Effectiveness of Waist Vibrotactile Feedback for Improving Standing Postural Balance

by

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ABSTRACT

Fine control of standing postural balance is essential for completing various tasks in daily activities, which might be compromised when interacting with dynamically challenging environments (e.g., moving ground). Among various biofeedback to improve postural balance control, vibrotactile feedback has an advantage of providing supplementary information about balance control without disturbing other core functions (e.g., seeing and hearing). This paper investigated the effectiveness of a waist vibrotactile feedback device to improve postural control during standing balance on a dynamically moving ground simulated by a robotic balance platform. Four vibration motors of the waist device applied vibration feedback in the anterior-posterior and medio-lateral direction based on the 2-dimensional sway angle, measured by an inertia measurement unit. Experimental results with 15 healthy participants demonstrated that the waist vibrotactile feedback is effective in improving postural control, evidenced by improvements in center-of-mass and center-of-pressure stability measures. In addition, this study confirmed the effectiveness of the waist vibrotactile feedback in improving standing balance control even under muscle fatigue induced by lower body exercise. The study further confirmed that the waist feedback is more effective in people with lower baseline balance performance in both normal and fatigue conditions.

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Chapter 1

INTRODUCTION

Standing postural balance, one of the most essential functions in daily activities, is a complex dynamic control task. In daily activities, people—while in their standing posture—are exposed to various dynamically challenging environments (e.g., standing in the bus, train, and ship). The challenging ground environments, which apply translational and rotational perturbations to the leg, can affect passengers' and crew members' postural stability and induce muscle fatigue [1; 2; 3] . If the body's adjustment to the challenging ground condition is impossible or insufficient when postural stability is threatened, people may fall and injure themselves. Therefore, it is essential to investigate the postural balance control under the challenging ground, and it is important to further investigate the effects of fatigue on postural balance.

The effects of various challenging ground conditions, such as rotational perturbation platform or wobble board, on standing postural stability have been studied and verified that the challenging ground conditions increase the body motion and decrease postural stability [4; 5] . Many studies have investigated the effects of fatigue on standing postural stability and demonstrated that fatigue induces postural instability and increases joint movement variability [6; 5; 7; 8] . Regardless of age, the negative effects of fatigue can increase the danger of falling [9; 10] . As a result, it is necessary to find effective methods (e.g., biofeedback) to improve postural balance control under challenging ground conditions and to reduce the negative effects of fatigue on postural stability.

Researchers have developed various types of biofeedback devices, such as vibrotactile [11; 12] , visual [13; 14] , or auditory [15; 16] feedback, to inform the state of the postural balance control. While the visual and auditory biofeedback devices may disrupt an individual's visual and auditory functions in their daily activities, the vibrotactile feedback delivers supplemental information about balance control without disrupting the core activities such as hearing and seeing, and thus it became popular as a practical method [17] .

There are various studies utilizing vibrotactile feedback to improve postural balance control. It has been shown that humans could modify their postural sway with vibrotactile feedback [11; 18; 4; 19] ; the vibrotactile feedback uses the position or velocity of the body sway as supplemental information. In most studies using vibrotactile feedback for postural balance, except for a study with the feedback system attached near the shoulder [19] , the feedback device was positioned on the waist near the center of mass (COM) position during the quiet standing posture. Some of the studies have investigated the effect of vibrotactile feedback on human postural stability under rigid ground conditions with different stances, such as Romberg or tandem Romberg stance [11; 18; 4] . Another study was performed under a challenging ground condition using a wobble board, which provides multi-directional rotational perturbation [4] , but the perturbations are random and could not be systematically controlled. In addition, most of the studies included enough break periods between trials and did not investigate how fatigue could affect posture balance control when vibrotactile feedback was used.

The main objective of this study is to investigate the effectiveness of a waist vibrotactile feedback device to improve postural control during standing balance on a dynamically challenging ground simulated by a robotic balance platform, and additionally under muscle fatigue induced by lower body exercise. The waist vibrotactile feedback device consists of four vibration motors of applying vibration feedback in both the anterior-posterior (AP) and medio-lateral (ML) directions based on the

2-dimensional (2D) sway angle, measured by an inertia measurement unit (IMU), which is positioned near the COM position. A dual-axis robotic platform developed by Nalam and Lee was utilized [20; 21; 22] to apply multi-directional rotational perturbations with varying but controlled frequencies and amplitudes. We hypothesized that the waist vibrotactile feedback improves the postural balance control under the challenging ground condition. We also hypothesized that the biofeedback is effective in improving postural balance control even under the fatigue condition.

Chapter 2

METHODS

2.1 Hardware

A) Waist vibrotactile feedback device

The waist vibrotactile feedback device consisted of three main components: (a) Inertial Measurement Unit (IMU) sensor, (b) vibration motors, and (c) Arduino mega board (Figure 2-1). The body orientation was measured by the 9-axis IMU sensor (BST-BNO055-DS000-12, Bosch Sensortec GmbH) which was securely attached to the subject's back near the COM position (about 10 cm lower than the navel position). Body orientation data in the AP and ML directions was used in real-time for the operation of the waist vibrotactile feedback and the analysis of postural balance control performance. Before using the IMU sensors, the accuracy of the IMU sensor was checked using a digital angle gauge (WR 300, Wixey). The IMU sensor and angle gauge measurements were compared at every 0.2° in the range of -3° to 3°. The maximum average error of the IMU sensor was 0.07°.

The vibration motors (10 mm vibration motors, DZS Elec) were located on each opposite side of the subject's waist in the AP and ML direction and 20 cm above the IMU sensor position to avoid IMU sensing of motion artifacts due to vibration. The vibration motors applied varying magnitude by changing pulse width modulation duty cycle from 0% to 100%.

