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Acute Effects of Combined Hypoxia and Fatigue on Balance in Young Men

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Abstract: The aim of this study was to determine the effects of maximal exercise and maximal exercise under hypoxic conditions on balance, the strategies of the balance-maintenance process and its sensory organization. A total of 60 men were randomly allocated to three experimental groups and a control group. All participants completed the sensory organization test for assessing balance. Participants in the experimental groups performed the same test after an hour of normobaric hypoxia (the first group), after supramaximal exercise (the second group) and after supramaximal exercise combined with 60 min of hypoxia exposure (the third group). The control group performed the test after 60 min of passive rest. Normobaric hypoxia conditions corresponded to an altitude of 2950 m (FIO_2 15%). Physical effort in normoxia and hypoxia significantly impaired the participants' stability on a stable platform with eyes open ($\eta^2 = 0.711$, $p = 0.001$; $\eta^2 = 0.583$, $p = 0.001$, respectively). On an unstable platform, a significant improvement in stability indices was observed in the group undertaking the exercise in hypoxia ($p = 0.04$, $\eta^2 = 0.249$). The experimental conditions increased the role of hip strategies in maintaining balance in the experimental groups during trials requiring somatosensory information. An analysis of sensory organization shows that maximal effort in hypoxia increases the role of somatosensory ($p = 0.002$, $\eta^2 = 0.69$) and vestibular ($p = 0.02$, $\eta^2 = 0.34$) information, whereas hypoxia alone increases reliance on visual ($p = 0.03$, $\eta^2 = 0.38$) and vestibular ($p = 0.02$, $\eta^2 = 0.36$) information. This study indicates that individuals have poorer stability after maximal exercise, which may cause difficulties in engaging in some dynamic forms of activity, especially those with a large number of visual stimuli.

Keywords: smart balance master dynamic posturography system; maximal exercise; sensory organization test (SOT); sway variables; normobaric hypoxia

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1. Introduction

The ability to maintain a vertical posture is the basis of typical human motor activity. The mechanisms of postural stability are affected in a variety of ways at any point in our lives, originating from both internal and external factors. Motor activity is accompanied by fatigue of varying intensity, affecting the effectiveness of postural stability mechanisms [1–3]. These influences are multiplied when motor activity is undertaken in adverse external environmental conditions, such as high altitude [4–7]. The balance control mechanisms may respond differently to changes in each of these factors. It is therefore important to determine their influence on the organization of the balance-maintenance process. This is particularly important for a wide variety of sports activities (skiing, snow-boarding, ski touring), with competitions in most of these disciplines taking place at altitudes approaching 2000 m and not infrequently above 2500 m. In these high-altitude sports/physical activities, excellent coordination and balance are usually required. This provokes questions about the extent to which fatigue, influenced by the additional factor of hypoxia, has a negative effect on athletes' performance. This problem will increasingly affect recreational activities as well. As a result of climate change, the practice of these activities (in the case of winter sports) will require increased adaptation to higher altitudes above sea level. The main factor that reduces performance is fatigue, which, depending on the type of exertion and intensity, can affect balance in different ways.

The effectiveness of the postural system depends on the integration of information between receptors, effectors and the central nervous system. If any of these links is impaired, a limitation in the effectiveness of the balance mechanisms is possible. Fatigue (increase in lactate levels) and consequent hyperventilation are determined by the type of exercise, intensity and duration [8], having a detrimental effect on postural stability. Prolonged exercise, through metabolic (e.g., interleukin-6 production), structural (e.g., cell membrane aging), functional and behavioral modifications, leads to central and peripheral fatigue [9]. These changes vary according to the intensity of exercise, the type of contraction or the muscle group working [10]. Running has been shown to disrupt balance parameters more than walking and cycling [11,12]. Short-duration, rapidly initiated maximal exercises disturb balance more than long-term exercises with less anaerobic glycolysis [13,14]. They lead to a transient change in global postural control [15] or are only limited to certain muscle groups [16]. The extent to which muscle fatigue can affect postural control is not entirely clear and may have both a metabolic and a neurosensory basis. Fatigue is a complex phenomenon. There are several mechanisms associated with fatigue at different levels of the nervous system that may affect the regulation of forces necessary for balance. At the peripheral level, these are likely to be pre- and postsynaptic mechanisms, including lack of nerve signal transmission or lack of muscle response to nerve excitation [17]. At the central level, fatigue may be induced by a lack of excitation of motor neurons, which is caused by changes in the nervous system [18,19]. Changes in motor neuron excitation are attributed to intrinsic motor neuron properties, inhibition or impaired reflexes [20].

