, trunk, thigh, calf, and foot on the final distal segment, the toe velocity. The velocity of the foot segment is the sum of the velocity of the whole-body center of mass (V_G) and the relative velocity of the foot segment with respect to the whole-body center of mass. That is, $V_{foot} = V_G + V_{foot/G}$, and if the velocity of the foot segment is further subdivided by the same method, it is as follows:

$$V_{foot} = V_G + V_{TK/G} + V_{hip/TK} + V_{knee/hip} + V_{ankle/knee} + V_{foot/ankle} \tag{1}$$

where $V_{TK/G}$ is the velocity of the body center of mass with respect to the whole-body center of mass, $V_{hip/TK}$ is the velocity of the hip joint with respect to the trunk center of mass, $V_{knee/hip}$ is the velocity of the knee joint with respect to the hip joint, $V_{ankle/knee}$ is the knee joint velocity, and $V_{foot/ankle}$ is the velocity of the center of the foot relative to the ankle joint. According to Ginsberg and Genin [27], the velocity ($V_{d/p}$) of the distal segment relative to the proximal segment can be expressed as follows:

$$V_{d/p} = \omega_{i/GR} \times r_{d/p} + (V_{d/p})rad \tag{2}$$

Here, $\omega_{i/GR} \times r_{d/p}$ is the tangential component of the relative velocity, $\omega_{i/GR}$ is the angular velocity of the segment with respect to the ground, and $r_{d/p}$ is the position vector of the distal segment with respect to the proximal segment. $(V_{d/p})rad$ is the centripetal component of the relative velocity. The following formula was applied to the trunk, thigh, calf, and foot:

$$\begin{gathered} V_{foot} = V_G + V_{TK/G} + \\ \omega_{TK/GR} \times r_{foot/TK} + \\ \omega_{thigh/TK} \times r_{foot/hip} + \\ \omega_{shank/thigh} \times r_{foot/knee} + \\ \omega_{foot/shank} \times r_{foot/ankle} + \\ (V_{hip/TK})rad + (V_{knee/hip})rad + (V_{ankle/knee})rad + (V_{foot/ankle})rad \end{gathered} \tag{3}$$

In the above equation, V_G is the contribution of the foot segment velocity to the whole-body center; $V_{TK/G}$ is the contribution of the trunk center mass to the whole-body center of mass; $\omega_{TK/GR} \times r_{foot/TK}$ is the contribution of trunk rotation; $\omega_{thigh/TK} \times r_{foot/hip}$ is the contribution of the rotation of the thigh segment; $\omega_{shank/thig} \times r_{foot/knee}$ is the contribution of the rotation of the calf segment; $\omega_{foot/shank} \times r_{foot/ankle}$ is the contribution of the rotation of the foot segment; and $(V_{hip/TK})rad$ + $(V_{knee/hip})rad$ + $(V_{ankle/knee})rad$ + $(V_{foot/ankle})rad$ includes the centripetal components for the relative velocities of the hip joint to the body's center of mass, the knee joint to the hip joint, the ankle joint to the knee joint, and the foot segment center to the ankle joint, respectively.

Since the direction of the contributing factors to the foot segment velocity by each body part obtained by this equation can be different from the foot segment velocity, it was projected onto the vector direction of the foot segment and calculated as the contributing factor to the foot segment velocity. The centripetal component was calculated as the result of excluding the remaining contributing factors to the foot segmental velocity.

For the contribution analysis, the MKF event, which is the moment when the knee of the kicking leg converts from bending to extension, and the impact event, which is the moment when the target's marker starts to move when the foot hits the target, were used. The contribution to toe velocity was calculated from whole-body movement, trunk movement, trunk rotation, thigh rotation, calf rotation, foot rotation, and others. Repeated-measures analysis of variance with footwork as a within-subject factor was used to determine whether there were any statistically significant differences between dependent variables among the footwork conditions (footwork without backstep, angle-change types, and distance change types). Post hoc tests were performed with the Bonferroni adjustment. Alpha (a) was set at 0.05 in all statistical analyses.

3. Results

3.1. Contributions of Body Segments in Minimum Knee Flexion (MKF) Event

Table 1 contains the contributions of the segments to the toe velocity in the minimum knee flexion (MKF) event with angle-change types of footwork. In all types of kicks, thigh rotation showed the most significant contribution with a rate of 51.0 to 64.4%, and trunk rotation had the second highest contribution rate (16.7 to 29.9%). Whole-body movement (10.1 to 13.4%) was ranked third, and the contribution rate of trunk movement was 4.6 to 7.8%, indicating a significant difference between types of footwork.

During the kick without a backstep, the toe velocity was 10.45 m/s in the MKF event, the contribution rate of thigh rotation was 53.9%, the contribution rate of trunk rotation was 24.3%, the contribution rate of whole-body movement was 12.4%, the contribution rate of trunk movement was 6.5%, the contribution rate of calf rotation was 2.5%, the contribution rate foot rotation was 0.2%, and the contribution rate of others was 0.3% The contribution of thigh rotation was the highest, followed by trunk rotation and whole-body movement.

The results from the types of one-foot backstep footwork showed that the toe velocity at F0° was 8.05 m/s, that at F22° was 9.05 m/s, that at F45° was 9.47 m/s, that at F67° was 9.85 m/s, and that at F90° was 10.87 m/s. The velocity of the toe increased with an increase in the angle, and there was a statistically significant difference.

Table 1. The contributions of the roundhouse kick with angle-change types of footwork in MKF event. Units: m/s.

