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Original Article

Impact of Fatigue on Balance and Sensor-Based Assessments of Proprioception: A Comparative Study Across Different Sensory Conditions

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Abstract:
Purpose: This study aims to investigate how fatigue impacts balance and proprioception through mobile sensor technology. **Methods**: A total of 251 participants [mean age = 19.83 ± 0.94 years] were classified into low [n = 211] and high [n = 40] fatigue groups based on the Fatigue Assessment Scale. Each participant performed the mini-CITSIB [Cognitive and Sensory Integration Balance] test under four conditions: eye open with a fixed surface, eye closed with a fixed surface, eye open with a foam surface, and eye closed with a foam surface. Mobile sensors [accelerometer, gyroscope, linear accelerometer, and magnetometer] were used to record movement and stability data. Key variables calculated included jerk, peak-to-peak, root mean square [RMS], range, standard deviation [SD], and the coefficient of detrended fluctuation analysis [coeff_dfa]. Data were analyzed using SPSS software, with independent samples t-tests comparing the fatigue groups for each condition. **Results**: Significant differences in sensor readings were observed between low and high fatigue groups across all conditions. The high fatigue group showed greater variability in movement and lower values in jerk, peak-to-peak, and RMS, indicating reduced stability and more erratic movements. Coefficients of DFA for rotation and side bending were significantly higher in the high fatigue group, suggesting increased fluctuations in movement. These differences were particularly pronounced in conditions that involved closed eyes or a foam surface, which challenge balance and proprioception. **Conclusion**: Fatigue negatively impacts balance and proprioception, with high fatigue individuals demonstrating greater movement instability and irregularities in sensor readings. Mobile sensors provide valuable insights into the effects of fatigue on balance and can be utilized for real-time monitoring in both clinical and research settings. This study underscores the potential of mobile sensor technology in assessing fatigue-related impairments in sensorimotor function.

Keywords: Fatigue; Balance; Sensor-Based Assessments; Proprioception.
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1. Introduction

Fatigue is a common feature of many physical, neurological, and psychiatric disorders. While often identified as a symptom of disease or a side effect of treatment, fatigue is primarily considered a subjective experience. Significant efforts have been made to define and conceptualize fatigue in a way that differentiates it from normal sensations such as tiredness or sleepiness [1]. Broadly, fatigue can be described as a decline in physical performance accompanied by an increase in the real or perceived difficulty of a task [2]. It has also been defined as the inability of muscles to sustain the required level of force during exertion [3] or as an exercise-induced reduction in a muscle's capacity to generate force. The term muscle fatigue specifically refers to a temporary decline in muscular capacity to perform physical activity [4].

Balance control is a complex motor skill that requires the planning and execution of coordinated movements and the integration of sensory input [5]. The central nervous system [CNS] integrates information from sensory modalities—including the somatosensory, visual, and vestibular systems—to maintain postural control and regulate reflexive movements [6]. However, balance is not solely dependent on sensory input; it also relies on the integrity of neural pathways, muscle function, and motor control within the CNS [7]. The CNS processes environmental inputs and selects appropriate motor responses to maintain postural stability [8, 9].

A more comprehensive understanding of balance control must also consider the acute depletion of physical or mental resources. Physical fatigue—whether from prolonged activities [e.g., walking long distances] or short bursts of intense effort [e.g., sprinting to catch a bus]—has been shown to impair both static and dynamic balance, regardless of age [10, 11]. Emerging evidence also suggests that mental fatigue—a psychobiological state induced by prolonged cognitive effort, characterized by changes in mood, motivation, and task performance [12-14]—may similarly disrupt balance [15]. Performing motor tasks over extended periods leads to motor fatigue, which is typically recognized as a reduction in force production capacity [16]. Muscle fatigue has been shown to impair joint proprioception [17] and neuromuscular control of the lower extremities. Although previous studies [18] have examined the effects of fatigue on proprioception, they have identified which components of the proprioceptive pathway—muscle receptors, joint receptors, the CNS, or other elements—are primarily responsible for these impairments. Grobe and colleagues, [19] hypothesized that the changes in balance may be due to cognitive resource allocation as significant evidence exists that balance is influenced by cognitive capacity.

While these studies have identified differences in balance after the performance of a cognitively fatiguing task, minimal evidence exists on whether individuals who report being fatigued have balance that differs from those who do not report being fatigued. Therefore, the objective of this study was to identify the differences in balance between individuals who reported being fatigued and those who did not.

