The Effects of Augmented Somatosensory Feedback on Postural Sway and Muscle Co-contraction in Different Sensory Conditions

Seo-hyun Kim¹, BPT, PT, Kyung-eun Lee¹, BPT, PT, One-bin Lim², PhD, PT, Chung-hwi Yi², PhD, PT

¹Department of Physical Therapy, The Graduate School, Yonsei University, ²Department of Physical Therapy, College of Health Science, Yonsei University, Wonju, Korea

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Corresponding Author

Chung-hwi Yi

E-mail: pteagle@yonsei.ac.kr

<https://orcid.org/0000-0003-2554-8083>

Key Words

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Background: Augmented somatosensory feedback stimulates the mechanoreceptor to deliver information on bodily position, improving the postural control. The various types of such feedback include ankle-foot orthoses (AFOs) and vibration. The optimal feedback to mitigate postural sway remains unclear, as does the effect of augmented somatosensory feedback on muscle co-contraction.

Objects: We compared postural sway and ankle muscle co-contraction without feedback (control) and with either of two forms of somatosensory feedback (AFOs and vibration).

Methods: We recruited 15 healthy subjects and tested them under three feedback conditions (control, AFOs, vibration) with two sensory conditions (eyes open, or eyes closed and the head tilted back), in random order. Postural sway was measured using a force platform; the mean sway area of the 95% confidence ellipse (AREA) and the mean velocity of the center-of-pressure displacement (VEL) were assessed. Co-contraction of the tibialis anterior and gastrocnemius muscles was measured using electromyography and converted into a co-contraction index (CI).

Results: We found significant main effects of the three feedback states on postural sway (AREA, VEL) and the CI. The two sensory conditions exerted significant main effects on postural sway (AREA and VEL). AFOs reduced postural sway to a level significantly lower than that of the control ($p = 0.014$, $p < 0.001$) or that afforded by vibration ($p = 0.024$, $p < 0.001$). In terms of CI amelioration, the AFOs condition was significantly better than the control ($p = 0.004$). Vibration did not significantly improve either postural sway or the CI compared to the control condition. There was no significant interaction effect between the three feedback conditions and the two sensory conditions.

Conclusion: Lower-extremity devices such as AFOs enhance somatosensory perception, improving postural control and decreasing the CI during static standing.

INTRODUCTION

Postural control is regulated by the visual, vestibular, and somatosensory systems ('somatosensory' refers to both cutaneous sensation and proprioception) [1]. During static standing, the most sensitive information on body sway is provided by proprioceptive musculoarticular cues (somatosensory cues from the lower extremities) [2-5]. Postural sway reflects poor coordination of musculoskeletal movements regulated by sensory and muscular feedback that are intended to maintain the standing balance [6-8]. Postural sway is most often characterized by displacements of the center of pressure (CoP), which reflects the

orientation of body segments, and bodily movements that seek to preserve the center of gravity [9].

In the diminishing of sensory and muscular feedback, alternate sources of sensation substitute for the missing information. For example, a light fingertip touch on a stationary external surface reduces postural sway [10-12]. Somatosensory feedback yields positional information, contributing to self-perception of bodily motion via mechanical stimulation of cutaneous mechanoreceptors. Such feedback can be exploited to induce desired changes in muscle contraction patterns; muscles respond to ankle-foot orthoses (AFOs) and vibration [13-15].

Although the effects of AFOs on balance remain controversial, a recent systematic review suggested that postural control improved if the ankle range of motion was not limited [16]. Smalley et al. [15] found that AFOs reduced postural sway but footplates did not. In addition, during static standing, vibration applied bilaterally over the Achilles tendons imparted the illusion of lengthening of dorsiflexor muscles, which are the primary muscles that control postural sway [17]. The illusion enhances the sensitivity of leg muscle spindles, improving postural sway [13].

In order to examine only the somatosensory system in the postural balance, a certain sensory condition could be used to reduce the effects of visual and vestibular system by closing eyes and tilting head back [18]. And the effects of the somatosensory feedback can be better examined in the sensory condition (eye closed and head tilted back) that is greatly affected by the somatosensory system than in a normal sensory condition with visual, vestibular and somatosensory systems [15].

Although augmented somatosensory feedback improves postural sway by changing muscle contraction patterns, few studies have explored the activities of ankle postural muscles. Subjects lacking appropriate regulation of balance feedback use co-contraction of the postural muscles to excess while standing, as a compensation [19,20]. Co-contraction of ankle joint muscles increases joint stiffness and may restrict postural control [21,22]. In high ankle joint stiffness, body movement during static standing was less characteristic of an inverted pendulum and more reliant on hip/mixed strategies which induce the large postural sway [23]. This may increase the risk of falling; it is essential to ensure that augmented somatosensory feedback does not induce such effects.