		Whole-Body Movement	Trunk Movement	Trunk Rotation	Thigh Rotation	Calf Rotation	Foot Rotation	Others	Toe Velocity
	Kick w/o Backstep	1.30 ± 0.20 12.4%	0.68 ± 0.21 6.5%	2.54 ± 1.20 24.3%	5.63 ± 0.76 53.9%	0.26 ± 1.32 2.5%	0.02 ± 0.31 0.2%	0.03 ± 1.24 0.3%	10.45 ± 1.69 100.0%
	PBS Kick $^{\#2}$	1.28 ± 0.15 12.9%	0.67 ± 0.23 6.8%	2.97 ± 0.95 29.9%	5.43 ± 0.47 54.9%	−0.22 ± 1.08 −2.2%	−0.04 ± 0.37 −0.5%	−0.19 ± 1.10 −1.9%	9.90 ± 1.60 100.0%
	F0° $^{\#3}$	0.85 $^{\#2}$ ± 0.13 10.5%	0.42 ± 0.18 5.2%	1.46 $^{\#2}$ ± 0.49 18.1%	5.18 ± 0.90 64.4%	−0.04 ± 0.76 -0.5%	0.06 ± 0.62 0.8%	0.12 ± 1.02 1.5%	8.05 ± 0.95 100.0%
	F22° $^{\#4}$	0.91 $^{\#2}$ ± 0.18 10.1%	0.41 ± 0.20 4.6%	1.51 $^{\#2}$ ± 0.48 16.7%	5.32 ± 1.17 58.8%	0.39 ± 1.03 4.3%	0.16 ± 0.51 1.8%	0.34 ± 1.16 3.8%	9.05 ± 1.84 100.0%
	F45° $^{\#5}$	1.12 ± 0.28 11.8%	0.69 ± 0.20 7.3%	2.05 ± 0.83 21.6%	5.47 ± 0.78 57.7%	0.17 ± 1.15 1.7%	0.04 ± 0.65 0.5%	−0.06 ± 1.35 −0.6%	9.47 ± 1.10 100.0%
	F67° $^{\#6}$	1.27 $^{\#3,4}$ ± 0.21 12.9%	0.69 ± 0.19 7.0%	2.26 ± 1.29 22.9%	5.48 ± 1.08 55.7%	−0.01 ± 0.63 −0.1%	0.20 ± 0.40 2.0%	−0.05 ± 1.05 −0.5%	9.85 ± 1.23 100.0%
	F90° $^{\#7}$	1.35 $^{\#3,4}$ ± 0.22 12.4%	0.73 ± 0.28 6.7%	2.51 ± 1.06 23.1%	5.54 ± 0.47 51.0%	0.76 ± 1.48 7.0%	−0.05 ± 0.33 −0.5%	0.03 ± 1.39 0.3%	10.87 $^{\#3}$ ± 1.79 100.0%
f	Velocity Contribution rate	10.685 1.349	4.602 1.280	4.233 1.770	0.230 1.199	1.115 0.661	0.437 0.345	0.236 0.197	4.183
sig.	Velocity Contribution rate	0.000 *** 0.258	0.001 *** 0.286	0.003 ** 0.135	0.948 0.322	0.363 0.654	0.821 0.883	0.945 0.962	0.003 **

In the table, the notation "#n" indicates a significant difference (p < 0.05) between the corresponding types. ***: p < 0.001, **: p < 0.01.

There was a statistically significant difference in toe velocity, and the difference in toe velocity was a result of increasing the contribution of whole-body movement, trunk movement, and trunk rotation. The toe velocity influenced by thigh rotation also increased with an increase in the movement angle, but it did not reach the increase rate of the toe velocity, so the contribution rate to the toe velocity decreased as the movement angle increased. The toe velocity influenced by trunk rotation also increased to 1.46 m/s, 1.51 m/s, 2.05 m/s, 2.26 m/s, and 2.51 m/s as the angle increased. The contribution rate was 18.1% in F0 and 16.7% in F22, in which the toe velocity was low, and it increased to 21.6%, 22.9%, and 23.1% as the angle increased.

Table 2 contains the contributions of the segments to the toe velocity in the minimum knee flexion (MKF) event with distance-change types of footwork. The toe velocity was 9.83 m/s for PB, 10.28 m/s for LB, 9.96 m/s for SB, 10.10 m/s for CBS, and 10.49 m/s for DSB. There was no statistical difference in the toe velocity across the distance-changes types of footwork. However, there was a statistically significant difference between SB and CBS, between SB and DSB in whole-body movement, and between SB and DSB in trunk movement. Similar to the results of the type of angle change, it was found that the contribution was greatest for thigh rotation, followed by trunk rotation, and whole-body movement.

Table 2. The contributions of the roundhouse kick with distance-change types of footwork in MKF event. Units: m/s.

		Whole-Body Movement	Trunk Movement	Trunk Rotation	Thigh Rotation	Calf Rotation	Foot Rotation	Others	Toe Velocity
	PB $^{\#2}$	1.16 ± 0.21 11.8%	0.61 ± 0.24 6.2%	2.60 ± 1.04 26.5%	5.58 ± 1.14 56.7%	0.04 ± 1.10 0.4%	−0.01 ± 0.43 −0.1%	−0.15 ± 1.08 −1.5%	9.83 ± 1.15 100.0%
	LB $^{\#3}$	1.24 ± 0.09 12.0%	0.68 ± 0.10 6.6%	2.27 ± 0.71 22.1%	5.78 ± 0.98 56.2%	0.46 ± 0.65 4.5%	0.29 ± 0.52 2.8%	−0.43 ± 0.99 −4.2%	10.28 ± 1.15 100.0%
	CBS $^{\#4}$	1.36 ± 0.14 13.4%	0.76 ± 0.18 7.5%	2.58 ± 0.96 25.6%	5.28 ± 0.89 52.3%	0.67 ± 0.85 6.7%	−0.30 ± 0.97 −3.0%	−0.26 ± 0.82 −2.6%	10.10 ± 0.80 100.0%
	SB $^{\#5}$	1.02 $^{\#10}$ ± 0.17 10.3%	0.50 ± 0.20 5.0%	2.48 ± 0.82 24.9%	5.67 ± 0.84 56.9%	0.38 ± 1.13 3.8%	0.00 ± 0.38 0.0%	−0.08 ± 0.63 −0.8%	9.96 ± 0.98 100.0%
	DSB $^{\#6}$	1.31 $^{\#11}$ ± 0.21 12.5%	0.82 $^{\#11}$ ± 0.31 7.8%	2.19 ± 0.96 20.9%	5.56 ± 0.78 53.1%	0.62 ± 1.34 5.9%	−0.19 ± 0.64 −1.8%	0.16 ± 1.45 1.5%	10.49 ± 1.87 100.0%
f	Velocity Contribution rate	5.837 2.314	3.575 2.381	0.418 0.387	0.382 0.613	0.580 0.609	1.252 1.176	0.449 0.272	0.430
sig.	Velocity Contribution rate	0.001 *** 0.072	0.013 * 0.066	0.794 0.816	0.821 0.656	0.679 0.659	0.303 0.334	0.773 0.895	0.786

The notation '#n' indicates a significant difference (p < 0.05) between the corresponding types. ***: p < 0.001, *: p < 0.05.

3.2. Contributions of Body Segments in Impact Event

Table 3 includes the contributions of the segments to the toe velocity in the impact event with angle-change types of footwork. Compared with the contributions in the MKF event, the contribution of thigh rotation decreased, while the contribution of the calf rotation increased significantly. In addition, the toe velocity was 15.52 m/s in the roundhouse kick without a backstep, and to reach this velocity, the contribution rate by thigh rotation was 39.8%, the contribution of calf rotation was 34.6%, the contribution of trunk rotation was 12.0%, the contribution of whole-body movement was 9.6%, the contribution of trunk movement was 8.4%, the contribution of foot rotation was 2.9%, and the contribution of others was −7.3%.

Table 3. The contributions of the roundhouse kick with angle-change types of footwork in impact event. Unit: m/s.