2. Materials and Methods

Participants

After obtaining IRB approval, participants were recruited from campus using flyers and campus announcements in classes. Participants were included in the study if they were between the ages of 18 to 25, any injuries that may impact balance, have neurological conditions, and had a Body Mass Index [BMI] < 35. A total of 251 individuals participated in this study, aged between 18 and 23 years [mean age = 19.83 ± 0.94 years]. The participants' height ranged from 150 cm to 196 cm [mean = 173.73 ± 9.35 cm], and their weight varied from 44 kg to 100 kg [mean = 72.07 ± 11.25 kg]. The Body Mass Index [BMI] of participants ranged from 18.02 to 33.41 [mean = 23.85 ± 3.03]. The gender distribution of the sample included 27 females [10.8%], 59 males [23.5%], and 165 men [65.7%].

Fatigue Assessment

Fatigue levels were assessed using the Fatigue Assessment Scale, a validated tool to quantify perceived fatigue. The scale categorizes fatigue into two levels: low [<22] and high [>22] fatigue. 1. [20, 21] Based on the results of the scale, 211 participants [84.1%] were classified into the low fatigue group, while 40 participants [15.9%] were classified into the high fatigue group.

Experimental Design

The experiment involved the use of the **Phyphox application** [version 1.1.7] for collecting sensor data during four distinct conditions of the **mini-CITSIB** [Cognitive and Sensory Integration Balance] test. The conditions are designed to assess balance and proprioception under different sensory manipulations and postural challenges. Each participant completed the test under four conditions: **Condition 1**: Eye Opened, Fixed Surface, **Condition 2**: Eye Closed, Fixed Surface, **Condition 3**: Eye Opened, Foam Surface, **Condition 4**: Eye Closed, Foam Surface.

Participants were asked to maintain a standing posture for 30 seconds in each condition, with the sensor data being recorded for the entire duration of the test.

Equipment

The mobile sensors used in this study were embedded in a mobile phone that was placed in a modified abdominal support belt. This belt was designed with a pocket to securely hold the phone near the participant's center of gravity. The sensors used were: **Accelerometer**: Measured linear acceleration in three axes [X, Y, and Z], **Gyroscope**: Measured rotational velocity around three axes [X, Y, and Z], **Linear Acceleration**: Captured linear movement of the phone, **Magnetometer**: Measured magnetic field strengths to track orientation.

The Phyphox application was used to collect the following parameters: jerk, peak-to-peak, RMS [Root Mean Square], range, standard deviation [SD], and the coefficient of detrended fluctuation analysis [coeff_dfa] for each sensor in each condition. The mobile phone's sampling rate was set to 800 Hz, and each experiment lasted for 30 seconds with a 3-second delay to stabilize the system before data collection.

Procedure

Before starting the experiment, informed consent was obtained from all participants. Basic demographic data, including gender, age, height, weight, and BMI, were collected. After participants were briefed on the procedures, the experiment began as follows: Participants were fitted with the mobile phone, which was securely placed in the abdominal support belt at the center of gravity. For each condition, participants were asked to maintain a specific posture for 30 seconds. In Condition 1 [Eye Opened, Fixed Surface], participants stood with eyes open on a stable surface. In Condition 2 [Eye Closed, Fixed Surface], they stood with eyes closed on the same stable surface. For Condition 3 [Eye Opened, Foam Surface], participants stood with eyes open on a foam surface, and in Condition 4 [Eye Closed, Foam Surface], they stood with eyes closed on the foam surface.

During each condition, the Phyphox application recorded data from the accelerometer, gyroscope, linear acceleration, and magnetometer. Data was collected wirelessly and displayed on a laptop screen via remote access from the mobile phone. The test was terminated when participants either opened their eyes in the eyes-closed conditions, raised their arms from their sides, or lost balance and required assistance to prevent a fall. The data from the Phyphox application were extracted and saved anonymously in CSV format for further analysis.

Data Preparation

Data preparation was performed using Python 3.10. Outliers were identified using quartile analysis, and Winsorization was applied to minimize their effect on the results. Data visualization techniques were employed to ensure no remaining outliers. Any missing data were imputed using suitable statistical methods to ensure complete datasets for analysis. The following variables were calculated for each dimension of each sensor under each condition: coefficient of detrended fluctuation analysis [coeff_dfa], entropy, jerk, maximum, mean, minimum, peak-to-peak, range, RMS, sampling rate, SD, and sway. These variables were also calculated for the overall RMS for each sensor under each condition.

