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Section IV – Psychological and Sociological Aspects of Sport and Exercise

Circadian-Dependent Effects of Sleep Restriction on Vestibular Function and Postural Control

by

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Balance is the ability to integrate vestibular, somatosensory, and visual inputs to maintain the body's center of gravity within its stability limits. While chronic poor sleep habits are known to impair postural control, the acute effects of a single night of bad sleep remain controversial. This study aimed to determine whether one night of poor sleep would affect postural control, using objective sleep and balance assessments. Forty-eight subjects (age = 22.15 ± 0.47 years; BMI = 22.20 ± 0.34) performed the modified Clinical Test of Sensory Interaction in Balance (m-CTSIB), which evaluates the vestibular, proprioceptive, and visual components of balance through four distinct conditions. The tests were conducted at 9:00 AM and 6:00 PM on separate days. Participants wore an actigraph the night before each test, and based on National Sleep Foundation cut-offs, they were classified as Good Sleepers (GS), Intermediate Sleepers (IS), or Bad Sleepers (BS). In the evening session, BS exhibited significantly higher oscillation index values than both GS and IS ($p = 0.01$), indicating worse balance control. No significant differences were found between GS and IS. Poor sleep quality and quantity can significantly impair balance, particularly its vestibular component, in the evening. These findings enhance our understanding of the physiological relationship between sleep and balance, with implications for athletic training and fall prevention.

Keywords: *sleep; sleep habits; balance; vestibular; actigraphy*

Introduction

Balance is a complex physiological function that integrates sensory inputs from the vestibular, somatosensory, and visual systems to maintain the body's center of gravity within its stability limits (Yim-Chiplis and Talbot, 2000). The vestibular system, located bilaterally within the inner ear, consists of three semicircular canals that encode angular head acceleration and two otolithic organs that encode linear acceleration. This system detects head motion and integrates it with proprioceptive inputs from muscle spindles and Golgi tendon organs, informing the central nervous system about body positioning, and with visual inputs from the retina, which provide spatial orientation. These afferent signals are processed in the vestibular nuclei and projected to neural structures that regulate posture and balance (Cullen, 2012).

Balance control is influenced by multiple central and peripheral factors, including muscle strength, nerve conduction, reflexes, joint range of motion, and cortical processing (Horak, 1987). Many of these factors fluctuate across the day following a circadian rhythm, characterized by an acrophase (peak), bathyphase (trough), and a midline value—Midline Estimating Statistic of Rhythm (MESOR) (Cornelissen and Otsuka, 2017). Muscle strength peaks between 4:00 PM and 6:00 PM (Douglas et al., 2021), similarly to joint range of motion, which closely linked to muscle viscoelastic properties; this is additionally enhanced by the increased body temperature observed in the afternoon. Cortical and spinal excitability also follow the circadian rhythm (Tamm et al., 2009),

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and their acrophase seems to be influenced by the chronotype (CT), i.e., the circadian typology of a subject (Adan et al., 2012).

The CT is shaped by genetic, social, and environmental factors (Roenneberg et al., 2007). Typically, three major CT categories are distinguished, thus individuals can be classified as: morning-types (M-types), who are usually good sleepers, more active early in the day and tend to be well-aligned with societal rhythms; evening-types (E-types), who are often poor sleepers, exhibit desynchronized rhythm compared to societal rhythms; neither-types (N-types), who display intermediate characteristics (Adan et al., 2012; Horne and Ostberg, 1976; Mulè et al., 2022).

Given the circadian regulation of neuromuscular and cognitive functions, it is reasonable to hypothesize that balance also follows the circadian rhythm. However, studies investigating time-of-day effects on balance have yielded inconsistent results (Deschamps et al., 2013; Russo et al., 2015). Some researchers propose that balance remains stable due to compensatory mechanisms, where deficits in one system (e.g., proprioception) are counterbalanced by other sensory inputs (Zouabi et al., 2016). On the other hand, other studies suggest that postural control deteriorates because of fatigue due to sleep deprivation (Morad et al., 2007; Nakano et al., 2001).

Sleep is a critical physiological process regulating numerous metabolic, cognitive, and motor functions (Pace-Schott and Hobson, 2002). Both sleep duration and quality influence exercise performance, but this relationship remains incompletely understood. Studies examining the effects of sleep restriction, deprivation, and impairment on strength, endurance, agility, and neurocognitive performance have reported mixed findings (Castelli et al., 2022; Ciorciari et al., 2023; Fullagar et al., 2015; Vitale et al., 2017). However, the literature seems to agree that chronic poor sleep appears to impair physical performance, and a recent systematic review suggests that even acute sleep deficits may disproportionately affect evening performance (Craven et al., 2022).

Regarding balance, strong evidence links chronic and acute sleep deprivation to postural control impairment (Umemura et al., 2022). Some research reports that chronic poor sleep quality impairs balance similarly to acute total sleep deprivation (Kirshner et al., 2022). However, most studies assessing the acute effects of sleep impairment focus on total sleep deprivation (Martin et al., 2018; Morad et al., 2007; Umemura et al., 2022), a condition rarely representative of real-world sleep patterns. It is essential to determine the cut-offs of sleep quality and duration in which balance starts being compromised. Furthermore, the majority of the above-mentioned studies performed field tests for the balance assessment and administered questionnaires to evaluate sleep rather than lab tests and objective sleep assessments such as actigraphy. Additionally, few studies have accounted for the chronotype (Martin et al., 2018), and balance has often been tested only once per day, neglecting potential circadian fluctuations and synchrony effects (Malek et al., 2023).