	Whole-Body Movement	**Trunk Movement**	**Trunk Rotation**	**Thigh Rotation**	**Calf Rotation**	**Foot Rotation**	**Others**	**Toe Velocity**
Kick W/O Backstep	1.48 ± 0.29 9.6%	1.30 ± 0.28 8.4%	1.86 ± 0.70 12.0%	6.18 ± 1.94 39.8%	5.38 ± 0.87 34.6%	0.45 ± 0.54 2.9%	−1.13 ± 1.63 −7.3%	15.52 ± 2.16 100.0%
PBS Kick #2	1.29 ± 0.29 8.7%	1.17 ± 0.26 7.8%	2.72 ± 1.12 18.3%	5.43 ± 1.36 36.5%	5.47 ± 1.58 36.8%	0.37 ± 0.64 2.5%	−1.57 ± 1.69 −10.6%	14.87 ± 2.18 100.0%
F0° #3	0.70 #2 ± 0.22 5.1% #2	0.45 #2 ± 0.18 3.3% #2	3.23 ± 1.53 23.7%	3.60 ± 2.02 26.4%	6.22 ± 0.92 45.5%	−0.20 ± 1.01 −1.5%	−0.35 ± 1.57 −2.5%	13.66 ± 2.38 100.0%
F22° #4	0.80 #2 ± 0.25 5.8%	0.66 #2 ± 0.25 4.8%	2.96 ± 1.41 21.6%	4.23 ± 1.48 30.8%	6.28 ± 0.95 45.8%	0.21 ± 1.21 1.5%	−1.42 ± 2.11 −10.3%	13.72 ± 2.32 100.0%
F45° #5	1.14 ± 0.40 8.1%	1.13 #3 ± 0.31 8.0% #3	2.52 ± 1.19 17.9%	4.68 ± 1.35 33.3%	6.30 ± 2.11 44.8%	0.01 ± 0.54 0.1%	−1.72 ± 1.45 −12.2%	14.06 ± 2.40 100.0%
F67° #6	1.40 #3,4 ± 0.36 8.9% #3	1.24 #3,4 ± 0.33 7.9% #3	2.78 ± 1.35 17.8%	5.09 ± 1.75 32.5%	6.31 ± 1.13 40.3%	0.01 ± 0.75 0.1%	−1.19 ± 1.75 −7.6%	15.64 ± 2.19 100.0%
F90° #7	1.53 #3,4 ± 0.32 9.9% #3,4	1.40 #3,4 ± 0.29 9.1% #3,4	2.86 ± 0.92 18.5%	5.49 ± 1.92 35.5%	4.94 ± 1.12 32.0%	0.38 ± 0.45 2.5%	−1.15 ± 1.11 −7.5%	15.44 #3,4,5 ± 1.21 100.0%
f Velocity Contribution rate	11.273 6.725	17.794 9.156	0.363 0.681	1.948 1.360	1.794 3.316	0.806 0.713	0.877 0.821	4.159
sig. Velocity Contribution rate	0.000 *** 0.000 ***	0.000 *** 0.000 ***	0.872 0.640	0.101 0.254	0.130 0.011 *	0.551 0.617	0.503 0.540	0.003 **

The notation '#n' indicates a significant difference ($p < 0.05$) between the corresponding types. ***: $p < 0.001$, **: $p < 0.01$.

In the roundhouse kick with PBS, the toe velocity was 14.87 m/s, the contribution rate of whole-body movement to reach the velocity was 8.7%, that of trunk movement was 7.8%, that of trunk rotation was 18.3%, that of thigh rotation was 36.5%, that of calf rotation was 36.8%, that of foot rotation was 2.5%, and that of others was −10.6%. In the angle-change types of footwork, the toe velocity at F0° was 13.66 m/s, the toe velocity at F22° was 13.72 m/s, the toe velocity at F45° was 14.06 m/s, the toe velocity at F67° was 15.64 m/s, and the toe velocity at F90° was 15.44 m/s. As the movement angle increased, the toe velocity increased. However, there was no statistically significant difference. The toe velocity by thigh rotation also increased to 3.60 m/s, 4.23 m/s, 4.68 m/s, 5.09 m/s, and 5.49 m/s with an increase in the angle, and the contribution rates also increased from 26.4% to 30.8%, 33.3%, 32.5%, and 35.5% as the backstep angle increased. Unlike the results of the kick without backstep, the contribution rate by calf rotation was higher than that of the thigh rotation, except for F90. The contribution rates of trunk rotation for PBS, F45°, F67°, and F90° were 17.8% to 18.5%, but those of F0° and F22° were 23.7% and 21.6%, respectively. The contribution rates of whole-body movement and trunk movement were similar at 7.8% to 9.9% for PBS, F45°, F67°, and F90°, but they were low at 3.3% to 5.8% for F0° and F22°.

Table 4 includes the contributions of the segments to the toe velocity in the impact event with distance-change types of footwork. The toe velocity of PB was 16.75 m/s, and to reach this velocity, the contribution rate of whole-body movement was 8.1%, the contribution of trunk movement was 7.5%, the contribution of trunk rotation was 19.5%, the contribution of thigh rotation was 37.9%, the contribution of calf rotation was 35.4%, the contribution of foot rotation was 1.6%, and the contribution of others was −10.0%. In the roundhouse kick with PB, thigh rotation contributed the most, followed by calf rotation, trunk rotation, and whole-body movement.

Table 4. The contributions of the roundhouse kick with distance-change types of footwork in impact event. Unit: m/s.

		Whole-Body Movement	Trunk Movement	Trunk Rotation	Thigh Rotation	Calf Rotation	Foot Rotation	Others	Toe Velocity
	PB $^{\#2}$	1.35 ± 0.32 8.1%	1.26 ± 0.26 7.5%	3.26 ± 1.06 19.5%	6.35 ± 1.55 37.9%	5.94 ± 1.67 35.4%	0.26 ± 0.57 1.6%	-1.68 ± 1.62 −10.0%	16.75 ± 2.06 100.0%
	LB $^{\#3}$	1.29 ± 0.14 8.5%	1.15 ± 0.18 7.6%	2.44 ± 0.94 16.1%	6.99 ± 1.99 46.2%	5.66 ± 1.17 37.4%	0.28 ± 0.64 1.8%	-2.68 ± 1.96 −17.7%	15.12 ± 2.04 100.0%
	CBS $^{\#4}$	1.46 ± 0.26 9.8%	1.30 ± 0.29 8.8%	2.85 ± 1.19 19.3%	5.30 ± 1.68 35.8%	4.22 ± 1.96 28.5%	0.79 ± 0.93 5.3%	-1.10 ± 2.22 −7.4%	14.81 ± 1.56 100.0%
	SB $^{\#5}$	$0.95^{\#8,10} \pm 0.20$ 6.6% $^{\#10}$	$0.81^{\#8,10} \pm 0.27$ 5.6% $^{\#10}$	2.36 ± 0.77 16.4%	5.37 ± 1.21 37.2%	5.01 ± 0.85 34.7%	0.34 ± 0.30 2.3%	-0.41 ± 1.36 −2.8%	14.43 ± 2.02 100.0%
	DSB $^{\#6}$	$1.56^{\#11} \pm 0.30$ 10.1% $^{\#11}$	$1.42^{\#11} \pm 0.24$ 9.2% $^{\#11}$	2.63 ± 0.75 17.0%	5.94 ± 1.73 38.4%	5.65 ± 0.94 36.5%	0.45 ± 0.62 2.9%	-2.17 ± 1.84 −14.0%	15.47 ± 2.00 100.0%
f	Velocity Contribution rate	8.446 6.234	8.741 4.789	1.437 0.788	1.835 1.490	2.464 1.830	1.130 1.245	2.384 1.949	2.095
sig.	Velocity Contribution rate	0.000 *** 0.000 ***	0.000 *** 0.003 **	0.237 0.539	0.139 0.221	0.059 0.140	0.354 0.306	0.065 0.119	0.097

