Differences in the effect of sleep deprivation on the postural stability among men and women

Marta Ołpińska-Lischka (✉ m.olpinska.lischka@tlen.pl)

Akademia Wychowania Fizycznego im Eugeniusza Piaseckiego w Poznaniu <https://orcid.org/0000-0001-5079-4548>

Karolina Kujawa

Akademia Wychowania Fizycznego im Eugeniusza Piaseckiego w Poznaniu

Janusz Maciaszek (✉ jmaciaszek@awf.poznan.pl)

Akademia Wychowania Fizycznego im Eugeniusza Piaseckiego w Poznaniu

Research

Keywords: sleep deprivation, postural control, posturography, gender difference

Posted Date: August 3rd, 2020

DOI: <https://doi.org/10.21203/rs.3.rs-48565/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Version of Record: A version of this preprint was published at International Journal of Environmental Research and Public Health on April 5th, 2021. See the published version at <https://doi.org/10.3390/ijerph18073796>.

Abstract

Objective: Sleepiness caused by poor sleep hygiene may increase the risk of injuries and damages during physical activity. Individual data so far indicate a generally better static postural stability of women regardless of sleeping conditions. The main aim of this study was to assess the impact of sleep deprivation on postural stability according to gender after 24 hours of sleep deprivation.

Methods: Participants included 83 students (36 men and 47 women). Postural stability was measured with eyes open and closed eyes before and after sleep deprivation. Data from posturographic platform were used to assess postural stability objectively.

Results: The type of test determined the size of observed changes in postural stability. The data suggest that women are better able to cope with the effects of sleep deprivation than men.

Conclusion: Postural control system is very important in sport and in physically active people. The results show that men are more sensitive to sleep deprivation than women because they had higher COP path length values in tests. Less postural stability of the body due to sleep deprivation indicates a higher risk of injury during physical activity.

Introduction

The prerequisite for maintaining a stable posture is primarily the proper functioning of vestibular, somatosensory and visual systems. The lack of integration of one of these systems may lead to reduced postural stability [1].

Another factor that may affect postural stability is attention and concentration. Nurwulan et al. (2015) found that the dual task, which was based on texting while maintaining balance on the posturographic platform, contributed to lower postural stability in static student conditions [2]. Other studies by Donker et al. (2007) used the paradigm of the dual task in young men and women to study their postural stability using the posturograph. The authors observed that more difficult attempts to say specific words backwards ("Simon" – "nomis") decreased the postural control [3].

The next factor causing postural instability of the body is a small amount of sleep, which is often characterized by young people [4]. As a result of insufficient sleep, motor fitness, and especially postural body control, deteriorates [5]. Gomez et al. (2008), who applied sleep deprivation to young people, noticed a deterioration in postural stability after just 24 hours of sleep deprivation, but only in a task with closed eyes on a vibrating platform. Unexpectedly, after 36 hours of sleep deprivation, there was no further deterioration in postural stability, and the number of swaying was similar to that after 24 hours of sleep deprivation [6]. In several cases, even less swaying was recorded after 36 hours of sleep deprivation than after 24 hours of sleep deprivation. However, in the study conducted by Nakano et al. (2001), it was observed that 19-hour sleep deprivation negatively affected postural control in men, and swaying was greater in the sample with closed eyes than in the sample with open eyes [7].

The level of postural control may also vary between genders [8], but the results obtained so far are inconsistent. Gender differences in postural control have sometimes been reported under normal sleep patterns. Sullivan et al. (2014) during 60-second posturographic tests with closed and open eyes recorded better static stability in the female sex [8]. In the study by Greve et al. (2013), young women and young men aged 20–27 years were examined with two 20-second static measurements separated by one-minute intervals. Postural stability indicators were better in women than in men in the open-eye study [9]. However, the assessment of postural stability under conditions of relative silence with closed and open eyes among PE students clearly was in favour of women than men [10]. There are also some recent studies, which indicate better values of posturographic parameters of women, although the difference in these studies was small [11].

There are also studies available where no differences in postural stability between women and men have been shown [12]. In the Bryant et al. study (2005), there were no differences between men and women in the posturographic study during static samples [13]. Lee and Petrofsky (2018) even studied differences in postural control in men and women during menstruation and ovulation. There were no differences in postural control between women during menstruation and men. Significant statistical changes were observed only in women during ovulation, where men showed less body swaying in the position with their feet apart and eyes closed on hard surface and in the three most difficult tasks. The authors suggest that increased limpness in the main ligaments of the foot occurs during ovulation, and this may cause more frequent sports injuries in women during ovulation [14].