Although the impact of sleep on balance has been widely studied, certain unresolved questions remain. Therefore, this study aimed to address these gaps by employing objective assessments of sleep and balance through actigraphy and the modified Clinical Test of Sensory Interaction in Balance (m-CTSIB), and standardized categorization cut-offs to determine whether a single night of habitual, naturally occurring (i.e., not experimentally altered) poor sleep quality could influence postural control. Additionally, we investigated how different balance components (vestibular, proprioceptive, and visual) responded to sleep-related effects, identifying which was most susceptible. Finally, by assessing balance in both morning and evening sessions, this study explored potential *time-of-day* effects on postural stability.

Methods

Study Design

The study protocol was based on balance tests performed twice within the same week: once in the morning (9:00 AM; AM session), and once in the evening (6:00 PM; PM session). Participants visited the laboratory three times. The first was a preliminary session carried out on Monday, during which participants underwent anthropometric measurements, including body mass, height, and skinfold thickness assessments via plicometry. They also completed two validated questionnaires: the reduced Morningness-Eveningness Questionnaire (rMEQ) (Adan and Almirall, 1991) and the Mini-Sleep Questionnaire (MSQ) (Zoomer et al., 1985). After completing the questionnaires, participants were instructed to wear an actigraph the nights before the tests. The second and third visits at the laboratory were the test sessions, carried out on the weekdays (between Tuesday and Thursday) to avoid any potential confounders due to possible different sleep patterns associated with the weekends. During these sessions, participants randomly performed the balance test in the AM or the PM session.

Before the study commenced, potential participants were informed about the study's aims, methods, potential risks, and benefits, and they provided written informed consent. The study was conducted from March to December 2022, with testing suspended during summer. The protocol adhered to the 1964 Declaration of Helsinki and was approved by the University of Milan's Ethical Review Board, Milan, Italy (approval code: 82/22; approval date: 27 September 2022).

Participants

Forty-eight students (50% males, 50% females; age = 22.15 ± 0.47 years; BMI = 22.20 ± 0.34) from the Sport Science program at the University of Milan were recruited. Participants were excluded if they were undergoing pharmacological treatment or had any health conditions that could affect physical performance or sleep quality. General descriptive statistics of the participants are displayed in Table 1.

Chronotype and Sleep Assessment: Questionnaires and Actigraphy

The two administrated questionnaires were the rMEQ (Adan and Almirall, 1991; Montaruli et al., 2017) which assessed the chronotype (M-type, N-type, or E-type), and the MSQ (Natale et al., 2014; Zoomer et al., 1985), which evaluated subjective sleep quality over the past week. In our experimental protocol, the MSQ was used only to check whether the participants had a normal sleep the week before the test sessions, in order to avoid any confounding factor.

Participants wore the actigraph (MotionWatch 8, CamNtech, UK) on their non-dominant wrist for sleep monitoring. Although other methods, such as polysomnography, would have been more accurate, actigraphy represents a validated and reliable tool that allows the objective assessment of sleep variables in a less invasive manner (Ancoli-Israeli et al., 2003). The device, set to record at 60-s intervals, measured several variables, including sleep latency, actual sleep time, and the fragmentation index. Among these, sleep efficiency (SE) and assumed sleep (AS) (Galasso et al., 2023) were the key variables used in our main analysis. To mark their bedtime and wake time, participants pressed a button on the actigraph. The recorded data were analyzed using MotionWare 1.2.28 software (CamNtech, UK).

Balance Assessment: m-CTSIB

Balance was evaluated using the modified Clinical Test of Sensory Interaction in Balance (m-CTSIB, Prokin 252N, TecnoBody, Italy), a validated test assessing the integration of vestibular, visual, and proprioceptive inputs (Dawson et al., 2018). The test included four conditions:

- Eyes Open, Rigid Surface (EOR): a baseline condition,
- Eyes Closed, Rigid Surface (ECR): a condition with no visual afferents,
- Eyes Open, Soft Surface (EOS): a condition with limited proprioceptive afferents,
- Eyes Closed, Soft Surface (ECS): a condition under which vestibular function was isolated without additional visual or proprioceptive input.

Each trial lasted 30 s, during which participants stood barefoot on the stabilometric platform while a trunk-mounted sensor measured oscillations (oscillation index, OI). Moreover, an overall mean was calculated. The OI is an objective measure of the average postural sway exhibited by the subject's center of pressure (COP). It is calculated by triangulating the mean COP displacement on both the mediolateral and anteroposterior axes with the corresponding standard deviations. The resulting biaxial value, obtained through vector summation, reflects the overall degree of oscillation. The final OI value represents the mathematical average across all trials performed by the subject. A higher OI indicated poorer balance control. To ensure consistency, the same researcher supervised all tests, and participants maintained the same foot position across sessions. Before testing, participants were individually familiarized with the protocol, and they could ask all the questions they needed. The trial order was randomized to minimize test-specific motor learning effects. All postural tests were conducted under consistent lighting conditions in the same laboratory room. The space was illuminated by two ceiling-mounted fluorescent tubes (58 W, approximately 150 cm in length), each emitting between 5200 and 5400 lumens, for a total light output of approximately 10,400–10,800 lumens. The lights were positioned to avoid direct exposure to both the participant and the device screen, ensuring that illumination did not interfere with the testing procedure. All testing took place in a temperature-controlled, noise-free environment.