The notation '#n' indicates a significant difference ($p < 0.05$) between the corresponding types. ***: $p < 0.001$, **: $p < 0.01$.

In distance-change types of footwork, there were statistically significant differences in velocity and the contribution rate of whole-body movement and trunk movement, such as with the angle-change types of footwork. However, there was no statistical difference in toe velocity.

4. Discussion

The purpose of this study was to quantitatively examine the effects of various footwork techniques often used in Taekwondo sparring matches on the biomechanical contributions of body segments to toe velocity during Taekwondo roundhouse kicks. In this study, the authors analyzed the contributions on the basis of both angle-change-type footwork and distance-change-type footwork in two events, the MKF event and the impact event, and found that the footwork affected toe velocity and contribution variables significantly.

First, in the minimum knee flexion event, the thigh rotation showed the most significant contribution in all types of footwork, followed by trunk rotation and whole-body movement. On the other hand, the contribution rate of calf rotation was −2.2 to 7.0%, and the contribution rate due to foot rotation was −3.0 to 2.8%, indicating a negative value and impairing toe velocity. This is because of the characteristics of the MKF event, which is converted from flexion to extension motion. During roundhouse kicks with angle-change types of footwork, the toe velocity increased with the angle, and there was a significant difference in the toe velocity. However, in the distance-change types of footwork, there was no statistical difference in the toe velocity caused by footwork.

Second, in the impact event during the roundhouse kick with PBS, the contribution rate to the toe velocity was the largest from calf rotation, followed by thigh rotation, trunk rotation, and whole-body movement. In addition, the contribution rate of calf rotation in the angle-change-type footwork was higher than that of thigh rotation, except for F90. Although there was no significant difference in the velocity of calf rotation, the contribution rate decreased as the angle increased, indicating that the type with a smaller backstep angle relies on knee extension motion to kick more.

The contribution rates of whole-body movement and trunk movement were similar for PBS, F45, F67, and F90, but those for F0 and F22 were lower than those of the others. This means that when the movement angle was small, it depended more on trunk rotation than on trunk movement, and as the movement angle increased, it depended on whole-body and trunk movement rather than trunk rotation.

Third, as shown in Figure 6, as the Taekwondo round kick progresses from the minimum knee flexion event to the impact event, the contribution of thigh rotation is reduced, and the contribution of calf rotation is increased. This can be explained by the kinetic link theory proposed by Plagenhoef [28] and Bunn [29], that is, the deceleration of the thigh helps increase the velocity of the calf, and the deceleration of the calf contributes to the production of maximum toe velocity. This is also consistent with the results of Yoon's study [30], which showed that hip flexion contributes to the velocity of the foot segment, and when the rotation velocity of the thigh is decelerated, the rotation velocity of the calf increases and contributes to the velocity of the foot segment.

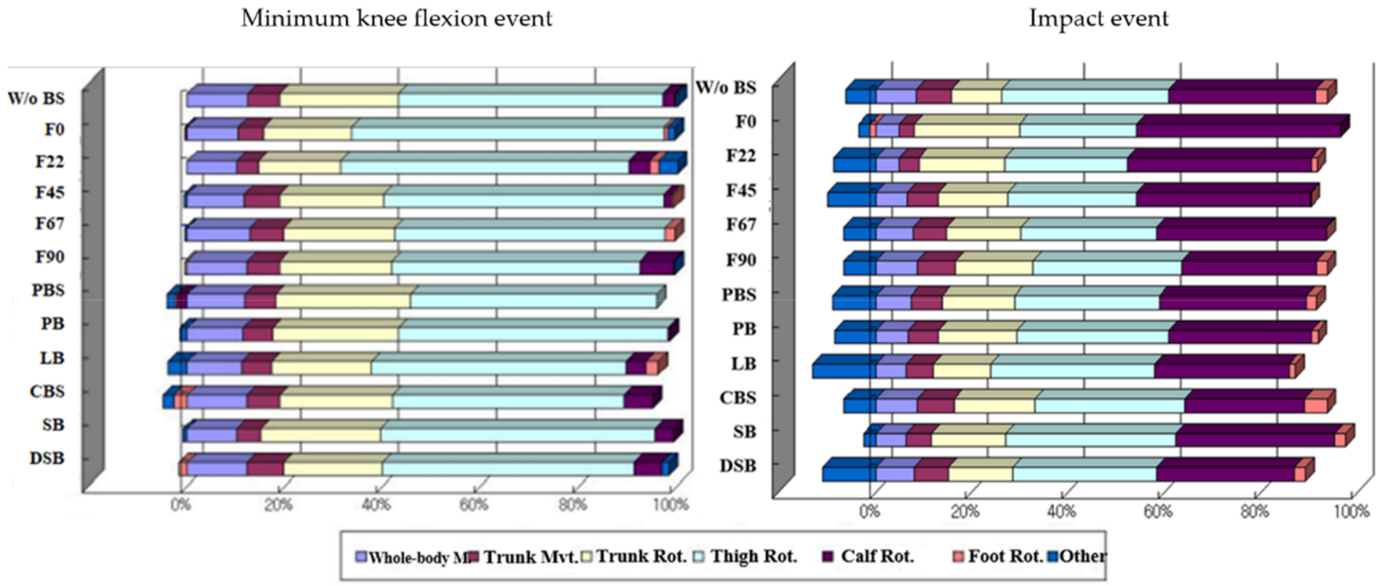

Figure 6. Comparison of the contribution rates in MKF and impact events.