Therefore, gender and sleep deprivation are factors that may affect postural stability [1]. Several studies are available that describe postural stability after sleep deprivation. However, postural stability is usually assessed after a normally sleepy night. In addition, the majority of studies in this area have been conducted mainly among people with visual impairment [15] and other clinical populations such as Parkinson's [16] and multiple sclerosis [17]. The results of studies in such populations usually provide more obvious and predictable results, but the mechanism of these changes may be more determined by the disease than by sleep deprivation. There is a lack of studies among young and healthy people and therefore studies in young people with impaired sleep hygiene, assessing gender differences in posture control seem to be necessary to analyse the differences and mechanisms of their development. Sleepiness caused by poor sleep hygiene may increase the risk of injuries and damages during physical activity. In addition, although individual data so far indicate a generally better static postural stability of women regardless of sleeping conditions, the data are insufficient. Therefore, the main aim of this study is to assess the impact of sleep deprivation on postural stability according to gender after 24 hours of sleep deprivation.

On the basis of literature review, two hypotheses were formulated:

1. COP path length will be extended after sleep deprivation, regardless of the role of sight in maintaining postural stability.

2. Sleep deprivation will negatively affect the postural stability level, increasing the COP path length more in men than in women.

Material And Methods

Ethics Statement

All participants gave their informed written consent prior to participation according to procedures approved by the Ethics Committee of the Poznan University of Medical Sciences in Poland, approval number 989/17.

Subjects

The test was conducted among students of physical education studies. The study entered 107 students. *Of the 107 subjects who were enrolled in the study, 24 subject withdrew due to: night work (N = 2), orthopedic problems (N = 5), complications without precise definition (N = 17).* A total of 83 young, healthy people took part in the experiment. The students were divided into two groups. The experimental group (EG) consisted of 25 women ($\text{Mean}_{\text{age}} 21 \pm 1,04 \text{ SD}_{\text{age}}$) and 17 men ($\text{Mean}_{\text{age}} 21,36 \pm 1,01 \text{ SD}_{\text{age}}$) and the control group (CG) of 22 women ($\text{Mean}_{\text{age}} 21,63 \pm 0,78 \text{ SD}_{\text{age}}$) and 19 men ($\text{Mean}_{\text{age}} 21,58 \pm \text{SD}_{\text{age}} 0,04 \text{ years}$). The study population was recruited after the lectures from the University of Physical Education. Subjects willing to participate in the study were selected and then divided into a control and an experimental group. Participants were divided with similar numbers of men and women in each study group. The number of subjects was considered sufficient [18–20]. The study included persons who met the following inclusion criteria.

The inclusion criteria were as follows: abandonment of the alcoholic and caffeine beverages on the day of study, consumption of the last meal until 8 pm not exceeding 350 kcal and consent to participate in the study. The exclusion criteria were also included: age between 18 and 30 years; use of sleeping pills, mental illness and acute medical conditions, no injuries on the legs and with no history of balance or orthopedic problems based on self-reports. During the qualification interview, the participants were informed about the scope of study and the possibility of resigning from participation in the experiment at each stage without giving any reason (Fig. 1).

Procedure

In this experiment, postural stability was examined using the AccuGait AMPI PJB-101 posturographic platform. Each student participated in three experimental conditions: initial measurements (zero test), which took place a few days earlier, aimed at familiarizing with the tests.

Subjects were tested two times for each group (CG: 1st session: non sleep deprivation and 2nd session: non sleep deprivation and EG: 1st session: non sleep deprivation, 2nd session: sleep deprivation). Testing

procedures were separated for one week. All measurements were taken between 6:30 and 8 am due to the possible influence of time-of-day on postural control (Forsman et al. 2008).

One week before each testing (1st and 2nd session) subjects had to maintain regular sleep schedules. Participants were advised to perform normal daily activities. No intake of caffeine, alcohol, energy drinks and late physical activity was allowed before each session.