Statistical Analysis

All statistical analyses were performed with SPSS v.28 (IBM) and GraphPad Prism v.10, with significance set at $p = 0.05$.

Data Normality, Sleep Quality Categorization and Group Comparisons

To evaluate data distribution and group characteristics, a Shapiro-Wilk test was used to assess normality, while the Levene's test was applied to verify variance homogeneity.

Participants were classified based on their actigraphic sleep quality from the night before each test, using National Sleep Foundation cut-offs (Hirshkowitz et al., 2015; Ohayon et al., 2017). Participants with SE of 85% or higher and AS of at least 7 hours were categorized as Good Sleepers (GS). Those with SE at or below 75% and AS of 6 hours or less were classified as Bad Sleepers (BS). Individuals whose sleep variables fell between these two thresholds were designated as Intermediate Sleepers (IS). In this way, we categorized as Good Sleepers only those participants who could be confidently considered as having good sleep, and as Bad Sleepers only those who could be confidently considered as having poor sleep, while the Intermediate Sleepers represented all cases in between. This classification was performed twice: once before the morning test (AM session) and once before the evening test (PM session) to specifically analyze the effects of sleep from the preceding night.

One-way ANOVA was conducted to compare age across sleep quality (GS, IS, BS) and CT (M-type, N-type, or E-type) groups, and an independent *t*-test examined potential sex-based differences in balance performance. Since no significant age and sex differences emerged, these two variables were excluded from the main analyses.

Main Analysis

A two-way ANOVA (SQ × CT interaction) examined whether sleep quality and the chronotype interacted to influence balance performance. Additionally, a repeated measures ANOVA assessed differences in balance across time of the day (AM vs. PM) based on the CT and SQ. When necessary, post-hoc analyses with Bonferroni correction were conducted. Effect sizes were calculated using Cohen's *d*.

Results

Following CT classification, 14 participants were identified as morning-types (M-types), 19 as neither-types (N-types), and 15 as evening-types (E-types) (Figure 1A and 1B).

Regarding sleep quality, the AM session included 16 good sleepers (GS), 28 intermediate sleepers (IS), and 4 bad sleepers (BS), while the PM session included 17 GS, 26 IS, and 5 BS (Figure 1C and 1D).

Actigraphic Data

Sleep variables recorded the night before both test sessions are reported in Table 2.

Balance Performance in GS, IS, and BS

Oscillation index (OI) values recorded during the m-CTSIB tests in both AM and PM sessions are presented in Table 3.

In the AM session, no statistically significant differences were found.

In the PM session, significant differences were observed under the ECS condition ($F = 4.71$, $df = 2$, $p = 0.01$, $\eta p^2 = 0.17$) and in the overall mean OI ($F = 5.05$, $df = 2$, $p = 0.01$, $\eta p^2 = 0.18$). Post-hoc analysis with Bonferroni correction revealed that BS had significantly higher OI values than both GS and IS under the ECS condition ($p = 0.01$, $p = 0.02$) and in the overall mean OI ($p = 0.01$, $p = 0.01$). No significant differences emerged between GS and IS.

Chronotype and Sleep Interactions

The two-way ANOVA (SQ × CT interaction) showed no significant interaction effects between sleep quality and the chronotype on balance performance.

Similarly, repeated measures ANOVA indicated no significant differences in balance across AM and PM sessions based on chronotype classification.

Table 1. Descriptive statistics of the sample (mean ± SE).

Age (yrs)	Body mass (kg)	Body height (m)	BMI (kg/m²)	MSQ score	Fat Mass (%)	Fat-free Mass (%)
22.15 ± 0.47	65.42 ± 1.63	1.71 ± 0.01	22.20 ± 0.34	23.08 ± 1.14	16.16 ± 1.12	83.84 ± 1.12

Table 2. Descriptive statistics of the actigraphic variables of the night before the AM and PM tests (mean ± SE).

		SLEEP VARIABLES OF THE NIGHT BEFORE THE AM TEST				
	n	Assumed Sleep (hh:mm)	Actual Sleep Time (hh:mm)	Sleep Efficiency (%)	Sleep Latency (hh:mm)	Fragmentation Index
GS	16	07:43 ± 0:11	06:30 ± 00:09	83.36 ± 0.79	00:03 ± 00:01	22 ± 1.5
IS	28	06:34 ± 00:10	05:03 ± 00:07	75.25 ± 1.52	00:08 ± 00:02	31.83 ± 2.15
BS	4	04:57 ± 00:16	03:37 ± 00:14	70.63 ± 3.12	00:09 ± 00:06	37.2 ± 6.42
		SLEEP PARAMETERS OF THE NIGHT BEFORE THE PM TEST				
	n	Assumed Sleep (hh:mm)	Actual Sleep Time (hh:mm)	Sleep Efficiency (%)	Sleep Latency (hh:mm)	Fragmentation Index
GS	17	07:54 ± 00:10	06:42 ± 00:09	83.45 ± 0.76	00:05 ± 00:01	21.45 ± 1.9
IS	26	06:41 ± 00:13	05:07 ± 00:09	74.31 ± 1.05	00:14 ± 00:03	32.08 ± 1.67
BS	5	05:32 ± 00:21	04:08 ± 00:15	68.14 ± 2.86	00:32 ± 00:13	26 ± 3.03

GS: good sleepers; IS: intermediate sleepers; BS: bad sleepers

Table 3. Mean OI and SE of the m-CTSIB in the AM and PM tests.