The effects of normobaric and hypobaric hypoxia on postural balance have been reported for both long exposure (24 h) [21] and short exposure (less than 60 min) [22]. Balance impairment can lead to falls and stumbles, and these issues have been observed at both high (1500–3500 m) and very high altitudes (above 3500 m) [5–7]. High altitude negatively affects postural stability and balance due to acute hypoxia [23–26]. The most commonly analyzed inducer of static imbalance is hyperventilation, which is a compensatory response to oxygen deficit [26]. This response generates vestibular and mechanical disturbances in balance. Cerebral hypoxia, leading to impaired balance control, motor skills and reaction time, may be related to impaired integration of sensory information [23–27]. The analysis of perturbations of particular receptor inputs, e.g., visual or vestibular [5,6], does not provide a complete picture of hypoxia-induced perturbations. No less important in this process are somatosensory stimuli, whose reduced performance has been observed at different altitudes [4,22].

During high-altitude activities, there are two simultaneous effects on balance, i.e., hypoxia and exercise-induced physical fatigue. The aim of this study was to determine the effects of fatigue and hypoxia on balance. We hypothesized that the simultaneous effects of hypoxia and exertion would have an exacerbated destructive effect on static and dynamic balance. We also assumed that each of these two factors could impair, to varying degrees, the functions of receptors, which are important for maintaining balance. The choice of these two factors is dictated by the assumption that they can significantly affect balance, as they induce changes of a biochemical, physiological and neurophysiological nature. Thus, among the many factors that determine and modify postural stability under dynamic conditions, their influence can have the strongest negative impact.

2. Materials and Methods

2.1. Study Design

The study was designed as a parallel randomized trial. All measurements were taken in one day. In the study, the sensory organization test (SOT) was administered both immediately before and immediately after the intervention, i.e., one hour apart. The study involved 60 men randomly allocated to four groups. The study groups differed in terms of the intervention between the SOT assessments. In the first experimental group (group H), the SOT was administered after an hour-long session in normobaric hypoxia; in the second experimental group (group F), the SOT was performed immediately after supramaximal anaerobic exercise (the 20 s Wingate test); the third group (group HF) performed the SOT after an hour-long session in hypoxia completed by the Wingate test in hypoxia. Study participants from groups H and HF performed the second SOT test under normobaric hypoxia (with masks attached to a hypoxia generator). The fourth group was the control group (group C), with no intervention between SOTs—participants rested passively for one hour between SOTs. The main inclusion criteria for the study were good health, no orthopedic injuries in the limbs (ankle and knee joint), and no contraindications to intense exercise. All participants underwent a medical qualification to confirm good health prior to the study. The exclusion criterion was participation in high-altitude training or prolonged exposure to altitudes above 1600 m above sea level in the period preceding the experiment. Prior to the study, participants were informed about the study and how to prepare for it. They were advised not to eat a heavy meal two hours before the test, to be adequately hydrated and not to undertake strenuous exercise 24 h before the test.

The study was approved by the Bioethical Commission of the Regional Medical Chamber in Krakow, Poland (opinion No. 70/KBL/OIL/2022; date 11 April 2022). All test procedures were conducted in accordance with the principles adopted in the Declaration of Helsinki. All participants gave their written informed consent to participate in the study.

2.2. Somatometric Measurements

During the medical qualification, participants underwent somatometric measurements. Body height (BH) and body mass (BM) were determined using a medical scale with a stadiometer (Radwag, C315.100/200.OW-1, Radom, Poland). Based on the data obtained, the body mass index (BMI) was calculated for each participant.

2.3. Participants

Participants were not involved in competitive sports, were non-smokers and had not been in areas above 1500 m above sea level in the 6 months preceding the study. They were physically active people, reporting moderate physical activity, no more than 3 times a week. The age and somatic parameters for each group are presented in Table 1.

Table 1. Age and somatometric measurements of the participants (data are presented as mean ± SD).