In the control group, two measurements were conducted on two separate dates always after a normally sleeping night (1st session and 2nd session) in their own homes. In the experimental group, the first session was the same as for the control group, i.e. after a normally sleeping night. The second session was conducted after 24 hours of sleep deprivation in the experimental group. On the day of study, in the morning, the experimental group received an actigraph (Caltrac). The participants were required not to take naps during the day, which was verified by a daily physical activity measurement using actigraphs. The experimental group received the actigraphs on the day of the experiment (8:00 am). The results were not presented in the text, because the measurement only had a control purpose to check whether the study participants were physically active during the day.

The experimental group spent the sleepless night in the university building under the care and control of the researchers. To ensure the testing procedure according to the protocol, participants were monitored under the supervision of a research staff throughout the night. During the test, activating forms were planned for the participants, such as: board games, playing cards, puzzles. Before the main study after sleep deprivation, students could have breakfast and drink water. The measurement after sleep deprivation (2nd session) was carried out in the morning (6:30 – 8:00 am) (Fig. 2).

Measure

Posturographic tests were carried out on the AccuGait AMPI PJB-101 platform. The sequence of tests was the same for each participant in the experiment. The duration of a single test was 30 seconds. The following measurements were conducted: measurement with eyes open in free position (EO), measurement with eyes closed in free position (EC). In addition, the Romberg index was calculated from these tests. Values that are higher than 1 indicate greater oscillation with the eyes closed. Zero or negative values mean lower postural oscillation with the eyes closed [21].

Among the parameters obtained from own observations and literature analysis, it was assumed that path length [22], sway area and velocity [23] are the most valuable for estimating postural stability. Therefore, the most commonly used parameter for analysis was COP path length, which determines the distance travelled by COP (mm).

Statistical analysis

For statistical evaluation, Statistica 10 software (StatSoft Inc., OK, USA) was used. Statistical calculations were conducted using ANOVA variance analysis. The effect of sleep deprivation in the control and experimental group was evaluated within the COP path length parameter in the sample with open and

closed eyes, and then the Romberg index was calculated with the following formula: [(surface EC/surface EO)]. Main effects and interaction effects in the studied groups were determined. Differences between control and experimental groups were explored using Mann-Whitney U-rank test. In order to characterize the collected material, the basic measures of descriptive statistics were calculated and presented using the arithmetic mean (Mean) and standard deviation (SD). Statistical significance was determined at the level of $p < 0.05$.

Results

Table 1 shows result of session 1st between each group. In eyes-closed conditions, the mean postural path length COP increase compared to eyes open condition (Table 1).

Tab. 1. Total path length during 30 s of quiet standing with the eyes open (EO) and closed (EC) in experimental and control group in 1st session.

	<i>Control</i>		<i>Experimental</i>			
Postural task	Men		Men		<i>U-test</i>	<i>p-value</i>
	<i>Mean</i>	<i>SD</i>	<i>Mean</i>	<i>SD</i>		
EO [mm]	68,17	8,33	66,45	8,35	129	.310
EC [mm]	82,02	20,02	87,94	17,08	126	.267
	Women		Women			
Postural task	<i>Mean</i>	<i>SD</i>	<i>Mean</i>	<i>SD</i>	<i>U-test</i>	<i>p-value</i>
EO [mm]	64,59	6,74	69,37	7,8	184	.053
EC [mm]	78,28	16,3	83,29	12,81	209	.162

Note: EO - eyes open; EC - eyes closed; SD - standard deviation; U-test - value of the Mann-Whitney U-test statistic; p-value - significant at the $p < .05$ level.

Analysis of the results with ANOVA test shows the size of changes in mean values for the parameter COP path length in standing position. In test 1 (EO) an increase in the value of path length after sleep deprivation was noted only in men ($F = 0.036$, $p = .849$). In the experimental group of women the path length range did not increase after sleep deprivation ($F = .119$, $p = .731$) (Table 2).

In the first session, in the EC test, higher COP path length values than in EO were observed. However, after 24-hour sleep deprivation, no path length extension was observed in the experimental group. No significant statistical changes were found in the tested groups (women $F = 1.221$, $p = .275$; men $F = 2.505$, $p = .123$) (Table 2).

Comparison of obtained Romberg indices for the COP path length parameter revealed statistically significant changes. The differences between the experimental and control groups of men were statistically significant ($F = 6.083$, $p = .019$), but not in women ($F = .924$, $p = .341$) (Table 2).