In the study by Yoon [30], the contribution of body segments to the toe velocity of the roundhouse kick was 5.81% whole-body movement, 3.25% trunk movement, 10.11% trunk rotation, 27.28% thigh rotation, 29.29% calf rotation, and 1.43% foot rotation. The results of this previous study were different from the results of the current study. The difference is due to the difference in the form of the roundhouse kick. According to the Taekwondo textbook [31], the roundhouse kick is executed by 'Bending the knee of the kicking leg while the weight is placed on the foot that is the front axle, and when turning the body, straighten the folded knee, and the foot rotates horizontally and strikes, and the support leg should stretch the knee and ankle so that the body rotates well'. In addition, it should be performed in the form of a shot slightly above the target. On the other hand, for the roundhouse kick in the case of a sparring match, the player should jump one step forward from the sparring posture, and the whole body should be thrown forward while the pelvis rotates [32].

The former (Taekwondo textbook) emphasizes the kick by the supporting foot and trunk rotation, while the latter emphasizes weight shift and hip rotation in the target direction. In the previous study, the contribution of whole-body movement was 5.81%, and that of trunk movement was 3.25%, and in this study, the contribution of whole-body movement was 9.6%, and that of trunk movement was 8.4%. The current study shows that the contributions of whole-body movement and trunk movement were higher than those in the previous study, so it is thought that the previous study used the roundhouse kick based on the former form, and the current study employed the roundhouse kick based on the latter form.

One limitation of the current study was that the footwork was predetermined and remained constant throughout the kick performance. Competitors in sparring constantly slide or step forward and backward and left to right to respond and execute the counter-attack. Naturally, the footwork type might be modified throughout the kick's execution, which requires the attacking competitor to adjust the footwork movement to compensate for the opposing contender's movement. Future studies should use a more realistic footwork condition plan, such as executing a counterattack with side footwork following the actual systematic alteration of attacking.

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Rapid Weight Loss Coupled with Sport-Specific Training Impairs Heart Rate Recovery in Greco-Roman Wrestlers

Roberto Roklicer [1,*], Carlo Rossi [2], Antonino Bianco [2], Valdemar Štajer [1], Nemanja Maksimovic [1], Marko Manojlovic [1], Barbara Gilic [3,4], Tatjana Trivic [1] and Patrik Drid [1]

1 Faculty of Sport and Physical Education, University of Novi Sad, 21000 Novi Sad, Serbia; stajervaldemar@yahoo.com (V.Š.); nemanjamaksimovic1998@gmail.com (N.M.); markomanojlovic1995@gmail.com (M.M.); ttrivic@yahoo.com (T.T.); patrikdrid@gmail.com (P.D.)
2 Sport and Exercise Sciences Research Unit, University of Palermo, 90144 Palermo, Italy; rcarlo97@hotmail.com (C.R.); antonino.bianco@unipa.it (A.B.)
3 Faculty of Kinesiology, University of Split, 21000 Split, Croatia; barbaragilic@gmail.com
4 Faculty of Kinesiology, University of Zagreb, 10000 Zagreb, Croatia
* Correspondence: roklicer.r@gmail.com

Abstract: Wrestling is a sport that can be classified with the use of alternating aerobic–anaerobic metabolism with moderate but high-impact energy expenditure. Heart rate recovery (HRR) is the difference between heart rate during exercise and a certain amount of time after the start of recovery. The goal of this study was to determine the difference in HRR between two phases: high-intensity sport-specific training (HISST) combined with rapid weight loss (RWL)—phase 1 (P1) and HISST only—phase 2 (P2). Ten national-level wrestlers were included in this study. All participants underwent HISST along with RWL procedures for P1. Seven days later, during P2, an identical training session was performed with no RWL included. We found a statistically significant difference in the values obtained after the first and second minutes of recovery in the second set for both cases (p = 0.034 and p = 0.037, respectively), with higher HR values recorded in P1. It can be concluded that there is undoubtedly a difference in HRR during training and RWL compared to HISST alone. Additionally, HISST along with RWL could compromise the aerobic component of recovery.

Keywords: aerobic recovery; wrestling; weight reduction; intermittent exercise

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1. Introduction

Wrestling is widely recognized as one of the oldest sports in human history, and as such, it was performed within the original events in the ancient Olympic Games [1]. Currently, two styles of wrestling are included in the Olympics: Greco-Roman style, which strictly allows upper body techniques only, meaning that holds below the waist are forbidden, and is only practiced by men. The second is freestyle wrestling where athletes are allowed to use lower extremity techniques and trips and is practiced by both men and women across the world [2,3]. Both styles are characterized as vigorous and intermittent and belong to weight-categorized sports. Due to the nature of the fight, physical demands include explosive strength, aerobic endurance, and anaerobic capacity in terms of achieving competitive success [4].

Although combat sports (CS) are predominantly formed by intermittent short-term high-intensity actions, where anaerobic glycolysis is used as an energy resource as numerous efforts are employed, aerobic metabolism is also involved. Therefore, following a period of training sessions with intermittent efforts, there is an increase in the activity of the sympathetic nervous system observed after HRV analysis [5]. Accordingly, heart rate variability (HRV) is an important tool for monitoring the training process by controlling training load [5]. Some previous research suggests that aerobic capacity belongs to one of the most important physical factors for achieving good results in wrestling competitions [6].

The aerobic system in CS primarily contributes to the athlete's ability to sustain effort for the span of the combat and to recover during the brief periods of rest or decreased exertion [7,8]. Heart rate response during exercise and the associated physiological mechanisms involved have been extensively studied [9,10]. Certain studies imply that heart rate recovery (HRR) following exercise is a marker of training-induced alterations in autonomic control [11,12].

A decrease in heart rate (HR) values in the first minutes of recovery following physical activity has been proposed as an inexpensive, non-invasive, valid, and simple indicator of parasympathetic activity, which is nowadays broadly used in clinical practice [13–15]. However, it is also employed in the monitoring and prescription of athletic training [16], along with cardiovascular condition assessment [17]. In addition, it is widely believed that faster HRR is related to better athletic performance [16]. Rapid recovery of HR following moderate to heavy exercise may be an important mechanism for preventing excessive cardiac work. Athletes characterized by high aerobic capacity could be better adapted to maximal control of the heart rate reserve [18]. Thus, monitoring HR in specific wrestling training sessions can provide information on setting the appropriate intensities and be very useful for creating a training program.

Combat sports athletes commonly engage in rapid weight loss (RWL) procedures to compete in the upper spectrum of a lower weight category and likely gain a competitive edge over their rivals [19]. Typically, RWL is defined as a reduction of 5% of body weight less than one week before the competition [20,21]. Rapid weight loss methods are largely similar between combat sports and commonly include reduced fluid and food intake, heated training, rubber suits, sauna use, increased physical activity, etc. The interactive effect of food restriction and fluid deprivation might provoke adverse physiological effects on the body, leaving the athlete potentially unprepared for competition [22]. Additionally, there is evidence that RWL of 5% combined with strenuous exercise before competition causes a significant degree of muscle damage in CS athletes, thus making the competitive performance fairly questionable [23]. Since CS athletes usually have to achieve their target weight in a relatively short period, they usually have to go through strenuous training along with other RWL procedures. In this way, such training could stimulate increased sweating and thus facilitate weight loss. This crossover study deals with monitoring the HRR in a group of Greco-Roman wrestlers during high-intensity sport-specific training on two different occasions.