Statistical Analysis

Data analysis was conducted using **SPSS** software. Normality of the data was assessed using the Shapiro-Wilk test to determine whether the data followed a normal distribution. For inferential statistics, comparisons between the low and high fatigue groups for each sensor and condition were performed using independent samples t-tests. A p-value of less than 0.05 was considered statistically significant. The primary focus of the analysis was to determine the effect of fatigue on balance and proprioception, as indicated by sensor-based measurements of jerk, RMS, and other derived variables across the different conditions of the mini-CITSIB test. Unpaired t test was used to compare between groups.

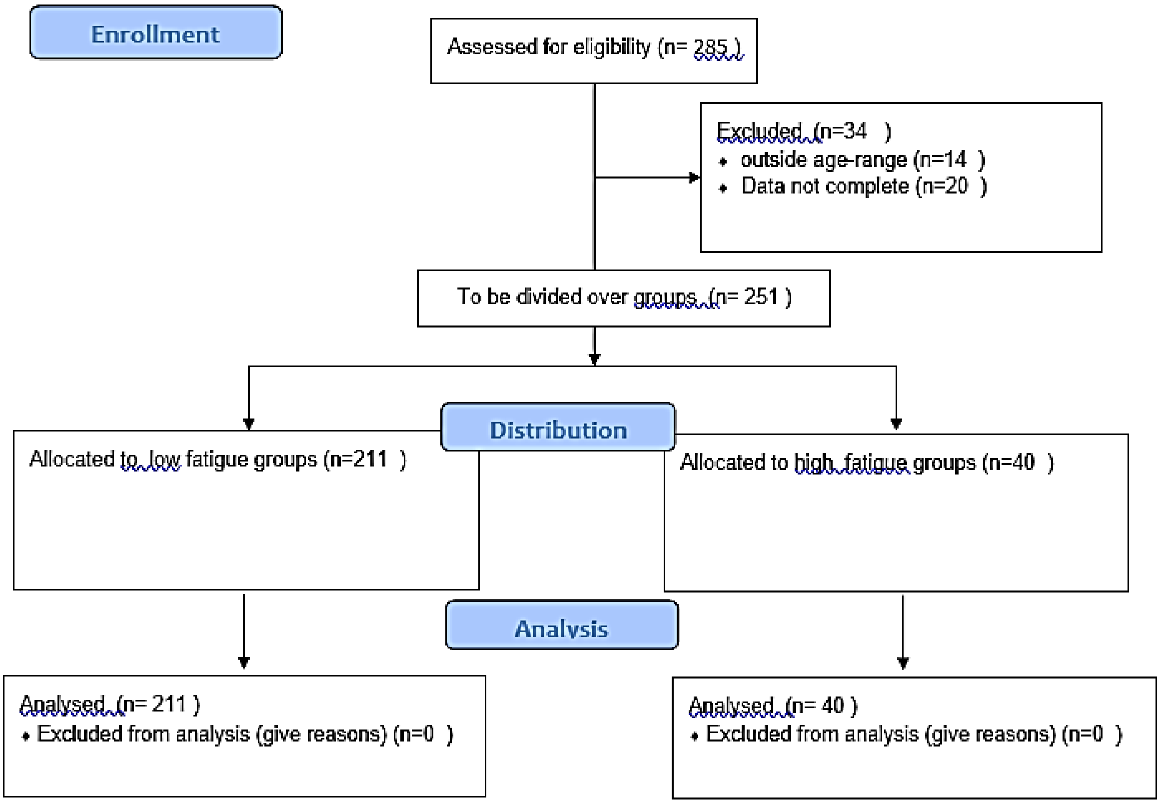

Figure [1]: The cosort Flowchart.

3. Results

The descriptive statistics for the sample of 251 individuals reveal the following: Age ranges from 18 to 23 years, with a mean of 19.83 ± 0.94 years. Height varies from 150 cm to 196 cm, with an average of 173.73 ± 9.35 cm. Weight spans from 44 kg to 100 kg, with a mean of 72.07 ± 11.25 kg. BMI ranges from 18.02 to 33.41, with a mean of 23.85 ± 3.03. Fatigue scores range from 14 to 47, with an average of 26.97 ± 7.13. The analysis included all 251 participants with no missing data.

The gender distribution of the sample includes 27 females [10.8%], 59 males [23.5%], and 165 men [65.7%]. In total, 251 participants were included in the dataset, with the valid gender categories making up 100% of the sample. The cumulative percentage indicates that the male participants represent the majority of the sample, comprising 65.7% of the total, followed by females at 23.5%.