AFOs and vibration improve postural sway; however, it remains unclear which form of feedback is optimal. No study has yet explored the effect of somatosensory feedback on ankle muscle co-contraction. Thus, the aim of this study was to compare the effects of feedback-free, AFOs and vibration on postural sway and muscle co-contraction with different sensory conditions. We hypothesized that augmented somatosensory feedback (AFOs and vibration) would reduce postural sway (the AREA and VEL parameters) and affect the co-contraction index (CI) during static standing.

MATERIALS AND METHODS

1. Subjects

Fifteen young age subjects (11 males, 4 females; mean age: 22.9 ± 1.7 years, height: 169.5 ± 6.8 cm, weight: 68.1 ± 10.6 kg) participated in the study. All lacked any neuromuscular balance disorder, had no history of knee or ankle surgery, and did not feel dizzy when standing. Before participating in the study, all subjects were informed of the study procedure and methods. This study was approved by the Yonsei University Wonju Institutional Review Board (approval No. 1041849-201910-BM-144-02).

2. Instruments

1) Static postural sway testing

A force platform (FDM S; Zebris Medical GmbH, Isny, Germany) was used to measure postural sway during static standing; signals were sampled at 100 Hz. CoP displacements were employed to extract the mean sway area of the 95% confidence ellipse (AREA, cm^2) and the mean velocity of CoP displacements (VEL, mm/s) [20]. The data were processed and verified using MR3 ver. 3.6.32 software (Noraxon Inc., Scottsdale, AZ, USA), which also synchronized and verified the electromyography (EMG) data.

2) Electromyography recording

The postural muscle activity of the ankle joint during static standing was measured using surface EMG (Noraxon TeleMyo DTS; Noraxon Inc.) at a sampling rate of 1,000 Hz. The tibialis anterior (TA) and gastrocnemius (GCM) muscle activities were recorded to explore ankle muscle co-contraction during static standing. Two unipolar electrodes were attached to each muscle, as recommended by Criswell [24]. For the TA muscle, two electrodes 2 cm apart were placed parallel to and just lateral to the medial shaft of the tibia (on the muscle belly); electrodes were placed directly on the GCM muscles [24]. Each TA and GCM EMG signal was normalized to the maximal signal obtained during static standing.

3) Muscle co-contraction analysis

EMG data were post-processed using Matlab (Matlab R2019a; MathWorks, Natick, MA, USA). Raw EMG signals were band-pass filtered at 15–500 Hz using a second-order Butterworth digital filter to remove noise or movement interference [20]. To

explore the extent of TA and GCM co-contraction, the CI was calculated using the method of Falconer and Winter [25] employing the following equation: $CI = \frac{2I_{ant}}{I_{total}} \times 100\%$

I_{ant} is the area of the total antagonistic activity calculated as $I_{ant} = \int_{t_1}^{t_2} EMG_{TA}(t)dt + \int_{t_2}^{t_3} EMG_{GCM}(t)dt$ where t_1 to t_2 is the interval during which the TA EMG signal is lower than the GCM signal and t_2 to t_3 is the opposite interval.

I_{total} is the integral of the summed TA and GCM EMG signals during task performance: $I_{total} = \int_{t_1}^{t_3} [EMG_{TA} + EMG_{GCM}](t)dt$

The higher the CI value, the greater the use of muscle co-contraction [25].

4) Augmented somatosensory feedback

AFOs (AOS-102; DOUM Medical, Seoul, Korea) were fabricated from 40 mm wide padded Velcro strapping consistent with the type used most frequently to secure orthoses. The flexible AFOs didn't restrict ankle range of motion in order not to directly affect the postural balance.

Vibration was delivered by two commercial vibrator (Magic Touch; Xiamen Lefan Wellness Science & Technology Co., Ltd, Xiamen City, Fujian Province, China). Each vibrator was circular with a diameter of 5 cm with a flexible pad to fit over the Achilles tendon and was set from 0 to 100 Hz. The vibration was applied continuously for one test.

3. Procedure

The subjects stand barefoot on the force platform with their feet together and their arms relaxed on both sides of the body. They were instructed to try not to sway during measurements taken over 60 s during all tests. Each subject was then asked to perform postural tasks with two sensory conditions: Eyes opened (EO), or eyes closed, and head tilted back (ECHB). Un-

der the EO condition, the subjects stared at a stationary sign on paper placed 2 m from the front of the platform. Under the ECHB condition, the subjects stared at a sign on the ceiling about 30 cm in front of the platform and then closed their eyes. The ECHB condition reduced influence of visual system and vestibular system to isolate the somatosensory control of postural control [7]. Three feedback conditions were tested in each sensory condition: 1) control, no AFOs or vibration (Figure 1A), 2) AFOs, Wearing the AFOs on both lower legs (Figure 1B), 3) Vibration, vibrators on both Achilles tendon (Figure 1C). The tests were performed in random order using a randomization sequence created by Microsoft Excel (Microsoft Corp., Roselle, IL, USA). The subjects sat for 60 seconds (rest periods) between each test.