The Arduino Mega board (ATMega 2560, Atmel) was used to control the waist vibrotactile feedback device. The board (control unit) received the IMU orientation data and computed the orientation information with a control algorithm explained

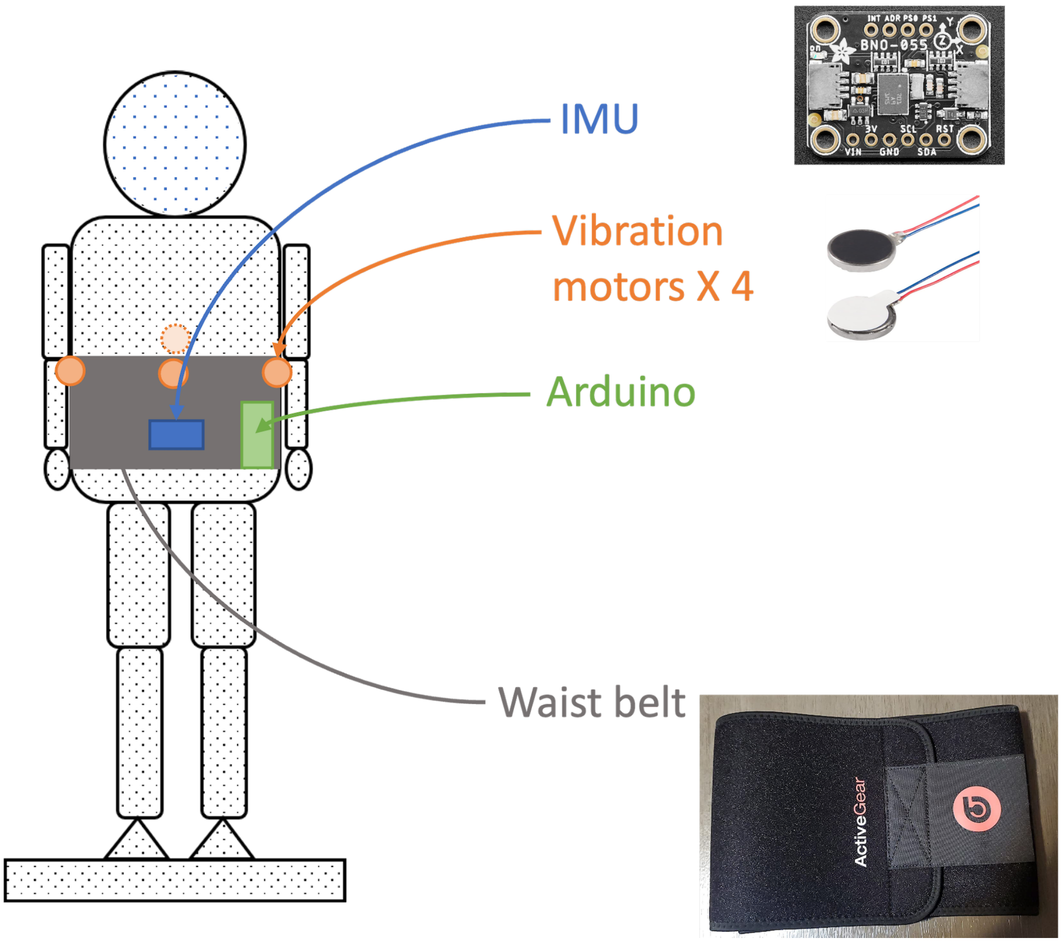

Figure 2.1: Description of the Waist Vibrotactile Feedback Device

in the next section. The control unit sent the command signals to operate the four vibration motors.

B) Vibrotactile feedback control

Three different feedback conditions were used: Feedback OFF, Feedback ON (Constant), and Feedback ON (Linear). In the Feedback OFF condition, the vibration motors were always turned off regardless of the subject's sway angle. In the Feedback ON (Constant) and Feedback ON (Linear) conditions, the vibration motors were activated when the sway angle exceeded a threshold (Figure 2-2): e.g., the front vibration motor was activated when the subject's orientation data exceeded the threshold in the anterior direction. In the Feedback ON (Constant) condition, the vibration mag-

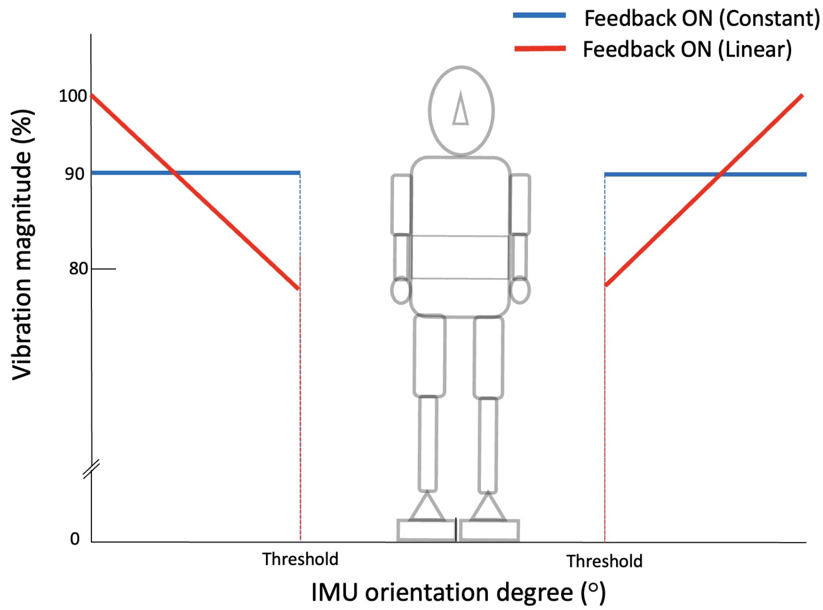

Figure 2.2: Relation between the orientation data and the vibration magnitude. In the Feedback ON (Constant) condition, the vibration motor operates when the orientation data is over a threshold, and the vibration magnitude is settled as 90% of maximum magnitude. In the Feedback ON (Linear) condition, the vibration magnitude value starts from 80% and increases linearly to 100%.

nitude was set as 90% of the maximum magnitude. In the Feedback ON (Linear) condition, the vibration magnitude increased linearly from 80% to 100% with the increase in sway angle beyond a threshold. The threshold is a boundary where the subject's sway angle is within the boundary for the 70% of the experiment duration.