		AM TEST SESSION				
AM	n	Oscillation Index EOR	Oscillation Index ECR	Oscillation Index EOS	Oscillation Index ECS	Oscillation Index Mean
GS	16	0.2 ± 0.02	0.28 ± 0.03	0.26 ± 0.02	0.6 ± 0.05	0.33 ± 0.02
IS	28	0.18 ± 0.01	0.23 ± 0.01	0.26 ± 0.01	0.54 ± 0.02	0.30 ± 0.01
BS	4	0.16 ± 0.03	0.2 ± 0.02	0.26 ± 0.04	0.54 ± 0.03	0.3 ± 0.01
		PM TEST SESSION				
PM	n	Oscillation Index EOR	Oscillation Index ECR	Oscillation Index EOS	Oscillation Index ECS	Oscillation Index Mean
GS	17	0.16 ± 0.01	0.24 ± 0.02	0.23 ± 0.01	0.55 ± 0.03*	0.3 ± 0.01#
IS	26	0.18 ± 0.01	0.23 ± 0.01	0.24 ± 0.01	0.54 ± 0.02°	0.3 ± 0.01§
BS	5	0.19 ± 0.04	0.27 ± 0.04	0.29 ± 0.01	0.77 ± 0.15*,°	0.38 ± 0.06#,§

*$p = 0.01$; * GS vs. BS (ECS); ° IS vs. BS (ECS), $p = 0.02$; # GS vs. BS (Mean), $p = 0.01$; § IS vs. BS (Mean), $p = 0.01$*

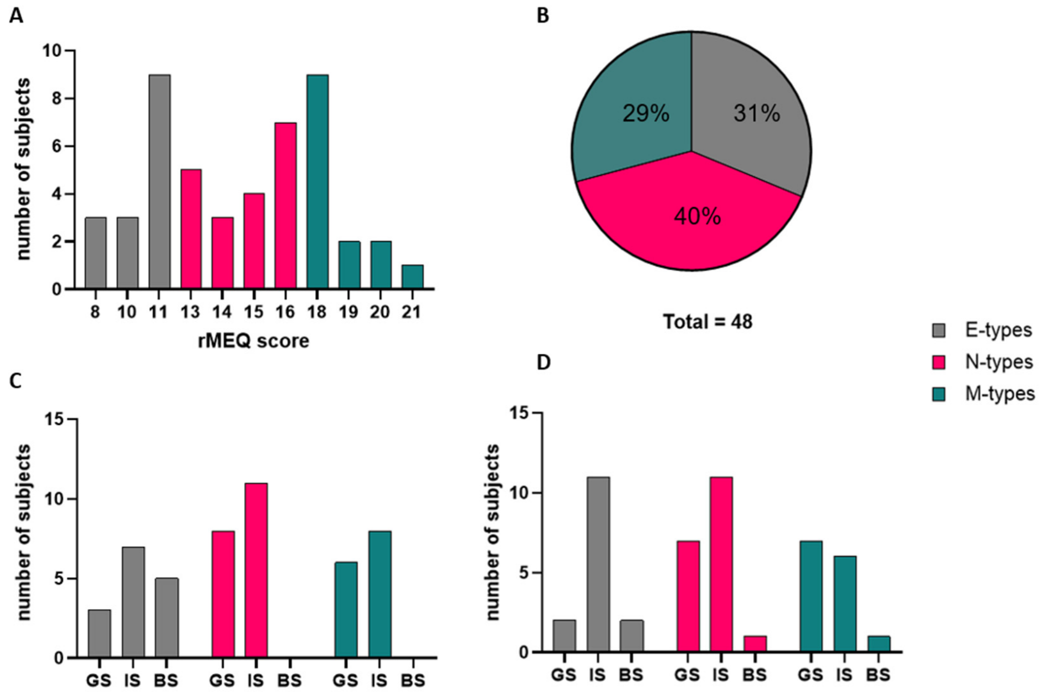

Figure 1. Sample distribution by chronotype and sleep quality. Figure 1A and 1B: chronotype distribution of the sample according to the rMEQ score (A) and cut-offs (B): M-types = 14; N-types = 19; E-types = 15. Figure 1C and 1D: chronotype distribution within the Good Sleepers (GS), Intermediate Sleepers (IS) and Bad Sleepers (BS) before the AM (C) and PM session (D).