Tab. 2. Changes in the path length of postural tests before and after sleep deprivation in control and experimental group.

Postural task	Men				Interaction <i>F(p)</i>
	<i>CG</i>		<i>EG</i>		
	<i>Mean</i>	<i>SD</i>	<i>Mean</i>	<i>SD</i>	
EO ¹ [mm]	68,17	8,33	66,45	8,35	F=0.036, p=.849
EO ² [mm]	71,16	8,46	69,49	12,53	
EC ¹ [mm]	82,02	20,02	87,94	17,08	F=2.505, p=.123
EC ² [mm]	86,81	20,30	83,43	19,88	
Romberg ¹	1,20	0,25	1,32	0,20	F=6.083, p=.019*
Romberg ²	1,21	0,25	1,00	0,49	

Postural task	Women				Interaction <i>F(p)</i>
	<i>CG</i>		<i>EG</i>		
	<i>Mean</i>	<i>SD</i>	<i>Mean</i>	<i>SD</i>	
EO ¹ [mm]	64,59	6,74	69,37	7,80	F=0.119, p=.731
EO ² [mm]	64,00	6,16	67,99	13,11	
EC ¹ [mm]	78,28	16,30	83,29	12,81	F=1.221, p=.275
EC ² [mm]	79,68	11,35	79,86	15,57	
Romberg ¹	1,21	0,20	1,20	0,17	F=0.924, p=.341
Romberg ²	1,24	0,13	1,14	0,31	

Note: ^{1,2} – session 1st, session 2nd, CG - control group, EG - experimental group

Discussion

The effect of 24-hour sleep deprivation on postural control in healthy young women and men was studied. It was found that 24-hour sleep deprivation did not adversely affect the posture control of examined women. In men, the results after sleep deprivation showed a deterioration in the open eye test and in the Romberg index. The Romberg index revealed the most statistically significant changes in men ($p < 0.05$).

Stable posture depends largely on visual stimuli. Our first measurement was conducted in a calm standing position with open eyes. Pham et al. (2014) believe that such a simple test is not enough to expect any changes in postural control after sleep deprivation [24]. However, in other studies [18, 25] and in our own study, this test constituted a reference point for the rest of tests. Usually the average values of open-eye stabilometric parameters are often lower than in other tests. This shows that this measurement is correctly used for comparison with other tests. An increase in the COP path length in the open eye test after sleep deprivation was only recorded in men in the experimental group, and this indicates less stable postural control of men after a sleepless night. The mechanism of change is unclear, but postural stability is strongly associated with lower limb muscle strength [26]. The study conducted by Kujawa et al. (2020) showed that 24 h sleep deprivation reduced lower limb muscle strength in young students [27], and this may have been due to a change in body temperature after 24 h sleep deprivation [28]. This in turn may have resulted in a decrease in muscle function [7]. Postural instability caused by sleep deprivation is probably correlated with this factor. However, these correlations require further studies with EMG.

Visual information may lead to both abnormal postural control of the body and its improvement [29]. In our study, the elimination of visual control resulted in higher COP path length values compared to the open eye study in the experimental and control group. However, based on a literature review [6, 18, 30], postural stability was expected to deteriorate after 24-hour sleep deprivation in the studied students. However, in the closed-eye sample, the COP path length recorded after sleep deprivation did not deteriorate in the experimental group of men and women. Unfortunately, due to the lack of such analyses of stability changes in sleep deprivation according to gender, our observations cannot be confronted with others. It is difficult to explain the reason for the lack of deterioration of body stability after sleep deprivation in the experimental group in this study. It is known that postural control is strongly related to attention processes [30], and cognitive load has an important role in postural control in sleep deprivation [31]. Sleep deprivation impairs cognitive functions and leads to a decrease in regional brain activity. The thalamus and prefrontal cortex regulate cognitive functions such as vigilance and attention. Due to increased sleepiness, tasks requiring more attention become more difficult to perform and require more effort [32]. However, healthy and young people are characterized by better cognitive processes than older people [33], and proper focus of attention can even improve posture control after sleep deprivation [34]. It can be assumed that students, despite the lack of visual control, were able to concentrate in such a way that the lack of sleep did not negatively affect their posture stability. In addition, other studies [35] noted that the subjects were more alert in standing position than sitting after 28 hours of sleep deprivation. The EEG measurement showed that the vertical position increased excitement and allowed them to maintain attention. This may be another aspect explaining the results. In addition, there is a relation between psychological processes and postural control of the body, whereas a reduced mood can have a destabilizing effect on postural control [36]. Thus, there are several different factors that may condition postural control of young people after sleep deprivation.