The objective of the study was to establish whether strenuous HISST along with RWL procedures affect the aerobic capacity in terms of HRR differently than HISST alone.

2. Materials and Methods

2.1. Participants

Ten male national-level Greco-Roman wrestlers participated in this study (n = 10; mean age: 22.44 $\pm$ 4.53 years; mean body weight: 73.36 $\pm$ 4.42 kg; mean body height: 174.43 $\pm$ 3.78 cm). At the time of the examination, all subjects were free of injury and voluntarily participated in the study by signing the informed consent. During the experiment, participants trained about 1–2 h daily following their regular training schedule. To be included in the study, each participant had to have a competitive experience of at least 5 years and have been performing rapid weight loss techniques over the last two years. Body composition parameters were measured using Omron weight scale BF511 (Omron, Japan). All athletes used increased exercise, skipping meals, and fluid restriction to reduce the desired 5% of body weight. The study was conducted in accordance with the Declaration of Helsinki.

2.2. Testing Protocol High-Intensity Sport-Specific Training (HISST)

This study included two phases. In phase one (P1), the group composed of combat sports athletes had to lose 5% of their body weight and carried out HISST while heart rate was monitored. In this phase, participants started losing weight rapidly two days before the day of the training. The day of training (testing) was the last day of their RWL period, after which the measurements were performed. In the second phase (P2), seven days later, an identical high-intensity training protocol was carried out with no rapid weight loss procedure included (Figure 1). The total duration of the training was 90 min. All the participants were familiar with the testing procedure. The participants were instructed to perform the protocol with the same sparring partner on both occasions (P1 and P2). The high-intensity sport-specific training consisted of four sets of a maximal number of throws with work to rest ratio: 15:45 s, with each set lasting 10 min with a break of 3 min in between. Heart rate recovery was measured at three time points: the first, second, and third minute after each set of throws. During the test, participants performed shoulder throws. A heart rate monitor was attached to all participants (Polar-H10 heart rate sensor, Polar Pro chest strap) from the beginning to the end of the training session. The heart rate monitoring was performed using an iPad Pro 10, Polar Team application.

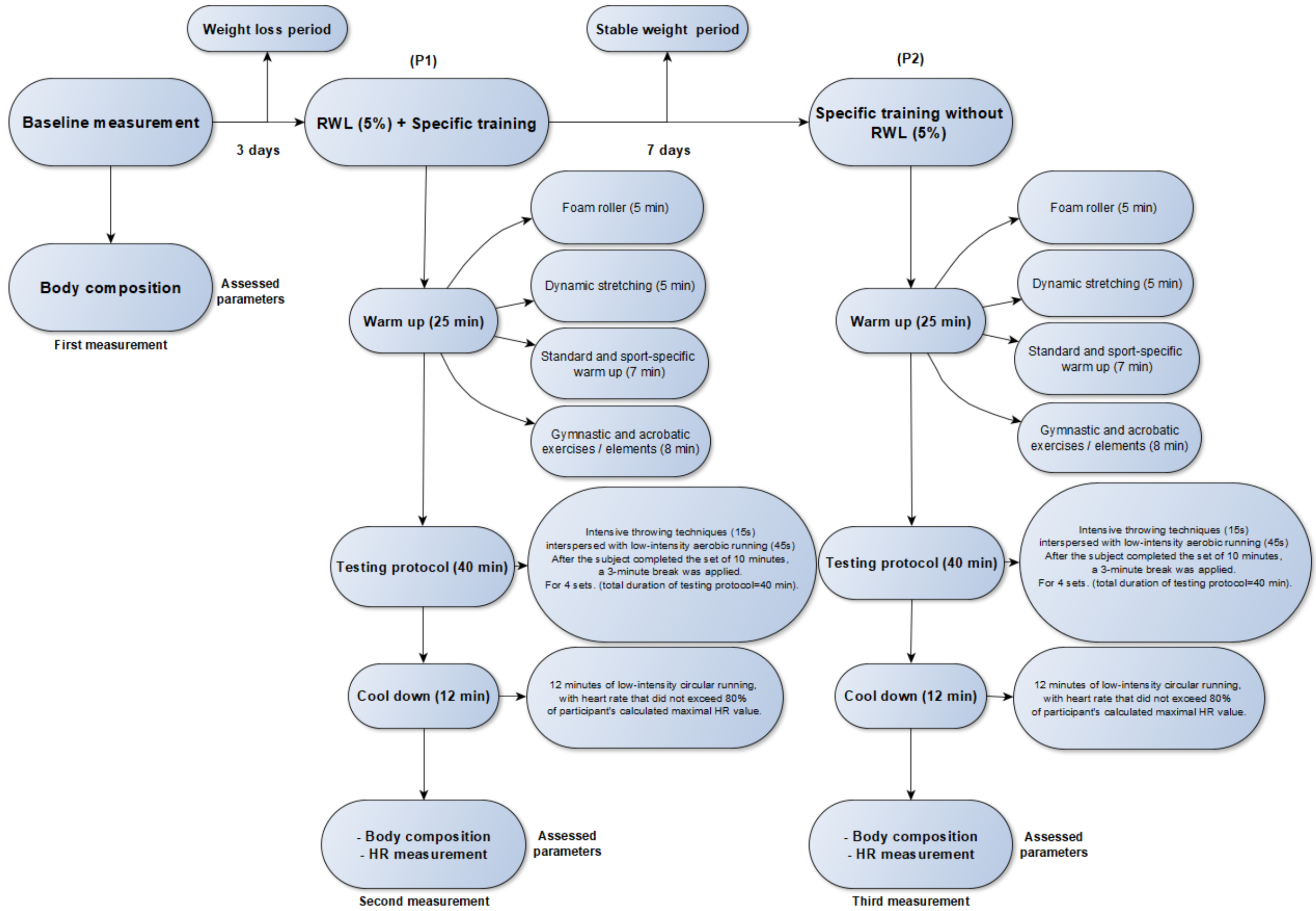

Figure 1. Experimental procedure design.

2.3. Warm-Up

Participants started with a warm-up that consisted of 5 min of foam rolling, followed by 5 min of dynamic stretching. Standard and sport-specific warm-ups were conducted for the next 7 min, after which 8 min of gymnastic and acrobatic elements were performed by wrestlers (total warm-up time = 25 min).