The fatigue levels within the sample show that 211 participants [84.1%] reported low fatigue, while 40 participants [15.9%] reported high fatigue. The total sample consisted of 251 individuals, and the cumulative percentage reflects that the majority of participants experienced low fatigue, with high fatigue being reported by a smaller portion of the sample.

The descriptive and inferential statistics of significant readings of mobile sensors within each condition in miniCITSIB test were presented in (**Tables 1-4)**

Table 1: The descriptive and inferential statistics of significant readings of mobile sensors between fatigue groups regarding condition 1 in mini-CITSIB test

Condition 1	Low Fatigue	High Fatigue	P Value	Effect size [d]
Acc_SB_Jerk|*	0.000086±0.000038	0.000115±0.000054	4.92283E-05	-0.62
Acc_SB_Peak_to_Peak*	62.095737±132.977601	5.827239±97.286991	0.011701612	0.48
Acc_SB_RMS*	111.217567±82.981807	73.713208±61.282831	0.007188415	0.51
Acc_Rot_Jerk*	0.000086±0.000039	0.000115±0.00005	5.72759E-05	-0.65
Acc_AP_Jerk*	0.000093±0.000044	0.000129±0.000068	2.67356E-05	-0.63
Mag_SB_Jerk*	0.001109±0.000621	0.0009±0.000511	0.047182435	0.37
Mag_Rot_Jerk*	0.001122±0.000657	0.000856±0.000475	0.015592676	0.46
Mag_Rot_coeff_dfa*	0.980427±0.211707	1.08139±0.202556	0.005972001	-0.49
Mag_AP_Sway*	0.007907±0.004402	0.010339±0.014374	0.046318836	-0.23

*Acc: Accelerometer; AP: Anteroposterior; coeff_dfa: coefficient of detrended fluctuation analysis; Mag: Magnetometer; RMS: Root Mean Square; Rot: Rotation; SB: Side bending.

Table [2]: The descriptive and inferential statistics of significant readings of mobile sensors between fatigue groups regarding condition 2 in mini-CITSIB test

Condition 2	Low Fatigue	High Fatigue	P Value	Effect size [d]
Acc_SB_Jerk*	0.000087±0.00004	0.000114±0.00005	0.000232146	-0.6
Acc_SB_Peak_to_Peak*	62.74319±136.084715	6.478087±93.338366	0.013223087	0.48
Acc_SB_RMS*	113.070269±83.876515	72.5798±59.810947	0.004013061	0.56
Acc_Rot_Jerk*	0.000087±0.000041	0.000114±0.000049	0.000305186	-0.6
Acc_AP_Jerk*	0.000094±0.000045	0.000129±0.000066	5.08116E-05	-0.62
Acc_AP_Range*	0.283096±0.118785	0.350697±0.229703	0.006542453	-0.37
Acc_AP_SD*	0.079639±0.033297	0.096311±0.054896	0.010984545	-0.37
Acc_AP_SwaRot*	0.001255±0.000607	0.001536±0.000851	0.013252707	-0.38
Mag_Rot_Jerk*	0.001129±0.00065	0.000854±0.000472	0.01180192	0.48
Mag_Rot_coeff_dfa*	1.005193±0.216731	1.091841±0.23064	0.023150568	-0.39
Mag_AP_coeff_dfa*	0.987417±0.205254	1.085446±0.207992	0.006349031	-0.47

*Acc: Accelerometer; AP: Anteroposterior; coeff_dfa: coefficient of detrended fluctuation analysis; Mag: Magnetometer; RMS: Root Mean Square; Rot: Rotation; SB: Side bending.

Table [3]: The descriptive and inferential statistics of significant readings of mobile sensors between fatigue groups regarding condition 3 in mini-CITSIB test

Condition 3	Low Fatigue	High Fatigue	P Value	Effect size [d]
Acc_SB_Jerk*	0.00009±0.000043	0.000116±0.00005	0.000588748	-0.56
Acc_SB_Peak_to_Peak*	67.740001±135.19213	17.857486±100.675262	0.027946927	0.42
Acc_SB_RMS*	112.886974±84.68757	75.477556±64.444004	0.008778524	0.5
Acc_Rot_Jerk*	0.000089±0.000043	0.000117±0.00005	0.000334511	-0.6
Acc_AP_Jerk*	0.000096±0.000048	0.00013±0.000064	0.000161467	-0.6
Mag_SB_coeff_dfa*	1.023427±0.215144	1.104385±0.196701	0.028559319	-0.39
Mag_Rot_Jerk*	0.001129±0.000654	0.000869±0.000458	0.017218272	0.46

*Acc: Accelerometer; AP: Anteroposterior; coeff_dfa: coefficient of detrended fluctuation analysis; Mag: Magnetometer; RMS: Root Mean Square; Rot: Rotation; SB: Side bending.