The Romberg test is used to compare body imbalance in position with open and closed eyes [37]. Many studies have been conducted using this test in conditions after a normal night's sleep, but only a few

studies have used sleep deprivation to test postural control. After sleep deprivation, Ma et al. (2009) did not report significant changes in (male) students' (Romberg's) postural control [25]. In another study, Bougard et al. (2019) found that the Romberg index values were higher in the closed-eye test, but did not deteriorate after sleep deprivation.¹⁹ In our experiment, the analysis of changes in the Romberg index values showed a higher sensitivity to visual stimuli in the male group than in the female group after sleep deprivation ($p < 0.05$). This means that men are more sensitive to lack of visual information which affects their less stable body posture. Collins and DeLuca (1995) put forward a hypothesis that the lack of visual stimuli increases the rigidity of musculoskeletal system, which leads to destabilization of postural control [38], and this could be the reason for greater changes in postural stability in the male group. However, further physiological studies between muscle activity and COP displacement are needed to confirm this assumption [39]. Since the obtained Romberg's coefficient values cannot be referred to any other publication which is based on a similar test procedure, assessing gender differences in detail, further measurements (in other study groups) are needed to confirm the recorded results.

Some papers reported a greater variability in postural stability throughout the day [40], which was still present on the day after the sleep reduction in subjects. However, repeated postural control studies in other papers showed inconsistent results [20]. Due to the postural variability suggested by the above mentioned researchers, depending on the time of day, it is worthwhile to carry out measurements more often during the whole day, especially in the case of healthy people. Our study was conducted in the morning hours and the measurement was conducted only once at each of session. Since other parameters were analyzed at the same time, it would be tiresome and tedious for the subjects to test postural stability several times at two measurement sessions. This could be a factor determining the results obtained in subsequent measurements. It is possible that several measurements of postural control during the day after sleep deprivation would show greater differences between men and women.

In addition, when measuring with open and closed eyes (EO, EC), it was noticed that the mean COP path length results of the control group women between sessions did not deteriorate significantly ($p > 0.05$). Such a result may indicate differences in the quality of sleep in women. Therefore, sleep quality should be assessed before and during the entire experiment to confirm if the same pattern of changes for EO and EC conditions in each group exists.

Perspectives and significance

There is widespread interest in the study of gender differences in various domains, but sex differences in postural stability is seldom studied. Our results confirm the tendency that women have better postural stability than men. The differences were especially noticeable in the eyes-closed task after sleep deprivation. This could be the result of a number of factors, such as the chronic poor quality of sleep that often characterizes young people. More research are needed to investigate these and other potential correlate factors to confirm these findings.

Conclusions

In conclusion, it was found that sleep deprivation did not affect the deterioration of postural control in all the tests. The type of test (with open eyes or closed eyes) determined the size of observed changes in postural stability. Therefore, the first hypothesis should be rejected.

The data suggest that women are better able to cope with the effects of sleep deprivation than men. This confirms the second hypothesis that young female students show more stable body posture than men after sleep deprivation.

Postural control system is very important in sport and in physically active people. The results show that men are more sensitive to sleep deprivation than women because they had higher COP path length values in tests. Less postural stability of the body due to sleep deprivation indicates a higher risk of injury during physical activity.

Declarations

Ethics approval and consent to participate

The study has been approved by the Ethical Committee of the Poznan University of Medical Sciences in Poland.

Competing interests

The authors declare no competing interests.

Acknowledgements

We gratefully acknowledge the participants who contributed to this work.

Authors' contributions

M.O.-L.: conception, methodology, writing—original draft, visualization, project administration; K. K.: supervision; J. M.: conception, methodology, writing-review & editing, formal analysis.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding authors on reasonable request.

Funding

None.

Consent for publication

Not applicable.