2.4. Testing Protocol

The main part of the training consisted of an intensive throwing technique (15 s) interspersed with low-intensity aerobic running (45 s). In fact, the participant initially began a low-intensity circular run (45 s). Five seconds before the throwing part of the test, the participant was instructed to place himself at a point 9 m away from the sparring partner. At the sound signal, he had to run to his sparring partner as fast as possible and perform the throwing technique. Immediately after the throw, he had to return to the starting point of 9 m. Participants had to perform 4 shoulder throws together with sprints during this period of 15 s. When the throwing part was completed, participants started the next set of low-intensity running. After the subject completed the set of 10 min, a 3 min break was applied. Four sets of the explained protocol were completed (total duration of testing protocol = 40 min).

2.5. Cooldown

At the end of the main part of the training, a cooldown phase was employed. This phase consisted of 12 min of low-intensity circular running, with heart rate not exceeding 80% of participants' maximal calculated HR values.

2.6. Statistical Analysis

The results of the study are presented as mean values and standard deviations. For the normality of distribution, the Shapiro–Wilks test was performed. A paired sample *t*-test was used to compare the means between the two measurements using IBM SPSS Statistics for Windows, 20.0 (IBM Corp 20, Armonk, NY, USA). The statistical significance level was set at $p < 0.05$.

3. Results

The characteristics of combat sports athletes are presented in Table 1. The differences in body composition are visible across three time points: baseline values, P1, and P2 (Figure 2).

Table 1. Descriptive characteristics of wrestlers' body composition (n = 10).

	Baseline Values	RWL and Training Phase (P1)	Training-Only Phase (P2)
Bodyweight (kg)	73.36 ± 4.42	69.27 ± 4.12 *	72.38 ± 4.17 #
BMI (kg/m^2)	24.11 ± 0.96	22.62 ± 0.98 *	23.64 ± 1.07 #
Fat mass percentage (%)	16.37 ± 2.22	12.74 ± 3.15 *	14.98 ± 2.47 #
Muscle mass percentage (%)	42.51 ± 1.41	44.64 ± 2.14 *	43.36 ± 1.71 #
Visceral body fat (%)	6.11 ± 1.05	4.88 ± 1.16 *	5.66 ± 1.32 #
Basal metabolic rate (kcal)	1717.33 ± 64.98	1677.11 ± 61.49	1704.11 ± 56.43

Note: The values are presented as mean values ± standard deviation; * statistically significant difference in relation to the baseline values, $p \leq 0.001$; # statistically significant difference in relation to phase P1, $p < 0.01$.

Statistically significant differences were evident for all variables, except for the basal metabolic rate when baseline values were compared to P1 ($p \leq 0.001$). Additionally, significant differences were visible when P1 was compared to P2 ($p < 0.01$) for all examined variables except basal metabolic rate.

Heart rate recovery values for the two phases (P1 and P2) are presented in Figure 3. Greater values are observed in P1 for all performed sets except the second minute of recovery in the third set, which was slightly but not significantly lower ($p < 0.66$).

Statistically significant differences were observed in two recovery periods. These were evident in the first and second minute of recovery after the second set of the testing protocol. Higher values after the first minute of recovery in the second set during P1 were achieved in comparison with P2, 169.77 ± 8.94 vs. 158.22 ± 12.07 bpm, respectively ($p = 0.034$). Likewise, the second minute of recovery for the same set was also significantly higher in P1 compared to P2, 151.44 ± 11.92 vs. 143.88 ± 11.78 bpm, respectively ($p = 0.037$). A large difference was visible after the third minute of recovery in the third set, as higher values were achieved in P1 compared to P2; Nevertheless, it was not statistically significant ($p = 0.083$).

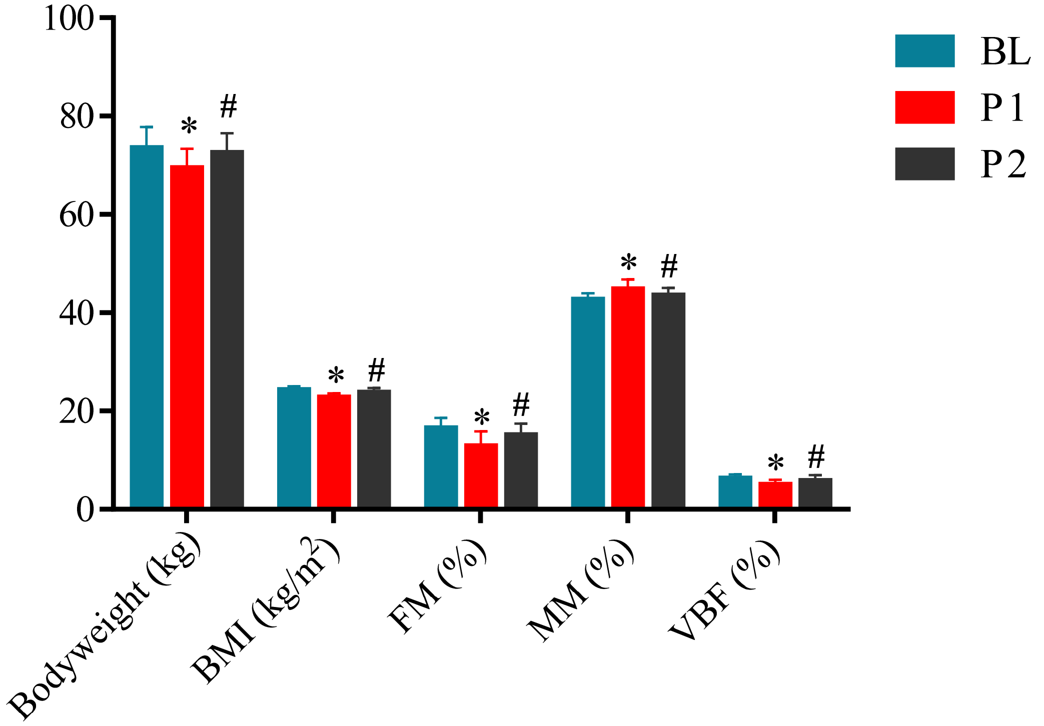

Figure 2. Descriptive characteristics of wrestlers' body composition. Legend: BL—baseline values; P1—phase one: HISST combined with RWL; P2—phase two: HISST with no RWL procedures included; BMI—body mass index (kg/m^2); FM—fat mass (%); MM—muscle mass (%); VBF—visceral body fat (%); * statistically significant difference in relation to the baseline values, $p \leq 0.001$; # statistically significant difference in relation to phase P1, $p < 0.01$.