Variable	Group	M ± SD
Age (yrs)	C	22.2 ± 3.2
	H	20.7 ± 0.7
	F	21.3 ± 0.9
	FH	21.0 ± 0.9
BH (cm)	C	181 ± 6.0
	H	178.8 ± 5.6
	F	180.1 ± 6.2
	FH	180 ± 5.6
BM (kg)	C	78.8 ± 8.8
	H	75.1 ± 10.0
	F	81.1 ± 12.1
	FH	78.1 ± 14.4

Table 1. *Cont.*

Variable	Group	M ± SD
BMI	C	23.8 ± 1.8
	H	23.4 ± 2.5
	F	24.9 ± 2.7
	FH	23.9 ± 3.9

BH: body height; BM: body mass; BMI: body mass index; C: control group; H: hypoxia-treated group; F: fatigue induced by anaerobic exercise; FH: fatigue induced by anaerobic exercise in hypoxia.

2.4. Sensory Organization Test

The sensory organization test (SOT) assesses the participant's ability to maintain balance under various conditions of sensory stimulation, including sensory conflicts. During the test, the participant stands on a tensometric platform, which can be stable or tilt in an anteroposterior direction. The participants were shielded by an enclosure that mimicked the visual environment. During the dynamic trials, the device moves the platform plate and the enclosure to imitate the visual surround in such a way that both the base surface and the enclosure imitating the visual surround tilt in response to the test subject's tilt. The SOT consists of six trials, each of which is repeated three times:

Condition 1: test on stable platform with eyes open;
Condition 2: test on stable platform with eyes closed;
Condition 3: test on stable platform with eyes open and moving surround;
Condition 4: test on unstable (moving) platform, stable surround and with eyes open;
Condition 5: test on unstable (moving) platform with eyes closed;
Condition 6: test on unstable (moving) platform with eyes open and moving surround.

In the SOT test, scores for equilibrium (ES), sensory analysis (SA) and strategy (SS) are presented for each of the six conditions. The SA score is presented separately for the proprioceptive (SOM), visual (VIS), vestibular (VES) and visual preference (PREF) systems (Table 2). All results are given as percentages, where 100% means no sway. The study was conducted on the smart balance master dynamic posturography system (NeuroCom International, Inc., Clackamas, OR, USA, 2000).

Table 2. Method for calculating sensory analysis (SA) for individual systems and interpretation of indices (NeuroCom International, Inc., Clackamas, OR, USA, 2000).

SOM	Condition 2 Condition 1	patient's ability to use input from the somatosensory system to maintain balance
VIS	Condition 4 Condition 1	patient's ability to use input from the visual system to maintain balance
VEST	Condition 5 Condition 1	patient's ability to use input from the vestibular system to maintain balance
PREF	Condition 3 + 6 Condition 2 + 5	degree to which the patient relies on visual information to maintain balance, even when the information is incorrect

2.5. Interventions

Participants from all groups of four were subjected to two SOT measurements carried out one hour apart. In the experimental groups, the second measurement was preceded by one form of intervention or passive rest in the control group. The second SOT measurement followed immediately after the intervention.

2.5.1. Anaerobic Exercise (Wingate Test)

The anaerobic effort involved the 20 s version of the Wingate test, performed with a load equivalent to 8.3% of the participant's body mass. Before the test, the participants performed a 5 min warm-up on the cycloergometer with a load of 1.0 kg. The pedaling rhythm during the warm-up was 60 rpm. After the 2nd and 4th minutes of the warm-up, the participants performed two 3 s maximal accelerations before returning to a pedaling rhythm of 60 rpm. The main exercise was performed two minutes after the warm-up at a temperature of 21 ± 0.5 °C and a humidity level of 41 ± 1%. The test participant's task was to pedal as fast as possible for the duration of the exercise (all-out exercise) [28].

2.5.2. Hypoxia

Subjects were exposed to a hypoxic stimulus via an Everest Summit II-Altitude Generator (Hypoxico, New York, NY, USA), which administered hypoxic air through an individual mask. Exposure lasted 60 min at 21 ± 0.5 °C and 41 ± 1% humidity. Normobaric hypoxia was 15%O2, corresponding to an altitude of 2950 m above sea level.