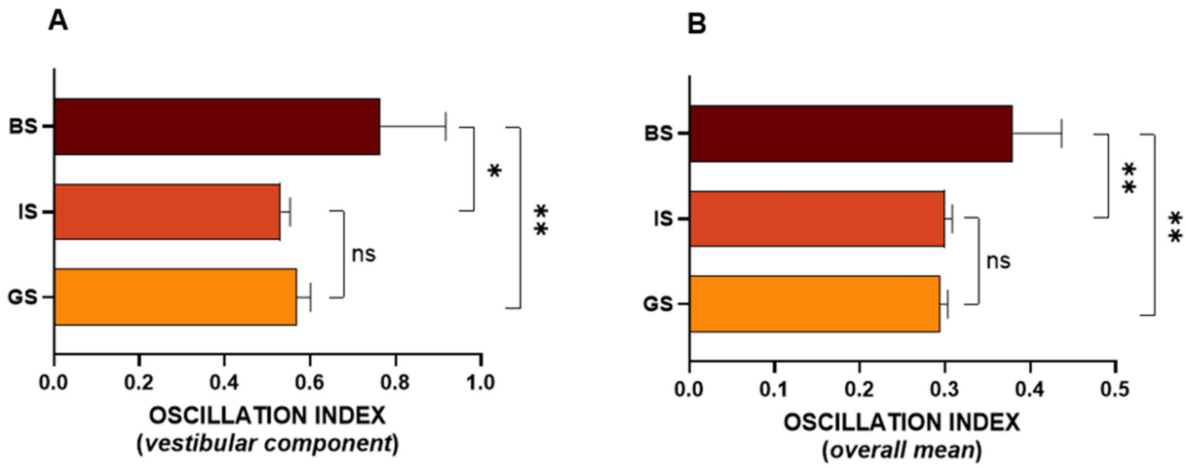

Figure 2. Sample distribution by chronotype and sleep quality. Comparison among GS, IS, and BS under the m-CTSIB ECS condition (A) and in the overall Mean in the PM test (B).

$* p < 0.05$; $** p < 0.01$

Discussion

This study examined the acute effects of sleep quality on postural control using objective sleep (actigraphy) and balance (m-CTSIB) assessments. The findings indicate that poor sleep quality significantly impaired balance, particularly its vestibular component, in the evening performance. Bad Sleepers (BS) exhibited a 29% higher oscillation index (OI) than Good Sleepers (GS) and Intermediate Sleepers (IS) under the vestibular-only condition (ECS), as well as in the overall balance score during the PM session. However, no significant differences were observed in the morning performance, suggesting a possible circadian modulation of sleep-related balance deficits.

While previous research has established that chronic sleep deprivation negatively affects balance (Martin et al., 2018; Morad et al., 2007; Umemura et al., 2022), these results suggest that even a single night of poor sleep can impair vestibular function, particularly in the evening. However, our data indicate that only severe impairments in both sleep quality and duration compromise performance. This aligns with the conclusions of Umemura et al. (2022) who found that sleep deprivation began to impair balance only after a certain threshold of sleep loss was reached. The IS group, which included individuals with either low sleep quality or short sleep duration (therefore, individuals experiencing only mild sleep disturbances), did not show significant differences compared to GS, reinforcing the idea that both quality and duration must be severely compromised for balance deficits to emerge.

Interestingly, the CT did not appear to influence these results, which may be due to an imbalance in group sizes, as the BS category was predominantly composed of E-types. Given that E-types tend to perform better in the evening than M- and N-types (Ciorciari et al., 2023, 2024; Facer-Childs et al., 2018; Vitale and Weydahl, 2017), this further supports our findings. The higher OI in BS during the PM session could be explained by the fact that E-types are more vulnerable to sleep debt, whereas M- and N-types generally show greater adaptability to sleep impairments (Glavin et al., 2021). However, a further interpretation of our findings in relation to the chronotype, sleep quality, and postural control can be proposed. Recent evidence suggests that the interaction between the chronotype and time since awakening may significantly influence physical and cognitive performance (Facer-Childs and Brandstaetter, 2015). Facer-Childs and Brandstaetter (2015) demonstrated that peak athletic performance occurred after specific hours since awakening depending on the chronotype, with M- and N-types reaching their peak approximately 5.5 and 6 hours after waking, respectively, while E-types peaked around 11 hours post-awakening. This temporal dynamic may be particularly relevant when interpreting our results, as the significant effects of poor sleep emerged only during the afternoon postural task. One possible explanation is that the extended time awake prior to the afternoon session may have increased the vulnerability to the negative effects of sleep loss, offsetting the potential benefits of circadian alignment, which in theory should favor performance later in the day. In other words, while circadian factors might support better postural control in the evening, the detrimental impact of accumulated wakefulness and insufficient sleep could outweigh these benefits, leading to the impaired performance we observed. In line with this, Cheng et al. (2018) reported that mental fatigue following sleep deprivation increased as a function of time since awakening, leading to poorer performance in postural control tasks. These findings support the notion that the duration of wakefulness may act as a compounding factor, amplifying the detrimental effects of insufficient sleep on postural stability. Our results appear to align with this perspective, suggesting that both sleep quantity/quality and timing relative to wakefulness should be considered when evaluating postural performance.

Vestibular System Vulnerability to Sleep Problems

The vestibular system is crucial for postural control, and the ECS condition was the only one to include a test in which participants could not rely on alternative sensory inputs to stabilize posture, making it possibly the most sensitive to sleep-related impairments. At the central nervous system level, sleep deprivation disrupts thalamic sensory integration and cerebellar motor coordination, both essential for maintaining balance (Umemura et al., 2022). Additionally, autonomic nervous system imbalances induced by poor sleep create a stress-like physiological response similar to overtraining syndrome, which may impair motor control and postural stability (Fullagar et al., 2015).