References

1. Montesinos L, Castaldo R, Cappuccio FP, Pecchia L. Day-to-day variations in sleep quality affect standing balance in healthy adults. *Sci Rep*. 2018;8(1):1–10.
2. Nurwulan NR, Jiang BC, Iridiastadi H. Posture and texting: effect on balance in young adults. *PLoS ONE*. 2015;10(7):e0134230.
3. Donker SF, Roerdink M, Greven AJ, Beek PJ. Regularity of center-of-pressure trajectories depends on the amount of attention invested in postural control. *Exp Brain Res*. 2007;181(1):1–11.
4. Ahrberg K, Dresler M, Niedermaier S, Genzel L. The interaction between sleep quality and academic performance. *J Psychiatr Res*. 2012;46:1618–22.
5. Avni N, Avni I, Barenboim E, Azaria B, Zadok D, Kohen-Raz R, Morad Y. Brief posturographic test as an indicator of fatigue. *Psychiatry Clin Neurosci*. 2006;60:340–6.
6. Gomez S, Patel M, Berg S, Magnusson M, Johansson R, Fransson PA. Effects of proprioceptive vibratory stimulation on body movement at 24 and 36 h of sleep deprivation. *Clinic Neurophysiol*. 2008;119(3):617–25.
7. Nakano T, Araki K, Michimori A, Inbe H, Hagiwara H, Koyama E. Nineteen-hour variation of postural sway, alertness and rectal temperature during sleep deprivation. *Psychiatry Clin Neurosci*. 2001;55(3):277–8.
8. Sullivan EV, Rose J, Rohlfing T, Pfefferbaum A. Postural sway reduction in aging men and women: relation to brain structure, cognitive status, and stabilizing factors. *Neurobiolog Aging*. 2009;30(5):793–807.
9. Greve JM, Cug M, Dülgeroğlu D, Brech GC, Alonso AC: Relationship between anthropometric factors, gender, and balance under unstable conditions in young adults. *BioMed Res Intr*. 2013, 1–5 (2013).
10. Polechoński J, Błaszczyk J. The effect of acoustic noise on postural sway in male and female subjects. *J Hum Kinet*. 2006;15:37–52.
11. Wiegmann S, Felsenberg D, Gast U, Börst H, Armbrrecht G, Dietzel R. Balance performance across the lifespan assessed by the Leonardo Mechanograph: a cross-sectional study. *J Funct Morphol Kinesiol*. 2019;5:1.
12. Røgind H, Lykkegaard JJ, Bliddal H, Danneskiold-Samsøe B. Postural sway in normal subjects aged 20–70 years. *Clin Physiol Funct Imaging*. 2003;23:171–6.
13. Bryant E, Trew ME, Bruce A, Kuisma R, Smith AW. Gender differences in balance performance at the time of retirement. *Clin Biomech*. 2005;20(3):330–5.
14. Lee H, Petrofsky J. Differences between men and women in balance and tremor in relation to plantar fascia laxity during the menstrual cycle. *J Athl Train*. 2018;53(3):255–61.
15. Soares AV, Oliveira CS, Knabben RJ, Domenech SC, Junior B. N. G.: Postural control in blind subjects. *Einstein (Sao Paulo)*. 2011;9(4):470–6.