4. Statistical Analysis

The one-sample Kolmogorov-Smirnov test confirmed that the data were normally distributed. A 3×2 (three feedback conditions $\times$ two sensory conditions) repeated-measures analysis of variance was used to compare the CoP and EMG data; the Bonferroni correction was applied during post-hoc testing. A p-value < 0.05 was taken to indicate statistical significance. SPSS software ver. 25 (IBM Corp., Armonk, NY, USA) was used for all statistical analyses.

RESULTS

The AREA, VEL, and CI values derived under the three feedback conditions in both positions are listed in Table 1.

1. Postural Sway

No significant (three feedback conditions $\times$ two sensory conditions) interaction was evident for either AREA ($F = 0.395$,

Figure 1. The three feedback conditions [A: control, B: AFOs, C: vibration]. AFOs, ankle-foot orthoses.

Table 1. Postural control and CI data derived under the three feedback conditions (N = 15)

Variables	Control		AFOs		Vibration	
	EO	ECHB	EO	ECHB	EO	ECHB
AREA (cm ²)	721.8 ± 363.8	1,340.1 ± 777.1	551.5 ± 250.0	838.5 ± 314.7	714.7 ± 411.8	1,152.1 ± 540.5
VEL (mm/s)	12 ± 3.0	20.4 ± 6.2	9.9 ± 2.6	15.9 ± 3.2	11.7 ± 3.5	20.6 ± 4.1
CI (%)	36.5 ± 8.5	39.3 ± 9.2	29.3 ± 9.5	35.4 ± 9.7	35.7 ± 11.5	36.4 ± 8.4

Values are presented as mean ± standard deviation. CI, co-contraction index; AFOs, ankle foot orthoses; EO, eye open; ECHB, eye closed and head tilted back; AREA, the mean sway area of the 95% confidence ellipse, VEL, the mean velocity of the center of pressure displacements.

Table 2. ANOVA analyses by two positions and three feedback conditions

Variables	Feedback		Sensory		Feedback × Sensory	
	F	p-value	F	p-value	F	p-value
AREA	0.680	0.005*	1.004	0.002*	0.395	0.131
VEL	1.061	< 0.001*	2.380	< 0.001*	0.422	0.100
CI	0.747	0.002*	0.451	0.114	0.279	0.349

AREA, the mean sway area of the 95% confidence ellipse; VEL, the mean velocity of the center of pressure displacements; CI, co-contraction index. *p < 0.05.

Figure 2. Post-hoc comparisons of the effects of the three feedback conditions (control, AFOs, and vibration) on the (A) AREA, (B) VEL, and (C) CI values during static standing. AREA, the mean sway area of the 95% confidence ellipse; VEL, the mean velocity of the center of pressure displacements; CI, co-contraction index; AFOs, ankle-foot orthoses. *p < 0.05.

p = 0.131) or VEL (F = 0.422, p = 0.100). In three feedback conditions (control, AFOs, and vibration), significant main effects on AREA (F = 1.004, p = 0.002) and VEL (F = 2.380, p < 0.001) were apparent (Table 2). AFOs had significant difference with the control (p = 0.014) and vibration (p = 0.024) in AREA (Figure 2A). In addition, AFOs had significant difference with the control (p < 0.001) and vibration (p < 0.001) in VEL (Figure 2B). Vibration (compared to the control condition) did not exhibit any significant effects on AREA or VEL. Significant main effects of the two sensory conditions (EO and ECHB) on AREA (F = 0.680, p = 0.005) and VEL (F = 1.061, p < 0.001) were apparent (Table 2). AREA and VEL of postural sway were had significant increase under the ECHB condition than under the EO condition (p = 0.002, p < 0.001) (Figure 3A, B).

2. Ankle Muscle Co-contraction

There was no significant interaction effect in terms of CI (F = 0.279, p = 0.349). The three type of feedback exerted significant main effects on CI (F = 0.747, p = 0.002) (Table 2). The AFOs significantly decreased the CI compared to the control condition (p = 0.004), but the effects of AFOs and vibration did not differ significantly (p = 0.133). The effect of vibration did not differ significantly from that of the control condition (p = 0.403) (Figure 2C). When comparing the two sensory conditions, no significant main effect on CI was evident (F = 0.451, p = 0.0114) (Figure 3C).