Beyond its role in balance, the vestibular system also interacts with sleep regulation. Vestibular disorders are known to be associated with sleep disturbances (Mutlu and Topcu, 2022), but the reverse effect—how sleep deprivation influences vestibular function—has been less explored. Moreover, the vestibular system is involved in biological rhythms, affecting body temperature cycles in rodents (Martin et al., 2015) and interacting with orexinergic neurons which regulate wakefulness (Besnard et al., 2018). These connections suggest that sleep problems may directly disrupt vestibular function, leading to increased postural instability, particularly when alternative sensory mechanisms are unavailable. These mechanisms likely explain why balance impairments in BS participants were most evident in the vestibular-dependent condition.

The impact of time of the day on balance remains a topic of debate. While some studies report that postural stability remains stable over a 24-hour period (Deschamps et al., 2013; Russo et al., 2015), others indicate that sleep loss exacerbates balance deficits (Morad et al., 2007; Nakano et al., 2001). The present findings contribute to this discussion by demonstrating that the effects of acute sleep problems on balance are time-dependent, emerging specifically in the evening. Most prior studies have focused on chronic sleep deprivation rather than acute sleep problems regarding both quality and duration, leaving open the question of how much sleep is required to maintain postural stability and how good its quality needs to be. In this regard, the results of the present study align with the conclusions of Umemura et al. (2022) who emphasized the need for further investigation into the threshold at which sleep loss begins to impair balance. Additionally, these findings reinforce the importance of objective assessments in sleep research, as actigraphy and m-CTSIB provide more reliable data than self-reported sleep measures, which are often subject to recall bias and variability.

Strengths and Limitations

This study has several strengths, including the objective assessment of both sleep and balance, the rigorous participant categorization, and the evaluation of balance at both morning and evening time points. By analyzing all three balance components (vestibular, proprioceptive, and visual), it provides a comprehensive perspective on sleep's impact on postural control. The use of National Sleep Foundation criteria also ensured standardized classification of sleep quality and duration. However, some limitations should be acknowledged. The small sample size of the BS group limits the generalizability of the findings. Moreover, actigraphy was used only on the night preceding each test, while habitual sleep over the previous week was assessed through the Mini-Sleep Questionnaire. Although this approach helped us exclude the influence of chronic sleep problems, extending actigraphic monitoring to multiple consecutive days would have provided a clearer and more objective picture of participants' usual sleep condition. Also, given that both balance and sleep are strongly influenced by age, future studies should include a wider age range to determine whether these effects persist across different populations. Finally, incorporating data on participants' habitual training times could offer further insights into the acrophase of their rest-activity circadian rhythm, improving the precision of future analyses.

Conclusions

In conclusion, these findings have important implications for both sports performance and fall prevention. By simultaneously assessing both sleep duration and efficiency, this study provides a more comprehensive understanding of how acute sleep influences postural control. Unlike previous research that often considers only one of these factors, our approach acknowledges that long sleep duration does not necessarily imply high sleep quality, and vice versa. Athletes who rely on postural control should prioritize both sleep quality and duration, particularly before evening competitions, to minimize the risk of balance impairments. Similarly, older adults may face a higher risk of falls after a poor night's sleep, especially when both sleep duration and efficiency are compromised. Future research should further explore how acute sleep affects dynamic balance and reaction time, investigate whether training adaptations can mitigate sleep-related impairments, and examine the influence of habitual training time and the chronotype on postural control.

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References

Adan, A., & Almirall, H. (1991). Horne & Östberg morningness-eveningness questionnaire: A reduced scale. *Personality and Individual Differences*, *12*(3), 241–253. https://doi.org/10.1016/0191-8869(91)90110-W

Adan, A., Archer, S. N., Hidalgo, M. P., Di Milia, L., Natale, V., & Randler, C. (2012). Circadian typology: A comprehensive review. *Chronobiology International*, *29*(9), 1153–1175. https://doi.org/10.3109/07420528.2012.719971

Ancoli-Israel, S., Cole, R., Alessi, C., Chambers, M., Moorcroft, W., & Pollak, C. P. (2003). The role of actigraphy in the study of sleep and circadian rhythms. *Sleep*, *26*(3), 342–392. https://doi.org/10.1093/sleep/26.3.342

Besnard, S., Tighilet, B., Chabbert, C., Hitier, M., Toulouse, J., Le Gall, A., Machado, M. L., & Smith, P. F. (2018). The balance of sleep: Role of the vestibular sensory system. *Sleep Medicine Reviews, 42*, 220–228. https://doi.org/10.1016/j.smrv.2018.09.001

Castelli, L., Walzik, D., Joisten, N., Watson, M., Montaruli, A., Oberste, M., Roveda, E., & Zimmer, P. (2022). Effect of sleep and fatigue on cardiovascular performance in young, healthy subjects. *Physiology & Behavior, 256*, 113963. https://doi.org/10.1016/j.physbeh.2022.113963

Cheng, S., Sun, J., Ma, J., Dang, W., Tang, M., Hui, D., Zhang, L., & Hu, W. (2018). Posturographic balance validity in mental and physical fatigue assessment among cadet pilots. *Aerospace Medicine and Human Performance, 89*(11), 961–966. https://doi.org/10.3357/AMHP.5128.2018

Ciorciari, A., Castelli, L., Galasso, L., Mulè, A., Esposito, F., Roveda, E., & Montaruli, A. (2024). Social jetlag affects jump skills in sub-elite volleyball players. *Frontiers in Sports and Active Living, 6*, 1443804. https://doi.org/10.3389/fspor.2024.1443804