2.5.3. Hypoxia + Anaerobic Exercise (Wingate Test)

The participants were exposed to two combined stimuli, i.e., 60 min of hypoxia followed by a 20 s Wingate test conducted according to the procedure described above. The participants also performed the Wingate test under normobaric hypoxia.

2.5.4. Passive Rest

Passive rest of 60 min took place under normoxic conditions in the laboratory at an altitude of 200 m above sea level, at 21 ± 0.5 °C and 41 ± 1% humidity.

2.6. Statistical Methods

The distribution of the results was checked with the Shapiro–Wilk test and presented based on the median (Me) and quarterly deviation (QD). The non-parametric Wilcoxon test was used to assess the significance of changes in the parameters studied before and after the experiment. The effect size was calculated based on the formula $\eta^2 = z^2/n$ (n = 15, the number of subjects per group). The following interpretation was adopted: no effect if $\eta^2 < 0.01$, small effect if $0.01 \leq \eta^2 \leq 0.09$, medium effect if $0.09 \leq \eta^2 \leq 0.25$, and large effect if $\eta^2 \geq 0.25$. STATISTICA 13.1 PL (StatSoft, Inc., Tulsa, OK, USA) was used for the calculations.

3. Results

3.1. Equilibrium Scores

Effort in normoxia ($p = 0.001$, $\eta^2 = 0.711$; group F) and hypoxia ($p = 0.001$, $\eta^2 = 0.583$; group FH) significantly impaired stability on the fixed platform with eyes open (Table 3). Under the conditions (ES 5) of an increasing role of vestibular information, significant improvements in stability indices were observed in the C ($p = 0.04$, $\eta^2 = 0.355$) and FH ($p = 0.04$, $\eta^2 = 0.249$) groups (Table 3).

Table 3. Effect of maximal effort in hypoxia and normoxia on stability indices.

Variable [%]	Group	Baseline Me ± QD	Post Me ± QD	p	η^2
ES 1	C	96.00 ± 0.75	96.50 ± 0.25	0.25	
	H	95.50 ± 0.75	94.25 ± 1.25	0.22	
	F	95.00 ± 1.00	91.50 ± 2.25	0.001	0.711
	FH	95.50 ± 0.75	92.50 ± 2.00	0.001	0.583
ES 2	C	92.25 ± 1.00	93.50 ± 1.75	0.15	
	H	92.75 ± 1	93.25 ± 1.75	0.23	
	F	93.00 ± 1.50	91.50 ± 1.50	0.08	
	FH	92.00 ± 1.75	92.00 ± 2.00	0.78	
ES 3	C	92.75 ± 1.50	94.50 ± 1.75	0.11	
	H	93.00 ± 1.5	93.25 ± 2.75	0.38	
	F	91.00 ± 1.50	90.00 ± 3.00	0.12	
	FH	93.00 ± 2.25	92.00 ± 2.75	0.89	

Table 3. *Cont.*

Variable [%]	Group	Baseline Me ± QD	Post Me ± QD	p	η^2
ES 4	C	90.25 ± 3.00	92.00 ± 1.75	0.08	
	H	85.75 ± 5	89.25 ± 3.25	0.05	
	F	89.00 ± 2.75	86.00 ± 2.75	0.20	
	FH	89.50 ± 3.25	86.50 ± 3.50	0.16	
ES 5	C	69.50 ± 5.25	75.50 ± 6.00	0.04	0.355
	H	66.75 ± 4	72.50 ± 3.25	0.07	
	F	70.50 ± 5.50	71.00 ± 6.00	0.39	
	FH	64.50 ± 5.75	74.50 ± 5.00	0.04	0.249
ES 6	C	75.50 ± 9.75	82.00 ± 2.00	0.02	0.417
	H	70.50 ± 5	74.00 ± 5	0.14	
	F	64.00 ± 9.25	63.00 ± 12.00	0.82	
	FH	66.00 ± 7.00	58.50 ± 11.50	0.46	

ES 1: equilibrium score cond. 1; ES 2: equilibrium score cond. 2; ES 3: equilibrium score cond. 3; ES 4: equilibrium score cond. 4; ES 5: equilibrium score cond. 5; ES 6: equilibrium score cond. 6; C: control group; H: hypoxia-treated group; F: fatigue induced by anaerobic exercise; FH: fatigue induced by anaerobic exercise in hypoxia; Me—median; QD—quartile deviation; η^2—effect size.

