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The Effects of Subjective Fatigue on Postural Stability during Static Stances in Healthy Adults

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Abstract: Postural stability decreased following fatigability induced by muscular fatigue and mental fatigue. However, little research has focused on investigating the effects of subjective fatigue (perceptions of fatigue) on postural stability. This study aimed to explore the effects of subjective fatigue on postural stability by investigating the body sway during static stances in individuals with or without subjective fatigue. After completing questionnaires, forty participants divided into fatigue and control groups. They were instructed to stand barefoot on a force plate under two different visual conditions. The trajectories of the center of pressure (COP) were recorded synchronously, and the range, RMS, velocity, the area of the COP were calculated. Frequency analysis was also employed to calculate the ratio of b ody sway across different frequency bands, as well as the fractal dimension of COP to determine the complexity of body sway. Participants reporting subjective fatigue exhibited significantly higher mental fatigue, as well as larger sway range and RMS in anterior-posterior direction. Both two groups showed increased sway range, RMS and velocity in medial-lateral direction after their eyes were closed. The frequency analysis showed a decreased ratio on the MF band in anterior-posterior direction in anterior-posterior direction. The non-linear analysis showed differential change of FD between the fatigue and the control group. Fatigue primarily affected postural control in the anterior-posterior direction,, and altered the frequency characteristics and complexity of postural sway. These findings have implications may inform interventions aimed at mitigating the risk of falls or balance impairments in fatigued populations.

1. Introduction

Postural control is crucial for everyday activities. The integrity of postural control involves a complex interplay of sensory inputs, motor outputs, and central nervous system processes to maintain an upright stance and prevent falls [1, 2]. It is often compromised under various conditions, including fatigue. Fatigue, a pervasive phenomenon experienced by individuals due to sleep loss, circadian phase, and workload, could significantly impact mental or physical performance capabilities [3, 4].

Repeated general or local muscular exercises, resulting in muscular fatigue, had been shown to cause a decline in postural stability [5]. Muscular fatigue led to an increase in the area and velocity of body sway [6]. Chronic muscular fatigue, induced by long-term standing, similarly resulted in an increase in body sway velocity [7]. In individuals experiencing exercise-induced fatigue, central postural control strategies also change when in facing with sudden postural perturbations. By adjusting the timing and intensity of the anticipatory postural adjustments, body sway following perturbations could be managed, thereby mitigating the impact on postural stability and balance [8]. Likewise, mental fatigue induced by repeated cognitive tasks had comparable effects on postural stability, including a decline in stability and alterations in central postural control strategies [9, 10]. The studies of the effects of fatigue on postural stability is, therefore, significant. Understanding the impact of fatigue on postural stability has significant practical implications. In occupations where maintaining balance was critical, such as aviation, surgery, or construction, managing fatigue was essential to ensure safety and prevent accidents [11]. Similarly, in sports, where balance and coordination were crucial for performance, understanding the effects of fatigue on postural stability could inform training and recovery strategies to enhance performance and reduce injury risk [12, 13]. In rehabilitation, identifying how fatigue affected postural stability could guide interventions to improve balance and prevent falls, particularly in populations with compromised balance, such as older adults or individuals with neurological conditions [14-16].

However, most studies on the impact of fatigue on postural stability had been conducted under conditions involving repetitive exercises or long-term cognitive tasks that induced physical or mental fatigue. These types of fatigue focused on the performance aspects and should be referred to as fatigability. Fatigability was defined as the magnitude or rate of change in performance relative to a reference value while performing a specific task, including physical performance and cognitive functions [17]. It was not surprising that changes in posture stability occured following exercise-induced or long-term cognitive task-induced fatigue. Conversely, the perception of fatigue referred to the subjective sensation of weariness, an increasing sense of effort, a mismatch between effort expended and actual performance, or exhaustion [17]. Previous studies had found that fatigability and perception of fatigue were independent. Researches had shown that patients with multiple sclerosis experience increased subjective fatigue after prolonged cognitive tasks, which did not correspond to changes in cognitive functions [18, 19]. Similarly, the decline in motor performance observed in Parkinson's patients was not consistent with their physical fatigue subscale scores on the Multidimensional Fatigue Inventory [20]. Older adults reported subjective fatigue after repeated walking, yet no changes in step speed were observed [21]. Research about workers in the oil and gas extraction industry also showed a low correlation between physiologic data assessing fatigue after work, such as heart rate, and results from questionnaires assessing fatigue perception [22]. The differences between fatigability and perception of fatigue suggested the need to distinguish between the two when exploring the effects of fatigue on postural stability. However, to our knowledge, research on the impact of subjective fatigue perception on postural stability is lacking.