Ciorciari, A., Mulè, A., Castelli, L., Galasso, L., Esposito, F., Roveda, E., & Montaruli, A. (2023). Sleep and chronotype influence aerobic performance in young soccer players. *Frontiers in Physiology, 14*, 1190956. https://doi.org/10.3389/fphys.2023.1190956

Cornelissen, G., & Otsuka, K. (2017). Chronobiology of aging: A mini-review. *Gerontology, 63*(2), 118–128. https://doi.org/10.1159/000450945

Craven, J., McCartney, D., Desbrow, B., Sabapathy, S., Bellinger, P., Roberts, L., & Irwin, C. (2022). Effects of acute sleep loss on physical performance: A systematic and meta-analytical review. *Sports Medicine, 52*(11), 2669–2690. https://doi.org/10.1007/s40279-022-01706-y

Cullen, K. E. (2012). The vestibular system: Multimodal integration and encoding of self-motion for motor control. *Trends in Neurosciences, 35*(3), 185–196. https://doi.org/10.1016/j.tins.2011.12.001

Dawson, N., Dzurino, D., Karleskint, M., & Tucker, J. (2018). Examining the reliability, correlation, and validity of commonly used assessment tools to measure balance. *Health Science Reports, 1*(12), e98. https://doi.org/10.1002/hsr2.98

Deschamps, T., Magnard, J., & Cornu, C. (2013). Postural control as a function of time-of-day: Influence of a prior strenuous running exercise or demanding sustained-attention task. *Journal of NeuroEngineering and Rehabilitation, 10*, 26. https://doi.org/10.1186/1743-0003-10-26

Douglas, C. M., Hesketh, S. J., & Esser, K. A. (2021). Time of day and muscle strength: A circadian output? *Physiology, 36*(1), 44–51. https://doi.org/10.1152/physiol.00030.2020

Facer-Childs, E. R., & Brandstaetter, R. (2015). The impact of circadian phenotype and time since awakening on diurnal performance in athletes. *Current Biology, 25*(4), 518–522. https://doi.org/10.1016/j.cub.2014.12.036

Facer-Childs, E. R., Boiling, S., & Balanos, G. M. (2018). The effects of time of day and chronotype on cognitive and physical performance in healthy volunteers. *Sports Medicine - Open, 4*, 47. https://doi.org/10.1186/s40798-018-0162-z

Fullagar, H. H. K., Skorski, S., Duffield, R., Hammes, D., Coutts, A. J., & Meyer, T. (2015). Sleep and athletic performance: The effects of sleep loss on exercise performance, and physiological and cognitive responses to exercise. *Sports Medicine, 45*(2), 161–186. https://doi.org/10.1007/s40279-014-0260-0

Galasso, L., Calogiuri, G., Castelli, L., Mulè, A., Esposito, F., Caumo, A., Montaruli, A., & Roveda, E. (2023). Theoretical construct into blocks of actigraphic-derived sleep parameters. *Chronobiology International, 40*(2), 174–185. https://doi.org/10.1080/07420528.2022.2157737

Glavin, E. E., Ceneus, M., Chanowitz, M., Kantilierakis, J., Mendelow, E., Mosquera, J., & Spaeth, A. M. (2021). Relationships between sleep, exercise timing, and chronotype in young adults. *Journal of Health Psychology, 26*(13), 2636–2647. https://doi.org/10.1177/1359105320926530

Hirshkowitz, M., Whiton, K., Albert, S. M., Alessi, C., Bruni, O., DonCarlos, L., Hazen, N., Herman, J., Adams Hillard, P. J., Katz, E. S., Kheirandish-Gozal, L., Neubauer, D. N., O'Donnell, A. E., Ohayon, M., Peever, J., Rawding, R., Sachdeva, R. C., Setters, B., Vitiello, M. V., & Ware, J. C. (2015). National Sleep Foundation's updated sleep duration recommendations: Final report. *Sleep Health, 1*(4), 233–243. https://doi.org/10.1016/j.sleh.2015.10.004

Horak, F. B. (1987). Clinical measurement of postural control in adults. *Physical Therapy, 67*(12), 1881–1885.

Horne, J. A., & Östberg, O. (1976). A self-assessment questionnaire to determine morningness-eveningness in human circadian rhythms. *International Journal of Chronobiology, 4*(2), 97–110.

Kirshner, D., Spiegelhalder, K., Shahar, R. T., Shochat, T., & Agmon, M. (2022). The association between objective measurements of sleep quality and postural control in adults: A systematic review. *Sleep Medicine Reviews, 63*, 101633. https://doi.org/10.1016/j.smrv.2022.101633

Malek, E. M., Navalta, J. W., & McGinnis, G. R. (2023). Time of day and chronotype-dependent synchrony effects exercise-induced reduction in migraine load: A pilot cross-over randomized trial. *International Journal of Environmental Research and Public Health, 20*(3), 2083. https://doi.org/10.3390/ijerph20032083

Martin, T., Gauthier, A., Ying, Z., Benguigui, N., Moussay, S., Bulla, J., Davenne, D., & Bessot, N. (2018). Effect of sleep deprivation on diurnal variation of vertical perception and postural control. *Journal of Applied Physiology, 125*, 167–174. https://doi.org/10.1152/japplphysiol.00595.2017

Martin, T., Mauvieux, B., Bulla, J., Quarck, G., Davenne, D., Denise, P., Philoxène, B., & Besnard, S. (2015). Vestibular loss disrupts daily rhythm in rats. *Journal of Applied Physiology, 118*, 310–318. https://doi.org/10.1152/japplphysiol.00811.2014