C) Robotic Force Platform

The robotic balance platform was designed to rotate in both AP and ML directions. Each degree of freedom has a sufficient range of motion (±15° and ±10° for AP and ML directions, respectively) to support the whole range of ankle motion during standing balance control [20] . The platform includes a force plate that measures the net center-of-pressure (COP) displacement. The platform was set to operate according to predefined sinusoidal perturbations (Figure 2-3 (a)). The perturbation was designed by a randomized cycle of the sine waves with different frequencies and amplitudes. The range of frequency was 0.5-1.5 Hz, and the range of amplitude was

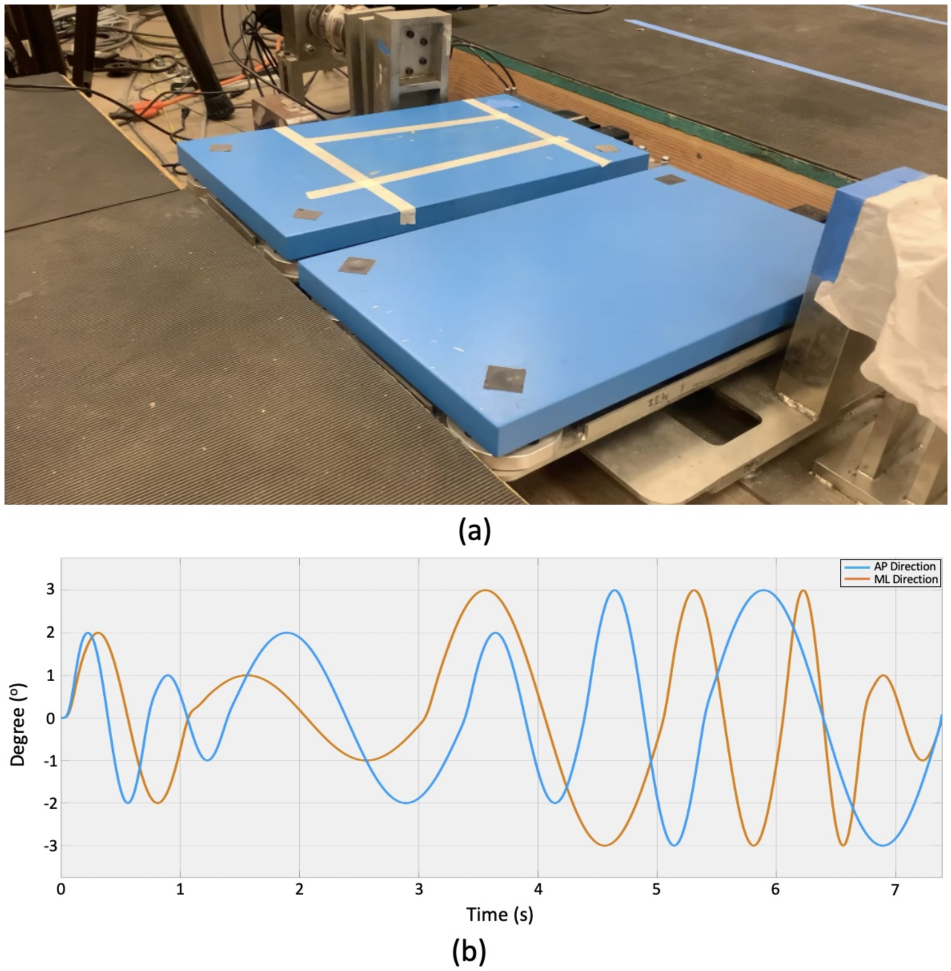

Figure 2.3: (a) The robotic balance platform and (b) plots of the AP and ML direction randomized sine wave. Both platforms were synchronized using the same perturbations.

-3-3°. The perturbation was low-pass filtered using a 4th order Butterworth filter with a cut-off frequency of 3 Hz. The same perturbations were consistently used for all subjects.

2.2 Participants

Fifteen healthy young adults (20 - 30 years, 9 males and 6 females) participated in the experiments. The inclusion criteria were no known history of disease or lower limb injury and normal cognitive abilities. The study was approved by the Institutional

Review Board of Arizona State University (STUDY00015392), and informed consent was obtained from each subject before testing.

2.3 Experimental Protocols

Subjects were asked to stand on robotic balance platforms without shoes, and their ankles were aligned with the axes of AP and ML rotational motors. They were instructed to stand as still as possible while wearing the waist vibrotactile feedback device and a safety harness. Slack of the safety harness was adjusted not to interfere body motion during the experiment. The three vibrotactile feedback conditions were not informed throughout the experiments. The predefined sinusoidal perturbations of the platform were equally applied to all subjects. Subjects were given with sufficient familiarization time to learn how the waist vibrotactile feedback systems and the platforms work.

This study was divided into Study 1 (first day) and Study 2 (second and third days). Study 1 used three feedback conditions: Feedback OFF, Feedback ON (Constant), and Feedback ON (Linear) to validate the effectiveness of the waist vibrotactile feedback device. It consisted of 2 experiments: threshold identification experiment and main experiment. Study 2 used two feedback conditions: Feedback OFF and Feedback ON (Constant) and two fatigue conditions: non-fatigue and fatigue conditions to investigate the effectiveness of the biofeedback under fatigue. Study 2 was conducted in two separate days. On one day of Study 2, the main experiment was performed without fatigue exercise experiment (non-fatigue condition), and on the other day, the fatigue exercise experiment was performed before the main experiment (fatigue condition). The order of the two days was randomized, and 8 subjects performed the non-fatigue condition first and 7 subjects performed the Fatigue condition first. A minimum of 3 days was provided between the two days to avoid any potential fatigue effect.

A) Study 1

a) Threshold identification experiment

For each subject, an experiment was performed to identify the threshold sway angle to trigger vibrotactile feedback in the main experiment. The threshold was defined as a boundary where the subject's sway angle is within the boundary for the 70% of experiment duration. Three tests, each consisting of 3 trials, were performed, and each trial lasted for 1 minute. After each test, the percentage of sway angle within the threshold was quantified and the threshold was updated for the next test to meet the 70% requirement. At the conclusion of 3 tests, the threshold was successfully identified in all subjects. Each subject's threshold was consistently used in all subsequent experiments.

b) Main experiment

The subject stood on the robotic balance platform, which applied predefined sinusoidal perturbations (Fig. 2-3 (b)). Three feedback conditions were used: Feedback OFF, Feedback ON (Constant), and Feedback ON (Linear). Three trials were repeated for each condition, and each trial lasted for 3 minutes. The order of the feedback condition was fully randomized to remove any potential biases. After every 2 trials, the subject took at least a 3-minute break.

B) Study 2

a) Fatigue exercise experiment

The fatigue exercise experiment was performed to induce fatigue in the lower body with five sets of lower body exercises. Each set consisted of three exercises: heel raise, squat, and lunge 20 times each and a 1-minute break between was given between exercises. All subjects were instructed to do their best, but if the subject could not perform five sets of the exercise, the experiment stopped at four sets.