3.2. Strategy Scores

Exercise ($p = 0.001$, $\eta^2 = 0.78$; group F), exercise in hypoxia ($p = 0.002$, $\eta^2 = 0.54$; group FH) and hypoxia ($p = 0.01$, $\eta^2 = 0.56$; group H) influenced the attenuation of the ankle joint strategy (Table 3) in the SS 1 condition. Also, without visual information (SS 2), there was an increase in the importance of the hip joint strategy in the groups performing the exercise test ($p = 0.001$, $\eta^2 = 0.70$; group F) and the Wingate test under hypoxia ($p = 0.004$, $\eta^2 = 0.49$; group FH) (Table 4).

Table 4. Effect of maximal exercise in hypoxia and normoxia on balance strategy.

Variable [%]	Group	Baseline Me ± QD	Post Me ± QD	p	η^2
SS 1	C	96.50 ± 0.50	95.50 ± 0.50	0.09	
	H	95.50 ± 0.75	95.00 ± 0.5	0.01	0.56
	F	95.00 ± 0.25	91.00 ± 3.00	0.001	0.78
	FH	95.00 ± 1.00	93.00 ± 1.75	0.002	0.54
SS 2	C	94.75 ± 1.00	94.50 ± 0.75	0.88	
	H	94.75 ± 0.5	94.25 ± 0.75	0.15	
	F	94.00 ± 1.50	91.00 ± 3.75	0.001	0.70
	FH	94.50 ± 1.00	91.50 ± 2.25	0.004	0.49
SS 3	C	94.75 ± 1.50	94.00 ± 1.00	0.51	
	H	94.25 ± 2	94.50 ± 0.75	0.89	
	F	90.50 ± 2.25	91.00 ± 4.25	0.41	
	FH	93.00 ± 1.50	92.50 ± 2.25	0.86	
SS 4	C	90.50 ± 1.00	91.75 ± 0.75	0.03	0.37
	H	88.50 ± 2.5	89.50 ± 1.5	0.13	
	F	89.00 ± 3.25	85.50 ± 2.75	0.1	
	FH	89.00 ± 1.25	86.00 ± 2.25	0.13	
SS 5	C	78.75 ± 3.75	83.25 ± 3.25	0.09	
	H	77.25 ± 4.25	83.00 ± 4.25	0.08	
	F	74.50 ± 5.75	74.00 ± 8.25	0.61	
	FH	77.50 ± 6.25	75.50 ± 4.75	0.85	
SS 6	C	84.25 ± 4.50	87.50 ± 2.00	0.01	0.43
	H	81.00 ± 4.5	84.50 ± 4	0.09	
	F	73.50 ± 7.75	71.50 ± 8.50	0.31	
	FH	79.50 ± 4.75	78.50 ± 8.50	0.65	

SS 1: strategy cond. 1; SS 2: strategy cond. 2; SS 3: strategy cond. 3; SS 4: strategy cond. 4; SS 5: strategy cond. 5; SS 6: strategy cond. 6; C: control group; H: hypoxia-treated group; F: fatigue induced by anaerobic exercise; FH: fatigue induced by anaerobic exercise in hypoxia; Me—median; QD—quartile deviation; η^2—effect size.

3.3. Sensory Analysis

Under the influence of exercise in hypoxia, the role of somatosensory SOM (p = 0.002, η^2 = 0.69; group FH) and vestibular (p = 0.02, η^2 = 0.34; group FH) information in maintaining balance increased significantly in the participants (Table 5). Hypoxia, on the other hand, significantly increased the role of visual information (VIS) (p = 0.03, η^2 = 0.38; group H) and vestibular information (VEST) (p = 0.02, η^2 = 0.36; group H) in the balance-maintenance process (Table 5).

Table 5. Effect of maximal effort in hypoxia and normoxia on the sensory organization of balance.