Thus, this study recruited university students with or without subjective fatigue to complete questionnaires assessing their fatigue levels, followed by measurements of their postural stability using a platform that recorded body sway during static stances under two sensory conditions: eyes open and eyes closed. By comparing body sway between the two groups under different vision conditions, the present study aimed to explore the effects of subjective fatigue on postural stability.

2. Methods

2.1. Participants

Forty participants (16 males, 24 females) were included in this study after providing informed consent. Half of the participants were medical students who reported significant fatigue caused by heavy study load, while half of the participants were students from the same university who reported no significant fatigue. The participants had a mean age of 22.27 (±1.74) years, a mean height of 164.96 (±4.10) cm, and a mean body mass of 58.35 (±7.78) kg. None of the participants had musculoskeletal disorders. Prior to testing, all participants were fully familiarized with the procedure of the test and signed an informed consent form approved by the hospital's Institutional Review Board (ethics approval number: 2024(E2)-KS-095).

2.2. Procedure

Each participant was instructed to complete a questionnaire. They were then asked to stand barefoot on a force plate with their feet together and their arms relaxed by their sides. Participants were instructed to maintain a static stance for 30 seconds under two visual conditions: eyes-open and eyes-closed. In the eyes-open condition, participants were instructed to gaze at a "+" mark positioned 1.5 meters away at eye level on the wall in front of them. In the eyes-closed condition, participants were instructed to keep their heads facing forward. The order of the visual conditions was randomized for each participant. Adequate rest periods were provided between the two trials. The force platform recorded the trajectory of center of pressure (COP) in real time throughout the static stand. Prior to testing, participants were fully informed of the procedure and given sufficient practice. For safety purposes, participants wore harnesses.

2.3. Instrumentation and Data Processing

The questionnaire consisted of two parts. The first part collected basic demographic information, including age, sex, height and weight. The second part utilized the Chinese version of the multidimensional fatigue inventory (MFI) , a valid and efficient tool for assessing self-reported fatigue [23]. The 20-item scale includes five subscales: General Fatigue, Physical Fatigue, Mental Fatigue, Reduced Motivation, and Reduced Activity. Higher scores indicate more severe fatigue. The Cronbach's α of the MFI was 0.84, indicating good construct and convergent validity.

COP displacements were collected using Wii Balance Board (WBB; Nintendo, Kyoto, Japan) and BrainBLox (Brain and Biomechanics Lab in a Box). The WBB is a rectangular platform with pressure sensors at its corners that transmit sensor data to a computer via Bluetooth for amplification and collection, which was proved to be an reliable technology and an easy-to-use tool that can be used to evaluate standing balance [24, 25]. BrainBLox software processes the collected data to compute COP displacements along the anterior-posterior (AP) and medial-lateral (ML) axes. Subsequent offline analysis of COP displacements was performed using MATLAB (MathWorks, Natick, MA, United States). The measures included range, root mean square (RMS), mean velocity, path length, sway area, spectral analysis, and nonlinear methods. Range measures the span between maximum and minimum COP displacements in both AP and ML directions, while RMS quantifies the variability in COP displacements. Mean velocity is derived by dividing COP excursion by standing duration in both AP and ML directions. Path length computes the total distance traveled by the COP. Sway area represents 85% of the total area covered by the COP trajectory [26, 27]. Spectral analysis utilizes a fast Fourier transform to generate power density spectra in both AP and ML directions, which are divided into low-frequency (0-0.3 Hz), median-frequency (0.3-1 Hz), and high-frequency (1-3 Hz) bands [28]. Spectral energy across these bands is normalized by the sum of the three bands and presented as a percentage. Nonlinear methods included fractal dimension (FD) analysis, which was calculated using Higuchi's method [29].

2.4. Statistical analysis

Each parameter was reported as a mean and standard deviation. Statistical analyses were performed using SPSS 22.0 (SPSS Inc., USA). Independent-sampled T-test was conducted to compare the MFI scores between the fatigue group and the control group. Mix-designed two factors analysis were conducted to compare COP features between eye-open and eyes-closed conditions and between the two groups. Simple effect tests were conducted if the interaction was significant. Statistical significance was set at $p<0.05$.