Table [4]: The descriptive and inferential statistics of significant readings of mobile sensors between fatigue groups regarding condition 4 in mini-CITSIB test

Condition 4	Low Fatigue	High Fatigue	P Value	Effect size [d]
Acc_SB_Peak_to_Peak*	76.660657±139.636504	25.108446±99.939723	0.027297492	0.42
Acc_SB_coeff_dfa*	1.033737±0.142464	1.095598±0.127484	0.011414018	-0.46
Acc_Rot_Jerk*	0.000095±0.000057	0.00012±0.000053	0.009930199	-0.45
Acc_AP_Jerk*	0.0001±0.000053	0.000135±0.000068	0.000369956	-0.57
Mag_SB_coeff_dfa*	1.039251±0.203098	1.132102±0.189195	0.008114103	-0.47
Mag_Rot_Jerk*	0.001132±0.000661	0.000875±0.000453	0.019833509	0.45
Mag_Rot_coeff_dfa*	1.028641±0.19277	1.09923±0.187348	0.03462728	-0.37
Mag_AP_coeff_dfa*	1.020075±0.1868	1.110632±0.180216	0.005260046	-0.49

*Acc: Accelerometer; AP: Anteroposterior; coeff_dfa: coefficient of detrended fluctuation analysis; Mag: Magnetometer; RMS: Root Mean Square; Rot: Rotation; SB: Side bending.

4. Discussion

The objective of this study was to identify differences in balance between individuals who reported low fatigue compared to those who reported high fatigue. Our findings suggest measurable differences in movement patterns, proprioception, and postural control between these two groups. Specifically, fatigue appears to amplify movement irregularities across all conditions, potentially due to disrupted sensory feedback and/or an impaired ability to adapt to balance challenges. These findings contribute to the existing literature by identifying specific ways in which balance differs between individuals experiencing high fatigue versus low fatigue.

The observed fatigue-induced changes in movement align with previous research on balance and postural control. Santos et al. [11] suggest that fatigue-related changes may stem from a combination of physiological and mental fatigue effects. Our results support this notion, showing significant impairments in postural stability across all mini-CITSIB conditions. These findings are consistent with prior studies that reported fatigue-related increases in postural sway [22, 23], sway velocity [24], and sway area [25]. Furthermore, Cooper et al. [26] found reductions in stability indices during both stable and unstable stance conditions, which aligns with the increased movement irregularities observed in our study.

Interestingly, our findings may be contrast with those presented by Boolani and colleagues [27] who found that declines in subjective energy levels influenced balance control rather than increased feelings of fatigue. Prior research examining energy and fatigue as distinct unipolar moods suggests that fatigue impacts balance primarily when standing on a firm surface with eyes open, whereas energy influenced balance variables across bothfirm and foam surfaces in the eyes-open condition [28, 29]. In our study, fatigue was assessed as the opposite of energy, which may explain the differences in findings compared to Boolani and colleagues .

Several studies have investigated the effects of subjective fatigue on balance. For studies that examined subjective feelings of fatigue only, Zech et al. [24] specifically examined localized and general fatigue effects on balance in handball athletes. Their findings of increased sway velocity post-fatigue suggest that both types of fatigue impair postural control. Similarly, Penedo et al. [23] noted increased postural sway without concurrent changes in muscle activation, indicating that proprioceptive deterioration and central nervous system alterations contribute to fatigue-induced instability.

Neuromechanical explanations for these effects have been proposed by Gandevia [30] and Paillard [31], who describe spinal and supraspinal mechanisms underlying fatigue-related declines in sensory processing and motor control. These include altered sensory input, changes in cortical excitability, and inhibitory processes affecting afferent feedback integration. Such mechanisms likely contribute to the increased variability in postural control observed in our study.