Variable [%]	Group	Baseline Me ± QD	Post Me ± QD	p	η^2
SOM	C	97.50 ± 1.50	98.00 ± 1.50	0.51	
	H	97.00 ± 1	98.50 ± 1	0.06	
	F	99.00 ± 2.00	99.00 ± 2.00	0.10	
	FH	96.00 ± 1.00	99.00 ± 1.00	0.002	0.69
VIS	C	94.00 ± 3.00	96.00 ± 1.50	0.12	
	H	90.50 ± 5.5	94.00 ± 2.5	0.03	0.38
	F	93.00 ± 4.50	96.00 ± 5.50	0.66	
	FH	94.00 ± 7.00	93.00 ± 3.50	0.98	
VEST	C	72.50 ± 6.00	78.50 ± 6.00	0.03	0.34
	H	70.00 ± 5.5	78.50 ± 6.5	0.02	0.36
	F	73.00 ± 6.50	79.00 ± 8.50	0.08	
	FH	68.00 ± 8.50	80.00 ± 7.00	0.02	0.34
VIS PREF	C	103.00 ± 2.00	104.50 ± 2.00	0.58	
	H	100.50 ± 6.5	97.00 ± 5	0.15	
	F	96.00 ± 5.00	96.00 ± 4.00	0.44	
	FH	103.00 ± 6.50	94.00 ± 6.00	0.13	

SOM: somatosensory; VIS: visual; VEST: vestibular; VIS PREF: visual preference; C: control group; H: hypoxia-treated group; F: fatigue induced by anaerobic exercise; FH: fatigue induced by anaerobic exercise in hypoxia; Me—median; QD—quartile deviation; η^2—effect size.

4. Discussion

In this study, we assumed that the two factors analyzed (fatigue and hypoxia) would differentially affect the sensory organization of balance maintenance. Furthermore, we expected a summative effect of their interaction. The above hypotheses were confirmed to a limited extent. Effort in normoxia and hypoxia impairs balance most strongly under reference conditions on a stable platform and with eyes open (ES 1). However, the combined effect of these stimuli does not exacerbate the impairment. Balance maintenance under dynamic conditions is enhanced by both normoxia and hypoxia conditions. Exercise only and effort in hypoxia under conditions requiring visual input (ES 4, ES 6) worsen postural stability. In dynamic conditions, the hierarchy of sensory inputs changes depending on the disturbing factor. Participants in hypoxia rely more on visual (VIS) and vestibular (VEST) information. Exertion in hypoxia increases the demand for somatosensory (SOM) and vestibular (VEST) information. An analysis of the changes in balance strategies indicates a decreasing role for the ankle joint strategy and an increasing role for the hip strategy under static conditions after exercise (also in hypoxia). In dynamic conditions, hypoxia, in turn, promotes a slight increase in the role of the ankle joint (ES 4, ES 5, ES 6) in postural stability.

The process of maintaining balance is realized by integrating information from three sense organs (receptor inputs): vision, the proprioceptor system and the peripheral vestibular organ. The integration of this information both statically and dynamically allows the nervous system to refer to one of the three strategies described by Nashner and McCollum [29] to maintain balance: the ankle joint strategy, the hip joint strategy, the stride or a combination of these. Dynamic posturography allows an objective analysis of the participants' balance under dynamic conditions and is more suitable for young, healthy and athletic persons. It allows the assessment of the participants' use of vestibular, visual or somatosensory information. The assessment was carried out in six conditions. In the first three conditions, the ground (platform) was stable despite changing visual stimuli: eyes open, eyes closed and center of gravity (COG)-dependent movement of the visual surround. The differences in body stability observed during these trials indicate whether the patient requires correct vision to maintain balance and whether they can inhibit incongruent visual information. In the next three conditions, the platform tilted according to the swaying of the subject. The moving platform disturbed the information coming from the proprioceptors. Each of the trials was performed in the same way as the first three trials under different visual conditions: with the eyes open, closed and with a moving visual surround. The last two allowed an isolated assessment of the vestibular organ.