16. Feller KJ, Peterka RJ, Horak FB. Sensory Re-weighting for postural control in Parkinson's Disease. *Front Hum Neurosci*. 2019;13:126.
17. Morrison S, Rynders CA, Sosnoff JJ. Deficits in medio-lateral balance control and the implications for falls in individuals with multiple sclerosis. *Gait Posture*. 2016;49:148–54.
18. Patel M, Gomez S, Berg P, Almbladh P, Lindblad J, Petersen H, Magnusson M, Johansson R, Fransson PA. Effects of 24-h and 36-h sleep deprivation on human postural control and adaptation. *Exp Brain Res*. 2008;185:165–73.
19. Bougard C, Lepelley MC, Davenne D. The influences of time-of-day and sleep deprivation on postural control. *Exp Brain Res*. 2011;209:109–15.
20. Martin T, Gauthier A, Ying Z, Benguigui N, Moussay S, Bulla J, Davenne D, Bessot N. Effect of sleep deprivation on diurnal variation of vertical perception and postural control. *J Appl Physiol (1985)*. 2018;125(1):167–74.
21. Tjernström F, Björklund M, Malmström EM. Romberg ratio in quiet stance posturography-test to retest reliability. *Gait Posture*. 2015;42(1):27–3.
22. Nagymáté G, Orlovits Z, Kiss RM. Reliability analysis of a sensitive and independent stabilometry parameter set. *PLoS ONE*. 2018;13(4):e0195995.
23. Hertel J, Gay MR, Denegar CR. Differences in postural control during single-leg stance among healthy individuals with different foot types. *J Athl Train*. 2002;37(2):129–32.
24. Pham QC, De Mello MT, Narciso FV, Mônico Neto M, Teixeira CW, Antonietti LS, Garbuio SA, Fernandes Júnior SA, Koyama RG, Duarte M, Tufik S. Robust evaluation of time since awakening using force platform posturography. *Rev Bras Eng Bioméd*. 2014;30(4):322–9.
25. Ma J, Yao YJ, Ma RM, Li JQ, Wang T, Li XJ, Han WQ, Hu WD, Zhang ZM. Effects of sleep deprivation on human postural control, subjective fatigue assessment and psychomotor performance. *J Int Med Res*. 2009;37:1311–20.
26. Han L, Yang F. Strength or power, which is more important to prevent slip-related falls? *Hum Mov Sci*. 2015;44:192–200.
27. Kujawa K, Ołpińska-Lischka M, Maciaszek J. The influence of 24-hour sleep deprivation on the strength of lower limb muscles in young and physically fit women and men. *Sustainability*. 2020;12(7):2762.
28. Landis CA, Savage MV, Lentz MJ, Brengelmann GL. Sleep deprivation alters body temperature dynamics to mild cooling and heating not sweating threshold in women. *Sleep*. 1998;21(1):101–8.
29. Luo H, Wang X, Fan M, Deng L, Jian C, Wei M, Luo J. The effect of visual stimuli on stability and complexity of postural control. *Front Neurol*. 2018;8(9):48.
30. Liu Y, Higuchi S, Motohashi Y. Changes in postural sway during a period of sustained wakefulness in male adults. *Occup Med*. 2001;51:490–5.
31. Robillard R, Prince F, Boissonneault M, Filipini D, Carrier J. Effects of increased homeostatic sleep pressure on postural control and their modulation by attentional resources. *Clin Neurophysiol*.

2011a;122(9):1771–8.

32. Thomas M, Sing H, Belenky G, Holcomb H, Mayberg H, Dannals R, Wagner H, Thorne D, Popp K, Rowland L, Welsh A, Balwinski S, Redmond D. Neural basis of alertness and cognitive performance impairments during sleepiness. Effects of 24 h of sleep deprivation on waking human regional brain activity. *J Sleep Res.* 2000;9(4):335–52.
33. Robillard R, Prince F, Boissonneault M, Carrier J. Aging worsens the effects of sleep deprivation on postural control. *PLoS One.* 2011;6(12):e28731.
34. Diekfuss JA, Janssen JA, Slutsky AB, Berry NT, Etnier JL, Wideman L, Raisbeck LD. An external focus of attention is effective for balance control when sleep-deprived. *Int J Exerc Sci.* 2018;11(5):84–94.
35. Caldwell JA, Prazinko B, Caldwell JL. Body posture affects electroencephalographic activity and psychomotor vigilance task performance in sleep-deprived subjects. *Clin Neurophysiol.* 2003;114(1):23–31.
36. Bolmont B, Gangloff P, Vouriot A, Perrin PP. Mood states and anxiety influence abilities to maintain balance control in healthy human Subjects. *Neurosci Lett.* 2002;23(1):96–100. 329).
37. Fabbri M, Martoni M, Esposito MJ, Brighetti G, Natale V. Postural control after a night without sleep. *Neuropsychologia.* 2006;44:2520–5.
38. Collins JJ, De Luca CJ. The effects of visual input on open-loop and closed-loop postural control mechanisms. *Exp Brain Res.* 1995;103(1):151–63.
39. Tanaka H, Nakashizuka M, Uetake T, Itoh T. The effects of visual input on postural control mechanisms: an analysis of center-of-pressure trajectories using the auto-regressive model. *J Human Ergol.* 2000;29:15–25.
40. Forsman P, Tietäväinen A, Wallin A, Haeggström E. Modeling balance control during sustained waking allows posturographic sleepiness testing. *J Biomech.* 2008;41:2892–4.

Figures

Figure 1

Flowchart of participants included in the study.

Figure 2

Schematic experimental design. Note: EO - eyes open; EC - eyes closed