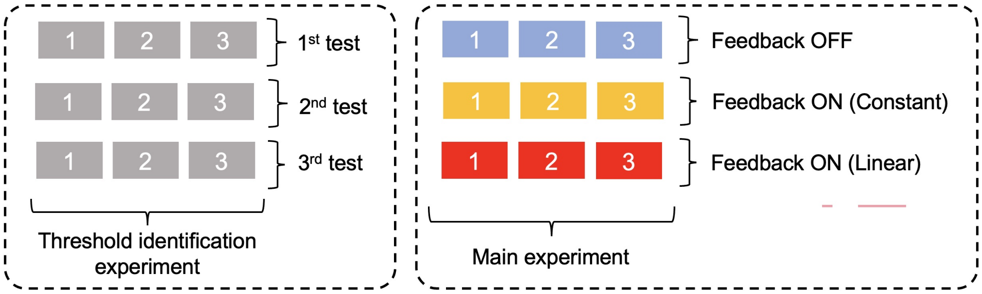

Figure 2.4: Study 1 Protocols. It consists of 2 experiments (threshold identification experiment and main experiment). A threshold identification experiment was performed to identify the threshold sway angle to trigger vibrotactile feedback in the main experiment. Each subject's threshold was consistently used in all subsequent experiments and the main experiment was performed in 3 feedback conditions (Feedback OFF / Feedback ON (Constant) / Feedback ON (Linear)).

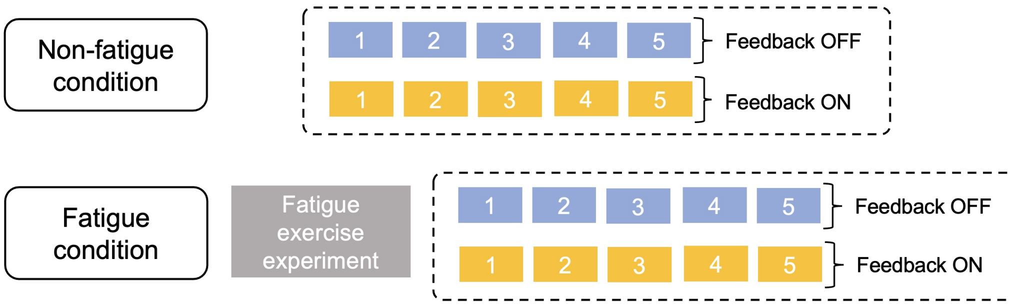

Figure 2.5: Study 2 Protocols. It consists of 2 experiments (fatigue exercise experiment and main experiment). The fatigue exercise experiment was performed to induce fatigue in the lower body with five sets of lower body exercises and the main experiment was performed in 2 feedback conditions (Feedback OFF / Feedback ON (Constant)). On one day, the main experiment was performed without fatigue exercise experiment (non-fatigue condition), and on the other day, the fatigue exercise experiment was performed before the main experiment (Fatigue condition).

b) Main experiment

The experimental setup and perturbations are the same as in the Study 1. Two feedback conditions were used: Feedback OFF and Feedback ON (Constant). Five trials were repeated for each condition, and each trial lasted for 3 minutes. The order of the feedback condition was fully randomized to remove any potential biases. After every 2 trials, the subject took at least a 3-minute break.

2.4 Data Processing and Analysis

The COP and IMU data were analyzed to investigate the effects of the waist vibrotactile feedback on controlling the postural balance. The COP data were extracted from the force plate on the robotic balance platform, and the sway data were extracted from the IMU sensors of the waist vibrotactile feedback device.

The COP data were recorded at a sampling rate of 2 kHz and low-pass filtered using a 4th order Butterworth filter with a cut-off frequency of 15 Hz. The two force plates on top of the platform recorded the COP displacement under each foot. The net COP displacements were calculated from COP displacements under the right COP and left COP [1] . area was calculated to quantify the controllability of the subjects' postural balance. COP sway area has the 95% confidence ellipse area which is expected to have 95% of the points on the COP. COP mean absolute velocity was also calculated, defined as the average of the absolute velocity of the COP data in the AP and ML directions. A decrease in the COP sway area and COP mean absolute velocity indicates that the subject showed better performance in postural control.

The orientation data of the IMU sensor was sampled at a frequency of 100 Hz. IMU dead zone percentage was calculated, which was defined as the percentage of time that the subject's sway angle was within the threshold during balance control. IMU mean absolute velocity was also calculated, defined as the average of the absolute velocity in the AP and ML directions. An increase in the IMU dead zone percent and a decrease in IMU mean absolute velocity indicate that the subject showed better performance in postural control.

2.5 Statistical Analysis

A series of statistical analysis was performed to investigate the effectiveness of the waist vibrotactile feedback device. For Study 1, one-way repeated measures ANOVA (rm-ANOVA) was used with Vibrotactile feedback condition (Feedback OFF / ON (Constant) / ON (Linear)) as the within-subject factor. For Study 2, two-way rm-ANOVA was used with Vibrotactile feedback condition (Feedback OFF / ON) and the fatigue condition (non-fatigue / fatigue) as the two factors. The ANOVA analysis was followed by pairwise comparisons with the Bonferroni correction.

In addition, to investigate how baseline balance performance (measured in the Feedback OFF condition) influences the effectiveness of the waist feedback in improving balance control, a linear regression was performed that relates balance performance improvement (Feedback ON condition – Feedback OFF condition) to the baseline performance (Feedback OFF condition). To quantify this relationship, the correlation coefficient (r value) and its significance (indicated by p value) were calculated. Data analysis was performed using Statistical Package for Social Science (SPSS, version 28.0.1.0, IBM Corporation, Armonk, NY, USA).

Chapter 3

RESULTS

3.1 Study 1: Validation of the Effectiveness of the Waist Vibrotactile Feedback Device

A) Effect of the biofeedback on Center of Pressure (COP)

The waist vibrotactile feedback device had a positive effect on decreasing the COP sway area, supporting the effectiveness of the waist vibrotactile feedback device in improving the controllability of postural balance. The COP sway area was reduced by 13% and 16% in the Feedback ON (Constant) and in the Feedback ON (Linear) condition, respectively (Fig. 3-1 (a)). The Feedback ON (Constant) condition significantly decreased the COP sway area ($p = 0.006$). However, the Feedback On (Linear) condition didn't reach the statistical significance ($p = 0.051$).