3. Methods

Table 1 The differences in the scores of MFI sub-scales between fatigue group and control group

Sub-Scale	Fatigue	Control	T	p
General Fatigue	11.80±2.91	8.65±3.39	3.15	0.003
Physical Fatigue	9.80±3.37	7.60±3.59	2.00	0.053
Mental Fatigue	10.95±2.89	8.15±3.59	2.72	0.010
Reduced Motivation	11.30±3.53	8.35±3.01	2.84	0.007
Reduced Activities	9.10±2.86	8.10±2.32	1.22	0.232
total	52.95±12.15	40.90±13.22	3.00	0.005

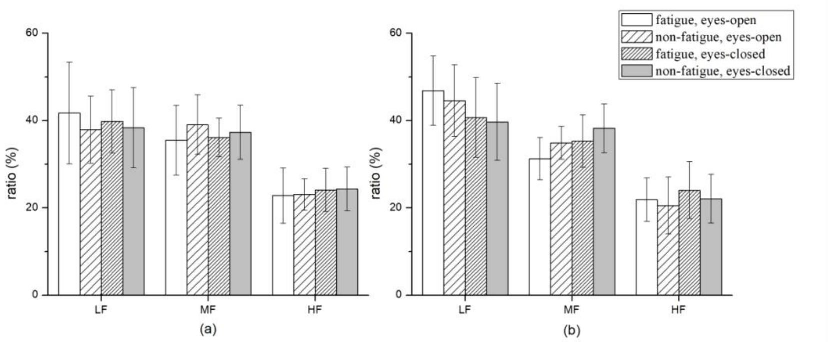
Table 2 The differences in the time-domain parameters of COP between the fatigue group and control group

Parameters	Scores of MFI	Eyes open	Eyes closed
Media-lateral			
Range (cm)	Fatigue	26.76±5.32	30.43±6.66
	Control	22.62±7.09	29.28±7.35
RMS (cm)	Fatigue	4.96±1.31	5.61±1.11
	Control	4.21±1.36	5.28±1.52
Velocity (cm/s)	Fatigue	14.02±2.32	15.81±3.62
	Control	14.20±1.69	15.90±2.28
Anterior-posterior			
Range (cm)	Fatigue	28.23±7.64	32.15±10.48
	Control	23.71±8.99	25.30±7.65
RMS (cm)	Fatigue	5.74±1.74	6.04±1.94
	Control	4.56±1.50	4.81±1.30
Velocity (cm/s)	Fatigue	12.29±2.53	14.70±2.77
	Control	11.12±2.00	13.02±2.37
Path (cm)	Fatigue	623.03±103.58	721.40±138.10
	Control	600.22±81.35	683.10±101.49
Ellipse area (cm2)	Fatigue	327.93±102.07	393.41±156.13
	Control	233.18±125.34	308.34±155.46

Table 1 presents the MFI scores and the comparison of differences between the fatigue group and control group. An independent samples T-test indicated that the total MFI score of the fatigue group was higher than that of control group. The scores of general fatigue, mental fatigue, and reduced motivation in the fatigue group were also higher than those in control group. There was no significant difference observed in the scores of physical fatigue or reduced activities between two groups.

Table 2 presents an overview of the results from the time-domain analysis. In the media-lateral direction, the range (F=14.94, p<0.001), RMS (F=10.74, p=0.002) and velocity (F=31.67, p<0.001) of COP in the eyes-closed condition were significantly greater compared to that under the eyes-open condition. No significant difference was found between the fatigue group and the control group in the range (F=2.66, p=0.111), RMS (F=2.71, p=0.108), or velocity (F=0.032, p=0.860). There was no significant interaction of vision and group for these features (range: F=1.25, p=0.270, RMS: F=0.63, p=0.432, velocity: F=0.02, p=0.881). In the anterior-posterior direction, there was no significant difference between eyes-open and eyes-closed conditions for the range (F=2.71, p=0.108)and RMS (F=0.67, p=0.417). However, there were significant differences between the fatigue and control groups for the range (F=6.62, p=0.014) and RMS (F=9.27, p=0.004). No significant interaction between vision conditions and groups was observed for the range (F=0.48, p=0.493) or RMS (F=0.01, p=0.951). The velocity of COP in the anterior-posterior direction was significantly increased under the eyes-closed condition (F=50.54, p<0.001). However, no significant difference was found between the two groups (F=4.06, p=0.051). No interaction between vision conditions and groups was found for the velocity in anterior-posterior direction (F=0.69, p=412).