Montaruli, A., Galasso, L., Carandente, F., Vitale, J. A., Roveda, E., & Caumo, A. (2017). If the Morningness-Eveningness Questionnaire (MEQ) is able to predict the actigraphy-based acrophase, how does its reduced, five-item version (rMEQ) perform? *Chronobiology International, 34*(4), 443–444. https://doi.org/10.1080/07420528.2017.1306708

Morad, Y., Azaria, B., Avni, I., Barkana, Y., Zadok, D., Kohen-Raz, R., & Barenboim, E. (2007). Posturography as an indicator of fatigue due to sleep deprivation. *Aviation, Space, and Environmental Medicine, 78*(9), 859–863.

Mulè, A., Galasso, L., Castelli, L., Ciorciari, A., Michielon, G., Esposito, F., Roveda, E., & Montaruli, A. (2022). Lifestyle of Italian university students attending different degree courses: A survey on physical activity, sleep and eating behaviors during the COVID-19 pandemic. *Sustainability, 14*(22), 15340. https://doi.org/10.3390/su142215340

Mutlu, B., & Topcu, M. T. (2022). Investigation of the relationship between vestibular disorders and sleep disturbance. *International Archives of Otorhinolaryngology, 26*(4), e688–e696. https://doi.org/10.1055/s-0042-1742763

Nakano, T., Araki, K., Michimori, A., Inbe, H., Hagiwara, H., & Koyama, E. (2001). Nineteen-hour variation of postural sway, alertness and rectal temperature during sleep deprivation. *Psychiatry and Clinical Neurosciences, 55*(3), 277–278. https://doi.org/10.1046/j.1440-1819.2001.00858.x

Natale, V., Fabbri, M., Tonetti, L., & Martoni, M. (2014). Psychometric goodness of the Mini Sleep Questionnaire. *Psychiatry and Clinical Neurosciences, 68*(7), 568–573. https://doi.org/10.1111/pcn.12161

Ohayon, M., Wickwire, E. M., Hirshkowitz, M., Albert, S. M., Avidan, A., Daly, F. J., Dauvilliers, Y., Ferri, R., Fung, C., Gozal, D., Hazen, N., Krystal, A., Lichstein, K., Mallampalli, M., Plazzi, G., Rawding, R., Scheer, F. A., Somers, V., & Vitiello, M. V. (2017). National Sleep Foundation's sleep quality recommendations: First report. *Sleep Health, 3*(1), 6–19. https://doi.org/10.1016/j.sleh.2016.11.006

Pace-Schott, E. F., & Hobson, J. A. (2002). The neurobiology of sleep: Genetics, cellular physiology and subcortical networks. *Nature Reviews Neuroscience, 3*(8), 591–605. https://doi.org/10.1038/nrn895

Roenneberg, T., Kuehnle, T., Juda, M., Kantermann, T., Allebrandt, K., Gordijn, M., & Merrow, M. (2007). Epidemiology of the human circadian clock. *Sleep Medicine Reviews, 11*(6), 429–438. https://doi.org/10.1016/j.smrv.2007.07.005

Russo, L., D'Eramo, U., Padulo, J., Foti, C., Schiffer, R., & Scoppa, F. (2015). Day-time effect on postural stability in young sportsmen. *Muscles, Ligaments and Tendons Journal, 5*(1), 38–42.

Tamm, A. S., Lagerquist, O., Ley, A. L., & Collins, D. F. (2009). Chronotype influences diurnal variations in the excitability of the human motor cortex and the ability to generate torque during a maximum voluntary contraction. *Journal of Biological Rhythms, 24*(3), 211–224. https://doi.org/10.1177/0748730409334135

Umemura, G. S., Furtado, F., Santos, F. C., Gonçalves, B. S. B., & Forner-Cordero, A. (2022). Is balance control affected by sleep deprivation? A systematic review of the impact of sleep on the control of balance. *Frontiers in Neuroscience, 16*, 779086. https://doi.org/10.3389/fnins.2022.779086

Vitale, J. A., Bonato, M., Galasso, L., La Torre, A., Merati, G., Montaruli, A., Roveda, E., & Carandente, F. (2017). Sleep quality and high intensity interval training at two different times of day: A crossover study on the influence of the chronotype in male collegiate soccer players. *Chronobiology International, 34*(2), 260–268. https://doi.org/10.1080/07420528.2016.1256301

Vitale, J. A., & Weydahl, A. (2017). Chronotype, physical activity, and sport performance: A systematic review. *Sports Medicine, 47*(9), 1859–1868. https://doi.org/10.1007/s40279-017-0741-z

Yim-Chiplis, P. K., & Talbot, L. A. (2000). Defining and measuring balance in adults. *Biological Research for Nursing, 1*(4), 321–331.

Zoomer, J., Peder, R., Rubin, A. H., & Lavie, P. (1985). Mini Sleep Questionnaire for screening large populations for excessive daytime sleepiness complaints. *Sleep '84,* 467–470.

Zouabi, A., Quarck, G., Martin, T., Grespinet, M., & Gauthier, A. (2016). Is there a circadian rhythm of postural control and perception of the vertical? *Chronobiology International, 33*(10), 1320–1330. https://doi.org/10.1080/07420528.2016.1215993