The regression analysis showed a trend of higher performance improvement in subjects with lower baseline performance. However, both feedback conditions did not reach the statistical significance: the Feedback ON (Linear) condition ($r = -0.51$; $p = 0.052$) than on the Feedback ON (Constant) condition ($r = -0.38$; $p = 0.161$) (Fig. 3-1 (b)).

Contrary to the COP sway area, the COP mean absolute velocity didn't show meaningful differences in Feedback OFF and ON conditions (Fig. 3-2).

B) Effect of the biofeedback on IMU orientation data

The waist vibrotactile feedback had a significant effect on increasing the IMU dead zone percentage, meaning that the vibrotactile feedback improved the control of body sway. The group results showed a significant effect of increasing the IMU dead

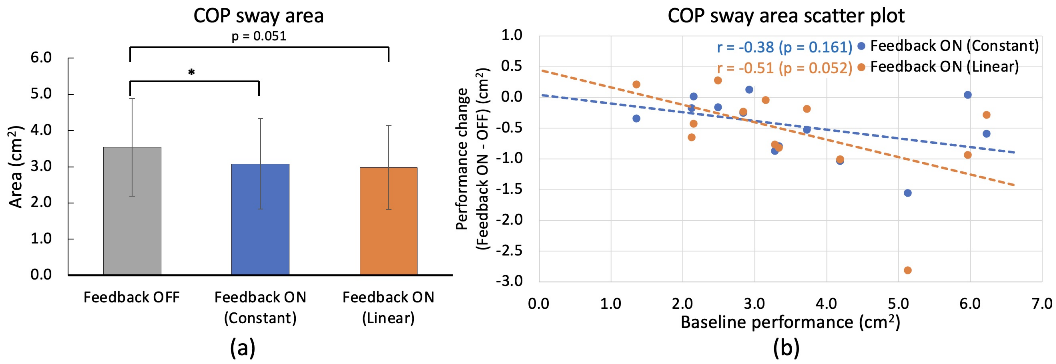

Figure 3.1: The results of the COP sway area (a) and scatter plot (b). The vibrotactile feedback had a significant effect on decreasing the COP sway area (a). There were higher performance improvement trends for those with worse baseline performance (b). The error bars represent the standard deviation of the mean obtained for all the participants. * Significant of rm-ANOVA: *p ¡ 0.05

zone percentage in both feedback conditions (p ¡ 0.001) (Fig. 3-3(a)).

The regression analysis showed a clear correlation between the degree of performance improvement and baseline performance in both feedback conditions (Fig. 3-3 (b)). It is worth to note that the ML direction results showed a stronger correlation than in the AP direction.

The group results showed a trend of decreasing IMU mean absolute velocity with the feedback but didn't reach the statistical significance (Fig. 3-4 (a)). However, the regression analysis showed a significant effect in subjects with lower baseline performance. A clear correlation between the degree of performance improvement and baseline performance was observed in both AP and ML directions in both feedback conditions (Fig. 3-4 (b)). Consistent with the group results, the correlation was stronger in the ML direction than the AP direction.

3.2 Study 2: Investigation of the Biofeedback Effectiveness under Fatigue Conditions

A) Effect of the biofeedback on Center of Pressure (COP)

The waist vibrotactile feedback device had a significant effect on decreasing COP

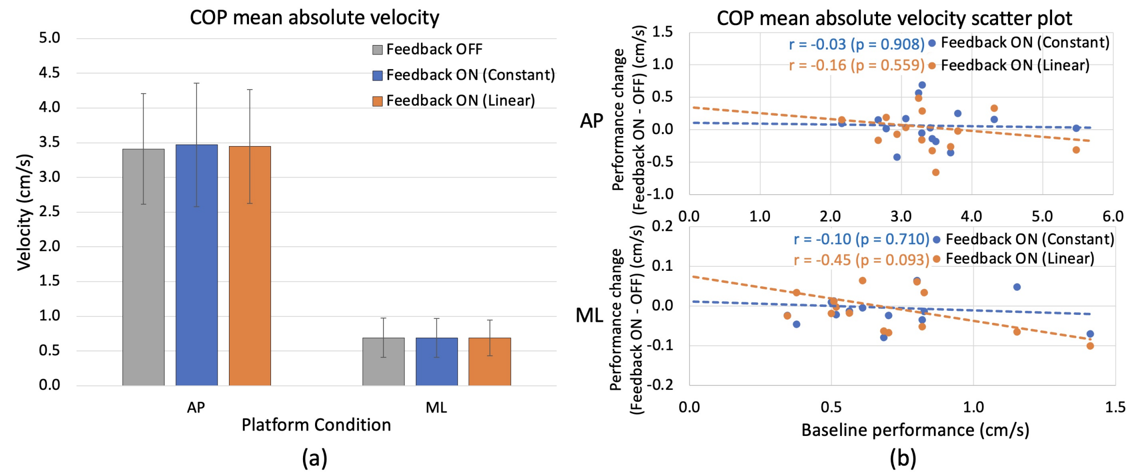

Figure 3.2: The results of the COP mean absolute velocity (a) and scatter plot (b). The vibrotactile feedback didn't have an effect (a). There was a trend of improvement for those with worse baseline performance in ML direction (b).