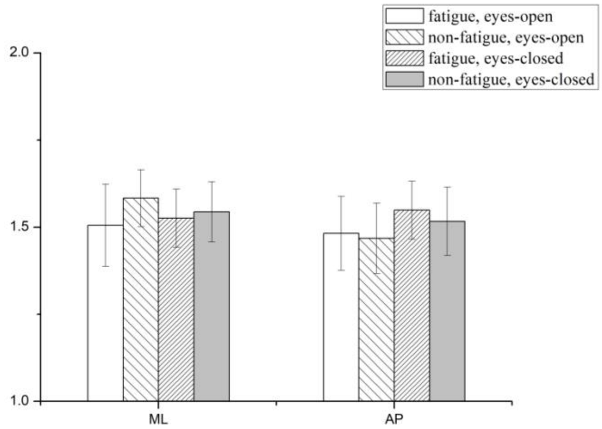
Figure 1 presents an overview of the frequency spectrum analysis of body sway. For the medial-lateral direction, there was no significant difference in LF, MF or HF between vision conditions (LF:F=0.25, p=0.619, MF: F=0.23, p=0.637, HF: F=3.83, p=0.058) or groups (LF: F=1.14, p=0.293, MF:F=1.98, p=0.168, HF: F=0.03, p=0.861). There was also no interaction between vision condition and group (LF: F=0.67, p=0.420, MF: F=1.08, p=0.306, HF: F<0.01, p=0.991). For the anterior-posterior direction, significant differences in LF (F=11.34, p=0.002), MF (F=11.26, p=0.002) or HF (F=4.24, p=0.046) were found between vision conditions. Specifically, the LF decreased under the eyes-closed condition, while the MF and HF increased. A significant difference in MF was found between groups (F=7.52, p=0.009), while no significant difference was observed in LF (F=0.60, p=0.445) or HF (F=0.97, p=330). Notably, the MF of the control group was higher than that of the fatigue group. No significant interaction between vision condition and group was found in LF (F=0.16, p=0.694), MF (F=0.09, p=0.760) or HF (F=0.12, p=0.730).



Graph showing the ratios of body sway across the low frequency (LF), median frequency (MF), and high frequency (HF) bands. (a) the ratios of body sway across the LF, MF, and HF bands in the medial-lateral direction. (b) the ratios of body sway across the LF, MF, and HF bands in the medial-lateral direction.

Figure 1 The results of frequency analysis of COP.

In addition to traditional measures, the fractal dimension in the medial-lateral direction indicated a differential change when the participants' eyes were closed in the fatigue group and control group (Figure 2). Neither the main effects of vision (F=0.56, p=0.459) and group (F=3.17, p=0.083) were significant. However, a significant interaction between vision and group was observed (F=5.71, p=0.022). Simple effect tests showed that in the control group, the FD in the medial-lateral direction decreased significantly under the eyes-closed condition (p=0.033), while no significant change was found in the fatigue group (p=0.253). Additionally, under the eyes-open condition, the FD of the fatigue group was greater than that of the control group (p=0.020), while no significant difference was found under the eyes-closed condition (p=0.506). In the anterior-posterior direction, the FD under eyes-open condition was significant larger than that under eyes-closed condition (F=15.95, p<0.001). However, no significant effect of group (F=0.73, p=0.398) nor interaction between vision and group (F=0.35, p=0.556) was found.



Graph showing the fractal dimension of COP in both medial-lateral direction (ML) and anterior-posterior direction (AP).

Figure 2 The results of fractal dimension analysis.

4. Discussion

This study investigated the effects of subjective fatigue on postural stability during static stance by measuring body sway using a force platform and assessing subjective fatigue using the Multidimensional Fatigue Inventory (MFI). The findings revealed that participants reporting subjective fatigue exhibited significantly higher levels of mental fatigue but did not demonstrate greater physical fatigue compared to the control group. The subjective fatigue group exhibited greater body sway in the anterior-posterior direction, and their use of vestibular information for integrating multisensory information was diminished. Additionally, differences were observed in the complexity and dynamics of body sway between the subjective fatigue group and the control group.