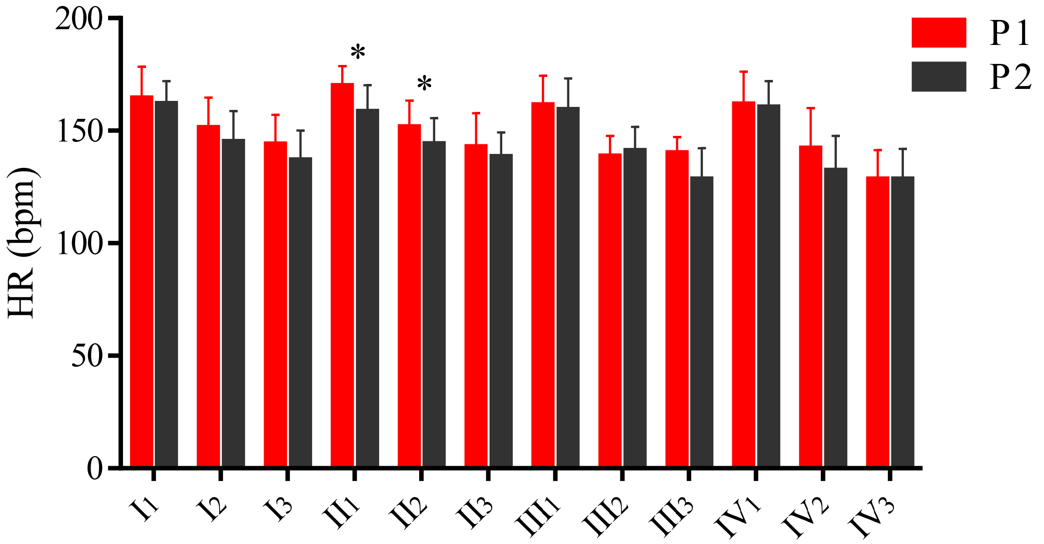

Figure 3. Heart rate recovery during 2 phases. Legend: I1—first minute of recovery in first round, I2—second minute of recovery in first round, etc.; P1—phase one: HISST combined with RWL; P2—phase two: HISST with no RWL procedures included; HR bpm—heart rate values; * statistically significant difference, $p < 0.05$.

4. Discussion

The objective of this study was to compare and evaluate the differences in HRR between HISST combined with RWL and HISST only, as participants went through identical training procedures during both phases of the experiment. The results of our study indicate a trend of higher values in P1 compared to P2. Such results demonstrate the lower ability of HRR when RWL procedures are included along with sport-specific training. The type of training and performance are additional components that can affect the HR response to recovery, as physiological adaptations of highly trained athletes can modify many aspects of exercise metabolism [24].

Heart rate variability is considered to be a helpful tool to monitor athletes' responses to training and recovery during competition, also including repeated anaerobic activities within and between matches [25]. Thus, it can be used for fitness evaluation of athletes and further prescription of the appropriate training program. Aerobic metabolism might be quite important in CS athletes to maintain the high intensity for the activities and assist with fast recovery of energy metabolism via resynthesis of creatine phosphate during the breaks and low-intensity activities [26,27]. Apparently, it seems that the ability to recover between aerobic efforts could determine the performance among CS athletes who are regularly engaged in high-intensity intermittent activity [25,28,29].

A study carried out by Ostojic et al. [24] examined HR recovery in ultra-short periods and found that athletes who engaged in intermittent endurance sports demonstrated faster recovery at 10 and 20 s following maximal effort compared to athletes competing in continuous sports. Specifically, the authors discovered that basketball, soccer, and handball players can recover faster compared to distance cyclists and runners. These results suggest that ultra-short heart rate recovery may be affected by the type of sports activity in well-trained athletes. Another study conducted by Ostojic et al. [18] on 32 healthy young soccer players that consisted of elite and sub-elite athletes assessed the HRR in ultra-short periods following an individualized ramp protocol to symptom-tolerated maximum using a treadmill system. The study revealed significantly lower HR values during the recovery period in elite compared to sub-elite players ($p < 0.05$) within the first 10 and 20 s. However, the first minute of HRR in elite soccer players can be compared with the values of wrestlers from our study during phase 1 (164 ± 5 and 164.2 ± 14.1 bpm, respectively). Another study conducted by Watson et al. [30] examined the short-term HRR in 84 collegiate male and female hockey and soccer players. These authors have found that HRR was faster at 10 and 30 s among intermittent sport athletes with a higher level of aerobic fitness. In this study, it was also stated that VO_2max was an independent predictor of more rapid HRR at 10 s, but not anytime thereafter. They found no significant independent relationship between HRR and sex, body fat percentage, or lean body mass at any of the time points measured. A study conducted by Suzic Lazic et al. [16] measured the HRR among 137 elite athletes competing in soccer, basketball, and water polo. Heart rate recovery was examined during the first, second and third minute following a progressive maximal ramp protocol on a treadmill. When compared to the results of our study, the first minute of HRR was comparable only with the P2 values of our study for all four sets, and the third and fourth set of P1. Heart rate recovery values after the second minute of recovery can be compared only to the last set of P2 in wrestlers. Nevertheless, the third-minute HRR values were much lower in this group of team sport athletes in comparison with participants from our study.

Although the two test procedures might not be quite comparable, according to the classificatory table for the Special Judo Fitness Test (SJFT) created by Franchini et al. [31], participants from our study demonstrated poor HRR after the first minute (range 162–165 bpm). Since the recovery could be hindered by merging the HRR with HISST, RWL procedures should most likely be altered by CS athletes ahead of the official weigh-in. In practice, this means that wrestlers should consider using either typical RWL methods or high-intensity training to achieve the targeted weight category, otherwise, they might attend the competition insufficiently recovered from weight-loss procedures by combining the two. However, athletes should employ less strict methods of weight loss before weigh-in. These results also suggest that HISST should be avoided before the competition.

This study has two limitations. The test procedure used in our study is not a standardized test protocol. However, it is created to simulate intensity during the in-season competitive period, including vigorous throws and sprints interspersed with low-intensity aerobic running. Additionally, the study was carried out on a relatively small number of participants. Further investigations should be conducted on a larger sample of athletes. To our knowledge, this extensive testing procedure and monitoring heart rate recovery for 40 min of the main training period (both in P1 and P2) was applied for the first time, which outlines the strength of the study.

5. Conclusions

Based on the results obtained, a trend of higher HR values during P1 was discovered, meaning remarkably higher HR values were present when RWL procedures were applied together with HISST. Current results might indicate a decrease in aerobic abilities in terms of HRR when RWL procedures are included along with sport-specific training. Wrestlers who choose to lose weight in this manner might not be adequately prepared for competition. Coaches and athletes around the world should be encouraged to avoid the combination of traditionally employed RWL techniques along with intensive training days prior to competition as it could impair athletes' recovery during and between matches.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of the University of Novi Sad, Faculty of Sports and Physical Education (protocol code. No. 46-06-02/2020-1).

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

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

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