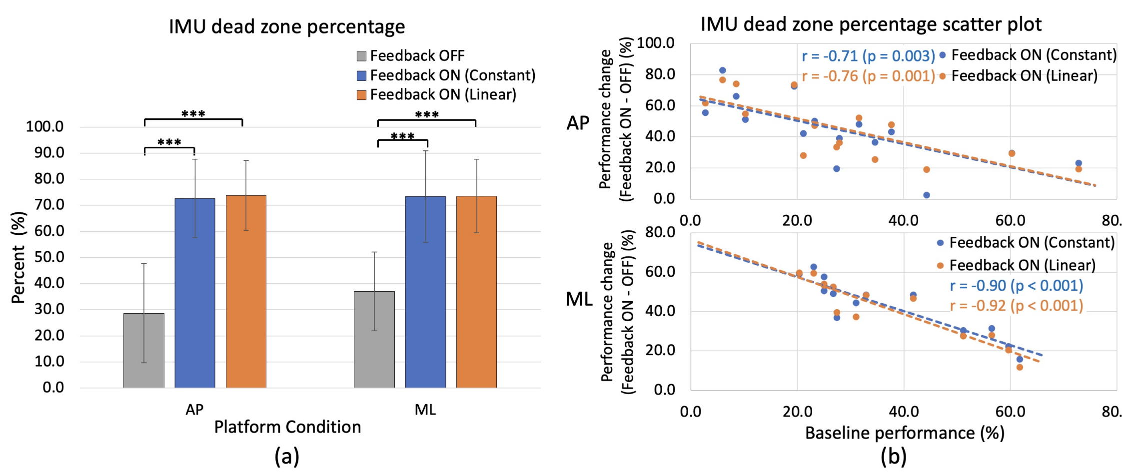

Figure 3.3: The results of the IMU dead zone percent (a) and scatter plot (b). The vibrotactile feedback had a significant effect on increasing the IMU dead zone percent (a). There were higher performance improvement trends for those with worse baseline performance (b). The error bars represent the standard deviation of the mean obtained for all the participants. * significance of rm-ANOVA: ***p ¡ 0.001.

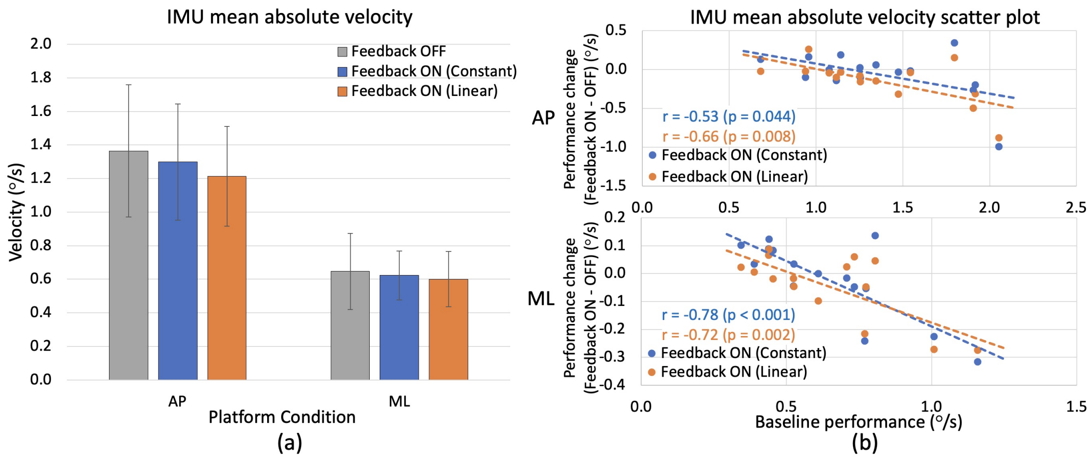

Figure 3.4: The results of the IMU mean absolute velocity (a) and scatter plot (b). It showed a trend of decreasing IMU velocity with the feedback, but not reached statistical significance (a). There was a higher significant performance improvement for those with worse baseline performance (b).

sway area after the fatigue exercise experiment, supporting the effectiveness of the waist vibrotactile feedback device in improving the controllability of postural balance even under fatigue. While the COP sway area was reduced by 12% under the non-fatigue condition (p = 0.041), it was reduced by 16% under the fatigue condition (p = 0.003) (Fig. 3-5 (a)). In addition, while there was an increase in the COP sway area after the fatigue exercise (p = 0.052), the feedback decreased the COP sway area in the fatigue condition to the level of non-fatigue condition (p = 0.071).

The regression analysis showed a significantly higher performance improvement in subjects with lower baseline performance: the non-fatigue condition (r = -0.73; p = 0.002) than the fatigue condition (r = -0.91; p ¡ 0.001) (Fig. 3-5 (b)).

Contrary to the COP sway area, COP mean absolute velocity didn't show meaningful differences in Feedback OFF and ON conditions as in the result of Study 1 (Fig. 3-6 (a)). The regression analysis showed a trend of higher performance improvement in subjects with lower baseline performance in both AP and ML directions and in both fatigue and non-fatigue conditions. However, the correlation was not strong (r = -0.56 -0.40) (Fig. 3-6 (b)).

B) Effect of the biofeedback on IMU orientation data

The waist vibrotactile feedback had a significant effect on increasing the IMU dead zone percentage in both AP and ML directions and in both fatigue and non-fatigue conditions, demonstrating the improved control of body sway with the vibrotactile feedback (p ¡ 0.001) (Fig. 3-7 (a)). There was a slight performance decrease in the ML direction under fatigue.

The regression analysis showed a clear correlation between the degree of performance improvement and baseline performance in both fatigue conditions (Fig. 3-7 (b)). It is noteworthy that, as in Study 1, the ML direction results showed a stronger correlation than in the AP direction.

The group results showed a trend of decreasing IMU mean absolute velocity with the feedback but the statistical significance was marginal in all conditions (Fig. 3-8 (a)). However, the regression analysis showed a significant effect in subjects with lower baseline performance. A clear correlation between the degree of performance improvement and baseline performance was observed in both AP and ML directions in both fatigue conditions (Fig. 3-8 (b)).

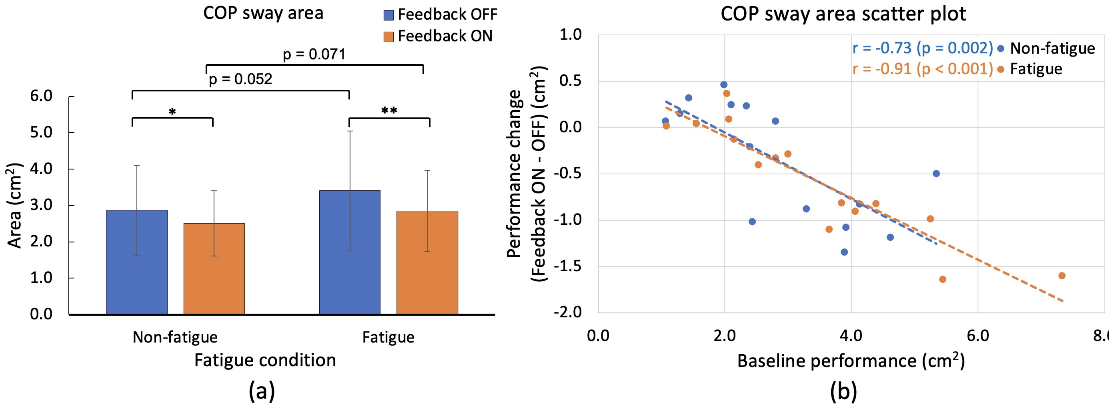

Figure 3.5: The results of the COP sway area (a) and scatter plot (b). The vibrotactile feedback had a significant effect on decreasing the COP sway area, and the fatigue condition had a more significant effect (a). Feedback was highly effective in reducing COP sway area in subjects with worse baseline performance even in the fatigue condition (b). The error bars represent the standard deviation of the mean obtained for all the participants. * significant differences of rm-ANOVA: *p ¡ 0.05, **p ¡ 0.005.