The higher total MFI scores and subscales of general fatigue, mental fatigue, and reduced motivation in the fatigue group indicated that subjective fatigue effectively differentiated the two groups. However, the lack of significant differences in physical fatigue and reduced activities suggested that subjective fatigue may manifest more prominently as psychological fatigue rather than physical fatigue. These results aligned with previous research, which suggested that several factors were associated with subjective fatigue, such as pain, stress, anxiety, and depression [30]. Thus, objective measured fatigue, namely fatigability, and self-reported fatigue were perhaps best viewed as measuring two different contributors to fatigue. A series of researches had revealed that mental fatigue resulting from repetitive cognitive tasks significantly impaired postural stability [9, 10]. In alignment with the previous researches, this study found that subjective fatigue related to mental fatigue impacted postural stability. The time-domain analysis demonstrated notable differences in range and RMS between the fatigue and control groups in the anterior-posterior direction. However, the presence of fatigue did not amplify postural instability in other time-domain features, particularly the features in medial-lateral direction. This result highlighted the specific vulnerability of postural control along the anterior-posterior axis to fatigue. One possible explanation could be that the participants' fatigue level, as measured by the MFI, was insufficient to induce a pronounced effect on postural control in the medial-lateral direction, particularly in the short-duration static stance tasks used in this study. Subjective fatigue, in addition to being potentially influenced by exercise and mental workload, was also susceptible to negative emotional states such as anxiety and depression [31]. Additionally, prolonged exposure to stress triggered the release of stress hormones like adrenaline and cortisol, which inhibit the body's arousal state, increased feelings of fatigue, and exacerbated the experience of subjective fatigue [32]. This may explain the differences in embodied manifestations of subjective fatigue compared to exercise- or cognitive task-induced fatigability during balance control tasks. Additionally, no interaction between vision and group was observed, suggesting that both the fatigue and control groups relied similarly on visual information to maintain medial-lateral stability.

Frequency-domain analysis offered further insights. Balance control relies on visual, vestibular, and proprioceptive sensory information [1, 33]. The central nervous system integrated multiple sensory information and reweighted this information based on its robustness and accuracy, helping to organize the most appropriate postural control commands to direct the activity of effectors such as joints and muscles [34, 35]. Visual input was a critical component of balance, providing continuous feedback to adjust posture and maintain stability [36]. The observed decrease in low-frequency (LF) components and increase in medium-frequency (MF) and high-frequency (HF) components in the anterior-posterior direction under the eyes-closed condition suggested a shift toward more rapid postural adjustments when visual information was unavailable. This shift reflected the increased reliance on vestibular and proprioceptive inputs in the absence of visual cues. Interestingly, the fatigue group exhibited significantly lower MF components than the control group, which could indicate a reduced dependence on vestibular input, a pattern that might reflect altered sensorimotor integration under fatigue. Furthermore, fractal dimension analysis, which assessed postural complexity [37], revealed a significant interaction between vision and group in the medial-lateral direction. The control group exhibited a reduction in FD under eyes-closed conditions, indicating less complex and more rigid postural control when deprived of visual input. In contrast, no significant change was observed in the fatigue group, suggesting that fatigue may disrupt the adaptability of postural control strategies when sensory conditions change. The higher FD in the fatigue group under the eyes-open condition could reflect compensatory mechanisms, where increased postural complexity serves to maintain stability despite the presence of fatigue. However, the lack of group differences under eyes-closed condition might point to a ceiling effect, where both groups reached a similar level of postural rigidity in the absence of visual input.

While this study offers insights into the effects of subjective fatigue on postural stability during static stances, it has several limitations. First, the sample size of this study was small, and the study only measured body sway. Future research could introduce more measures with a larger sample size to explore the relationship between fatigue and postural stability. For example, electromyography (EMG) could be used to observe muscle recruitment, while electroencephalography (EEG) and functional near infrared spectroscopy (fNIRs) could be used to investigate brain mechanisms. Neuroimaging and neurophysiological techniques could be employed to investigate the central nervous system’s response to fatigue and sensory deprivation, thereby shedding light on the neural correlates of postural instability. Second, the posture control task used in this study, static standing, was relatively simple. The research results indicated that fatigue had a more pronounced effect on complex tasks. Therefore, future research could incorporate more varied tasks, such as sudden posture perturbation tasks, to explore the impact of fatigue on central organization strategies for posture control, including changes in anticipatory and compensatory postural adjustments. Additionally, the study focused on healthy young adults, limiting the generalization of the findings to other populations, such as older adults or individuals with balance-affecting medical conditions. Future research should explore the effects of subjective fatigue on postural stability across different age groups and clinical populations to identify potential variations and appropriately tailor interventions.

5. Conclusion

The present study showed that fatigue primarily affected postural control in the anterior-posterior direction, particularly under visual deprivation, and altered the frequency characteristics and complexity of postural sway. These findings have implications for understanding how fatigue influences sensorimotor control and may inform interventions aimed at mitigating the risk of falls or balance impairments in fatigued populations.

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