Exercise has a significant effect on the impairment of balance [9,20,30]. One reason for this is the increased respiratory rate immediately afterwards (ES1) [3,13]. The increase in respiratory rate in response to lactate accumulation induces hyperventilation. Hyperventilation not only affects balance as a mechanical factor but is also responsible for interference with vestibular and somatosensory signals from the lower limbs [13,31]. Static balance disturbances under the influence of intensive exercise are of a short-term nature, which is confirmed in our study, and has been observed by other authors [2,13,32]. The lack of significant differences in the trial excluding visual information, and the significant differences in the trials with full access to visual information may confirm this (ES 2). This would indicate a disturbing role of visual information on balance, or more broadly, on cognitive function and sensory integration [5,33]. Our results do not correspond with those from studies indicating that strenuous exercise has a mild effect on balance and, at the same time, that vision is a sufficiently compensating factor for proprioceptive impairment. The exclusion of visual information did not significantly worsen balance in any conditions [2,34]. On the contrary, the exclusion of visual and deep sensory information also improved stability in the groups exposed to hypoxia, as well as in those performing the exercise in hypoxia (ES 5). This indicates that the distractors used have a mobilizing effect on the vestibular organ. Furthermore, we did not find that the duration of the test had a degrading effect on balance [23,26]. Improving stability scores in subsequent SOT tasks may indicate an adaptation of balance mechanisms to fatigue. However, this adaptation required allocating a larger proportion of cognitive resources to the active control of the balance task. This may explain the deterioration and subsequent improvement of balance under dynamic conditions [35]. In justifying such a sequence of events, the authors turn their attention to the noise in the input signal, which increases with fatigue. As a result of the adaptation of muscle spindles, this noise can be filtered out more effectively from the actual proprioceptive signal [35,36]. However, this adaptation requires dedicating a greater proportion of cognitive resources to the active control of the counterbalancing task. Hypoxia as a stand-alone factor did not significantly affect balance degradation. This does not mean, however, that it did not have a modifying effect on sensory organization. The visual system first responds to oxygen deficiency [37], but our study indicates a significantly increasing role of visual information to the hypoxic groups (VIS).

The observed increase in the hip strategy is confirmed by publications from authors who observed an increase in such responses in young athletes as a response to fatigue in the muscles around the ankle joint (triceps calf muscle, tibialis anterior) [38,39]. We observed this preference especially in static conditions, both with and without visual support. This is most likely due to peripheral neuromuscular fatigue and hyperventilation, which affect multiple links in the kinematic chain [31,39,40]. The methods we used in this study mainly led to muscle fatigue in the lower limbs, and especially in the ankle area. The effect of this can be a reduction in the effectiveness of reflex loops responsible for regulating the ankle joint strategy. In our study, dynamic conditions, excluding proprioception and even vision, did not result in post-exercise balance impairment (in SS 5 and SS 6 conditions). Thus, these findings do not confirm the results of previous studies, pointing to vestibular information as a source of post-exercise stability impairment [13]. Authors have also reported the effect of acute hypoxia on central nervous system disturbances, leading to impaired neuro-muscular coordination and consequently impaired stability in the anteroposterior plane [41]. Such an association could not be confirmed in our study. Similarly, the form of exercise (cycling) and its short duration did not affect neck muscle fatigue. This was raised by researchers as a factor impairing reflexes, which serve as the source of signals to the central nervous system [39,42,43].

Practical Application and Limitation of the Study

The present study, showing the simultaneous effects of fatigue and hypoxia on balance, is, to our knowledge, the first of its kind to show not only the effect of a combination of these two factors, but also their isolated effects. Our results are relevant to practitioners and especially important for those starting to train in high altitude conditions. We have shown in this study that the simultaneous effects of hypoxia and anaerobic exercise (fatigue) have little effect on balance. Nevertheless, in this study we did not analyze additional factors that may affect balance and these factors should be considered by practitioners. Among these factors, we should mention thermal conditions, wind, humidity, type of ground, a different altitude than the one simulated in this study and a different type of exercise. The results obtained indicate an increasing compensatory role for cognitive functions. This also suggests that this factor should also be taken into account when exercising at high altitudes.

5. Conclusions

The results indicate that short-term exposure to high altitude (hypoxia) combined with anaerobic exercise has no significant effect on balance. Therefore, the risk of consequences related to balance disorders (e.g., falls) is low. Our study showed differential effects of maximal anaerobic exercise and hypoxia on balance in young men. It confirmed considerable adaptive possibilities, especially under dynamic conditions, where vestibular and cognitive resources can be used to minimize the negative effects of fatigue. Short-term hypoxia does not negatively affect static balance, but has a moderate positive effect on dynamic balance when the vestibular and visual systems are used.

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Data Availability Statement: The datasets analyzed during the study are available from the corresponding author (P.B.) upon reasonable request.

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