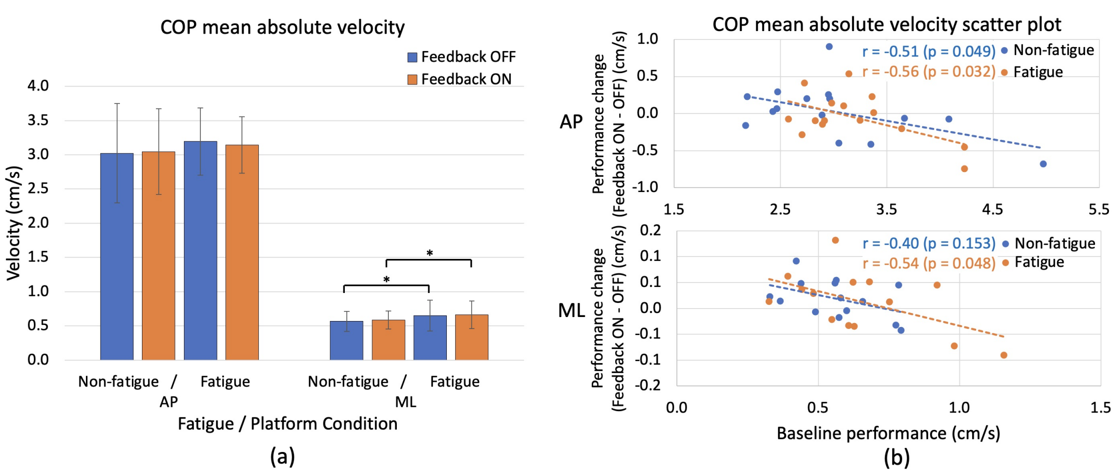

Figure 3.6: The results of the COP mean absolute velocity (a) and scatter plot (b). The vibrotactile feedback didn't have an effect, but COP mean absolute velocity significantly increased after fatigue protocol in ML direction (a). There was a trend of improvement for those with worse baseline performance in ML direction (b). * significant of rm-ANOVA: *p ¡ 0.05.

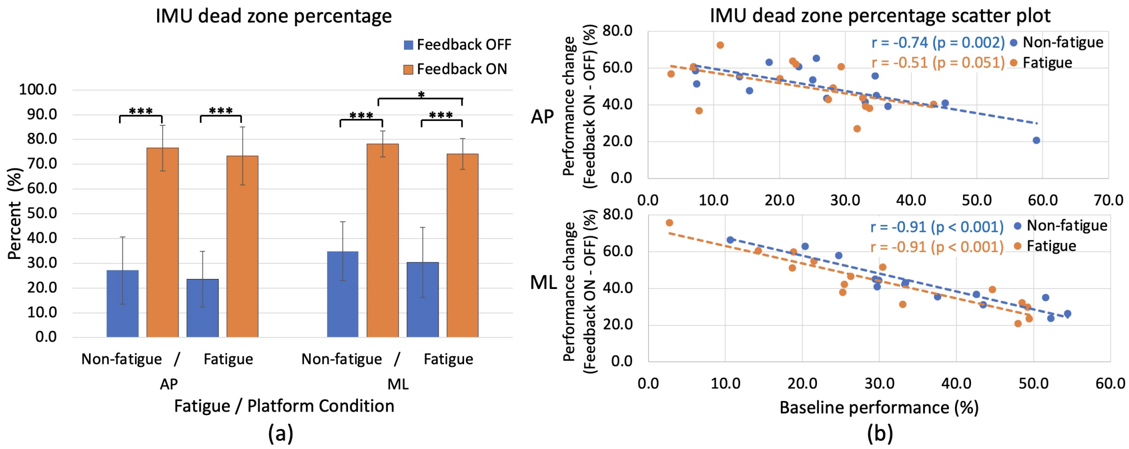

Figure 3.7: The results of the IMU dead zone percent (a) and scatter plot (b). The vibrotactile feedback had a significant effect on increasing the IMU dead zone percent (a). There were higher performance improvement trends for those with worse baseline performance (b). The error bars represent the standard deviation of the mean obtained for all the participants. * significant of rm-ANOVA: ***p ¡ 0.001.

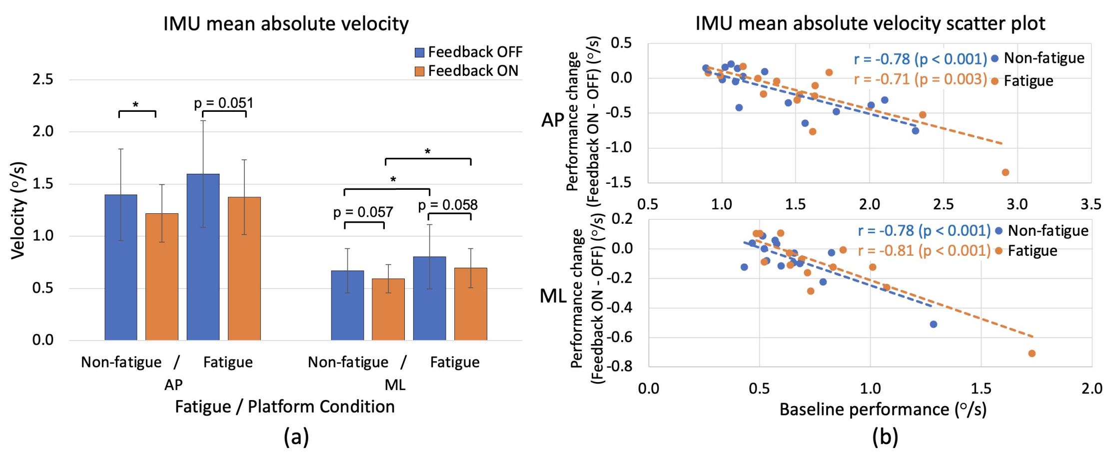

Figure 3.8: The results of the IMU mean absolute velocity (a) and scatter plot (b). It showed a trend of decreasing IMU velocity with feedback (a). There was a higher significant performance improvement for those with worse baseline performance (b). * significant of rm-ANOVA: *p ¡ 0.05.