Deschamps et al. [32] found increased body sway following mental fatigue during bipedal stance on a foam surface, a finding consistent with our results in the eyes closed feet on foam surface. Similarly, Hachard et al. [33] reported reduced sample entropy in postural sway after mental fatigue, suggesting increased cognitive contributions to maintain balance. Noé et al. [34] further noted that responses to mental fatigue vary between individuals and are more evident in non-linear measures like sample entropy rather than crude measures of center-of-pressure displacement or velocity.

Limitations and Future Directions:

This study has several limitations. First, while the sample size was sufficient for analysis, it was limited to young adults [ages 18 to 23], which may not fully represent how fatigue affects balance in older populations or those with chronic conditions. Second, the study utilized a fixed experimental setup that may not fully replicate real-world environments, such as varied surfaces or dynamic motion. Third, although mobile sensors were effective in balance assessment, factors such as phone placement, sensor calibration, and individual differences in body composition may have introduced measurement variability. Finally, while this study focused on short-term fatigue, the long-term effects of fatigue on balance and proprioception were not examined, leaving a gap for future research.

Although mental fatigue has been shown to impair postural control, [35] interactions between cognitive resource reduction, aging and balance complexity remain elusive. Our study does not directly address these challenges, but highlights that balance was significantly more irregular in high-fatigue participants. Future studies should explore how different types of fatigue [e.g. central vs. peripheral, physical vs. mental] interact to influence postural stability. Additionally, understanding individual variability in fatigue responses may help refine personalized fatigue monitoring and intervention strategies, particularly for populations at risk of balance impairments, such as athletes, military personnel, and aging individuals.

Additionally, future studies should examine energy and fatigue as two distinct moods, as there is both biological and biomechanical evidence suggesting that they may uniquely impact balance [27, 29, 36]. Prior research has demonstrated that energy and fatigue operate as independent, unipolar constructs rather than opposites, and their effects on movement control and stability could be influenced by separate underlying mechanisms. Investigating these differences could provide a more nuanced understanding of how variations in subjective energy and fatigue contribute to postural control and movement adaptation [37-39].

This study has several limitations. First, the sample size, though large, is limited to young adults [ages 18 to 23], which may not fully represent how fatigue affects balance in older populations or those with chronic conditions. Second, the study utilized a fixed experimental setup that may not fully replicate real-world environments, such as varied surfaces or dynamic motion. Third, the use of mobile sensors for balance assessment, while effective, may be influenced by factors such as phone placement, sensor calibration, and individual differences in body composition, which could introduce measurement variability. Finally, while the study focused on short-term fatigue, the long-term effects of fatigue on balance and proprioception were not addressed, leaving a gap for future investigation.

The results of this study suggest important practical applications for mobile sensor technology in monitoring balance and proprioception, particularly in environments where fatigue is a critical factor, such as healthcare settings, rehabilitation programs, and athletic performance assessments. Mobile sensors could be used to develop personalized interventions for individuals experiencing fatigue-related impairments by identifying movement irregularities in real-time.

Furthermore, wearable sensor technology can be integrated into daily life to enable continuous monitoring of balance, particularly for individuals prone to fatigue-related instability, such as older adults, athletes, and individuals with neurological conditions. These devices could provide early warning signs of deteriorating balance, potentially preventing falls and improving overall mobility. Future advancements in machine learning and data analytics could further refine these applications, enhancing the predictive capabilities of fatigue-related balance disruptions.

By leveraging mobile sensor technology, clinicians, trainers, and researchers can better understand how fatigue influences movement control, allowing for targeted interventions that improve postural stability and reduce injury risks. Expanding research efforts to integrate fatigue monitoring into practical applications will help bridge the gap between laboratory findings and real-world implementation.

5. Conclusions

Overall, this study provides compelling evidence that fatigue significantly impairs balance and proprioception, as demonstrated by altered sensor readings across various conditions in the mini-CITSIB test. Participants in the high fatigue group exhibited greater instability and irregular movement patterns, particularly under sensory-challenging conditions such as eyes-closed or unstable surfaces. These findings emphasize the detrimental impact of fatigue on sensorimotor function and highlight the potential of mobile sensor technology as a valuable tool for real-time balance assessment. By facilitating continuous monitoring and personalized interventions, these technologies can enhance clinical diagnostics, rehabilitation strategies, and athletic performance assessments, ultimately improving mobility and reducing fatigue-related fall risks. These findings underscore the importance of integrating fatigue monitoring into applications where balance and stability are critical, such as sports performance, occupational safety, and clinical rehabilitation.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.
Data Availability Statement: Data available from the author upon reasonable request.

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