DISCUSSION

AFOs and vibration were used to improve the postural

Figure 3. Post-hoc comparisons of the two positions [eyes open [EO], eyes closed with the head tilted back [ECHB]] on the (A) AREA, (B) VEL, and (C) CI values during static standing. AREA, the mean sway area of the 95% confidence ellipse; VEL, the mean velocity of the center of pressure displacements; CI, co-contraction index. * $p < 0.05$.

control. However, few studies have explored postural muscle co-contraction during augmented somatosensory feedback. Therefore, the aim of this study was to investigate whether postural sway (AREA and VEL) and CI changed during three feedback conditions delivered to subjects in two sensory conditions. The result suggested that AFOs not only improve postural control but also reduce postural muscle co-contraction. The AREA, VEL data revealed significant main effect of three feedback conditions; AFOs were better than both the control and vibration conditions. As the AFOs contact greater leg area than the vibrations, AFOs may deliver more sensory information. Menz et al. [26] founded that more proximal stimuli were more effective in reducing postural sway. The present study supports these results since the somatosensory feedback from the AFOs could deliver more proximal cutaneous information than vibration. In fact, vibration did not significantly improve postural sway compared to the control, even though many previous studies found that vibration applied both Achilles tendon improve postural sway [13,17,27,28]. With the subjects standing, vibration at 80–100 Hz applied to the Achilles tendon activated I a spindle afferents, inducing postural control improvement [29,30]; the vibration in this study was not always within the range of 80–100 Hz. The effect of vibration was insufficient to make significant improvement of postural sway.

During static standing, the plantarflexor are continuously activated to maintain stable balance; the center of mass lies in front of the ankle joint. Dorsiflexors are rarely activated during static standing, but subjects with impaired postural control frequently engage the dorsiflexors. Both muscles must be appropriately activated to stabilize postural sway [31]. AFOs provide adequate somatosensory cues to both the dorsiflexors and the

plantarflexors; the AFOs cover the entire lower legs. Thus, the postural muscles are alternately activated because both muscles receive enough bodily position information. On the other hand, vibration applied both Achilles tendon were received by only the plantarflexors. There was not enough information to control the dorsiflexors efficiently. Furthermore, somatosensory feedback stimulates mechanoreceptors, strengthening somatosensory perception and facilitating feedback that corrects directional changes. Enhanced sensitivity of bodily position awareness allows smaller counter-movements and result in less muscle activation [7,8,32]. The AFOs affording the greatest reductions in AREA and VEL values induced less body movement than other forms of feedback, reducing the need for ankle muscle activity, and, in turn, the CI value. Vibration did not significantly reduce the CI because it did not significantly improve either the AREA or VEL value.

We confirmed that two sensory conditions exerted main effect on AREA and VEL. A previous study founded no significant effect of somatosensory feedback in EO condition, but a significant effect in ECHB condition (Smalley et al. [15]). The EO condition is more associated with other sensory systems than ECHB condition; visual and vestibular cues deliver sensory information relevant to postural control [18]. However, we found no significant main effects of either sensory condition on the CI. The sensory conditions (EO, ECHB) differed in terms of the factors affecting postural sway; fewer useful cues were available in the ECHB condition than the EO condition. Also, we found no interaction effects among the three feedback conditions and the two sensory conditions, when static standing, the somatosensory system comes to the forefront; the results thus tended to be similar under either sensory condition.

Our study had several limitations. First, the vibrational frequency was not confined to 80–100 Hz, which is thought to be optimal in terms of postural control. Second, in this study, we studied only the TA and GCM muscles; the soleus can also affect the postural control. However, because the vibrators were attached to the Achilles tendon, measures of soleus muscle activity may have created noise. Third, we did not explore dynamic balance, which is critical in daily life. Further research should explore postural muscle co-contraction with dynamic balance.

CONCLUSIONS

Our results suggest that AFOs of the somatosensory feedbacks improve postural sway and reduce ankle muscle co-contraction. Such feedback stimulates muscle mechanoreceptors to enhance somatosensory awareness, rather than inducing excessive muscle contractions, and it is particularly sensitive to changes in body movements and position. Therefore, static balance training using flexible AFOs would effectively improve postural control while preventing excessive ankle muscle co-contraction during static standing. If further work shows that the effects persist even after removing the feedback, balance training would become more efficient.

CONFLICTS OF INTEREST

No potential conflict of interest relevant to this article was reported.

AUTHOR CONTRIBUTIONS

Conceptualization: CY. Data curation: SK, KL. Formal analysis: SK. Investigation: SK. Methodology: SK, OL. Project administration: SK, OL. Resources: SK, KL. Software: SK. Supervision: CY. Validation: SK. Visualization: SK. Writing - original draft: SK. Writing - review & editing: SK.

ORCID

Seo-hyun Kim: <https://orcid.org/0000-0002-6978-200X>
 Kyung-eun Lee: <https://orcid.org/0000-0003-4021-9181>
 One-bin Lim: <https://orcid.org/0000-0002-5281-3463>

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