Chapter 4

DISCUSSION

The purpose of this study was to validate the effectiveness of the waist vibrotactile feedback device to improve the postural balance control under the challenging ground condition (Study 1). Compared to previous studies performed under the rigid ground conditions or uncontrolled randomized perturbations, this study was performed under the randomized but controlled multi-directional rotational perturbations by utilizing the robotic balance platform. This study also investigated the effectiveness of the biofeedback under fatigue conditions (Study 2). The results of Study 1 and Study 2 demonstrated that the waist vibrotactile feedback improved the postural balance control in both non-fatigue and fatigue conditions. In addition, the regression analysis of COP and IMU data showed a correlation between the degree of performance improvement and baseline performance; the feedback had a higher effect on performance improvement for those with worse baseline performance.

The effect of vibrotactile feedback was more evident in the IMU-based measures than the COP-based measures in both non-fatigue and fatigue conditions. Improvement of spatial aspects of balance control was quantified by calculating the increase of IMU dead zone percentage and the decrease of COP sway area. While statistically significant decrease of the COP sway area was consistently observed with the feedback, the percentage decrease was substantially lower than the increase of IMU dead zone percentage. Improvement of temporal aspects of balance control was quantified by calculating the decrease of IMU mean absolute velocity and COP mean absolute velocity. While IMU mean absolute velocity showed a decreasing trend with the feedback, no clear trend was observed for COP mean absolute velocity. It is also worth to note that the feedback effect was more evident in the spatial measures than the temporal measures. These results are likely due to the way biofeedback was designed and used. Since the criterion to provide biofeedback was based on the IMU data, IMU-based measures were more directly influenced by the feedback. In addition, since the feedback was triggered based on the sway angle threshold, which is more relevant to the spatial aspect of balance control, clearer effects were observed in the spatial measures than the temporal measures.

The IMU sensor was placed near COM in this study (i.e., IMU position data closely represent COM position data). If there exists a high correlation between the COP data and IMU position data, we expect similar results in both the IMU-based measures and the COP-based measures. In fact, several previous studies showed that COM and COP data are highly correlated during standing postural balance [23; 24] , but they are less correlated as ground condition becomes more challenging [25] . The ground condition in our study was quite challenging with varying frequencies and amplitudes in multiple directions. In fact, our additional correlation analysis showed a weak correlation between COP data and IMU position data in all experimental conditions, which support our results of higher effect of vibrotactile feedback on the IMU based measures than the COP based measures. The highest correlation in the vibrotactile feedback condition was $r = 0.19$ (0.10) and 0.21 (0.12) for AP and ML directions, respectively.

The effect of the vibrotactile feedback device didn't show significant differences in the Feedback ON (Constant) and Feedback ON (Linear) conditions. As a result, only Feedback ON (Constant) condition was used in Study 2 to verify the effect of the vibrotactile feedback under the fatigue condition. However, this might be because vibration magnitude changes in this study were not evident, and subjects might not be able to differentiate the two vibration conditions (Constant vs. Linear). If the range of vibration magnitude is extended in the Linear condition (e.g., 50-100% rather than 80-100% vibration magnitude), subjects might easily feel the difference between the two conditions, and the effect of vibration profiles can be better evaluated. A future study seems warranted to investigate this.

Several limitations of this study should be acknowledged. The fatigue exercise experiments (heel raises, squats, and lunges) were performed to induce fatigue in the lower body, but quantification of muscle fatigue was not properly made. Electromyography (EMG) sensors were attached to the tibialis anterior (TA) and medial gastrocnemius (GAS) muscles to quantify muscle fatigue, but the median frequency of power spectrum of these muscles before and after fatigue didn't show a clear change, i.e., no indication of muscle fatigue. In fact, subject feedback informed that the fatigue exercise in this study was more focused on the upper leg than lower leg. For future studies, EMG sensors should be attached to the quadriceps and hamstring muscles for accurate quantification of muscle fatigue.

The feedback was strictly based on the orientation data, and this could be a limitation in certain situations, for example, when subjects suddenly lost their balance control. In standing balance, a clear change in acceleration data is seen first before angle data [3] . So, to give more instant feedback on controlling the postural balance, angular acceleration data of the IMU could be more beneficial than angle data. An area for future study is to compare the performance with a vibrotactile feedback device using acceleration data vs. position data.

——————————————— The final limitation of the study is that it was hard to control the postural balance with the orientation data when subjects suddenly lost their standing balance (Fig. 4-1). For controlling the postural balance, this study used the orientation data of the body tilt, not the acceleration data, which could be more effective in postural balance. In quiet standing, angular acceleration data first affect the standing posture before the angular velocity [3] . So, to give more direct feedback on controlling the postural balance, acceleration data of the IMU could be more beneficial. An area for further study is using a vibrotactile feedback device using acceleration data to improve postural balance control. To expand the applicability of these research results, the effects of fatigue and aging on postural balance are similar in the neurophysiological approach. Fatigue reduces muscular force generation and repeated muscular contraction delays sensory reactions [26; 27] . Similarly, as people age, their ability for muscle usage decreases, and their sensory responses become less sensitive [28; 29] . As a result, both fatigue and aging have similarities where their ability to control sensory reflexes and muscle control decreases [30] . Although this research was conducted on young healthy subjects, considering the similarity of muscle fatigue to neuromuscular symptoms caused by aging, it can be expected that this vibrotactile feedback device can be used to improve postural balance in both young and old people.

Chapter 5

CONCLUSION

This paper presents the effects of waist vibrotactile feedback on improving standing postural balance control under challenging ground conditions. It also suggests that the vibrotactile biofeedback is effective on standing postural stability even under fatigue conditions.

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