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Plantar Vibrational Stimuli Modify Dynamic Posture Control in Response to Translational Perturbations

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Abstract— **Declining superficial and deep sensory function, in addition to muscular weakness and other decreases in motor function, reduces balance in elderly people. In previous research comparing dynamic postural control following sensory disruption in young and elderly people, elderly participants took longer to achieve center of pressure (COP) recovery (i.e., to return to an upright standing position after perturbation cessation). We conducted the present study to determine how dynamic postural control in young and elderly people was affected by plantar sensory feedback with vibrational stimuli in accordance with the load acting on the soles. Six elderly people and five young people participated. With the participants standing on a motion platform, postural responses were analyzed following random translational perturbations in one of four directions (forwards, backwards, left, and right). The study combined four directions of translational perturbation with or without plantar vibrational stimulation for eight different conditions. In both groups, COP recovery was significantly quicker when vibrational stimuli were provided. This finding suggests that plantar sensory feedback with vibrational stimuli could help keep elderly people from falling.**

Index Terms— **plantar sensory feedback, vibrating tactor, dynamic postural control.**

I. Introduction

The elderly make up a growing proportion of the world's population and an increase in the population aging rate is a worldwide issue. Curbing the increase in medical costs among this growing demographic is essential. Falls are a cause of injury among the elderly. About 30% of elderly people have been injured in a fall [1]. Fall-related injuries among American elderly people cost US$20 billion to treat every year [2]. For the elderly, falls are both physically and psychologically traumatizing. After falling once, elderly people often develop a fear of falling that keeps them from activities such as going out and shopping. Elderly people who intentionally restrict activity may experience decreases in physical function that can lead to disuse syndrome [3]. It is pointed out that fear of falling also reduces quality of life in the elderly [4]. These negative outcomes highlight the critical need to keep elderly people from falling.

Posture control of the human body requires complex interactions among the musculoskeletal, nervous, and other systems [5]. Age-related degeneration reduces balance in the elderly. It has been pointed out that poor balance not only reduces muscle strength, range of joint motion, and other aspects of motor function but also affects postural control because of its debilitating effects on sensory function. Tanaka et al. examined the relationship between balance and plantar somatosensory sensitivity and found that age-related increases in plantar somatosensory threshold contribute to poor balance [6]. Wingert et al. investigated the relationship between age-related decline in hip joint proprioception and balance and suggested that age reduced the accuracy of hip joint kinesthesia and position sense and that declines in hip joint proprioception were associated with decreases in dynamic balance [7]. Anacker et al. identified a link between somatosensory declines in the ankle and decreasing dynamic balance [8]. Investigating the relationship between sensory sensitivity and the fear of falling in elderly women, Viljanen et al. found a greater likelihood of fear of falling in those with sensory sensitivity deficits in multiple sensory systems [9]. Eikema et al. claimed that elderly people take longer to adapt to proprioceptive changes than young people [10]. These findings in the literature show that preventing falls among the elderly requires not only a physical approach to increase muscle strength and flexibility but also a sensory approach.

Providing sensory feedback with vibrating devices has been shown to be one effective means for such a sensory approach. Shirogane et al. developed a balance training system that combines a force plate with stabilometer with a vibrating tactor. Elderly people and stroke victims undergoing balance training with this system achieved better Cross-test scores [11]. Heijmans et al. investigated static balance in patients with sensory disturbance attributable to diabetes who received plantar vibrational feedback [12]. During an attention-demanding task, participants in their study had better static balance when receiving vibrational feedback. Rusaw et al. used a vibrating tactor to improve balance in transtibial prosthesis users [13]. With a force

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transducer placed under the prosthetic foot to measure changes in load, the participants received feedback via a vibrating tactor attached to the thigh following postural changes. The transtibial prosthesis users achieved better static balance when using the device, indicating that vibrational feedback improves balance in those standing still. The efficacy of vibrational feedback for unexpected changes in balance, however, has not been evaluated in people walking or doing other dynamic activities.

Hip protectors are used to prevent fall-related injuries in people engaged in dynamic activities. Hip protectors prevent fractures and other trauma by absorbing the impact of falls but do not prevent falls themselves. Shortcomings include a lack of efficacy in elderly people at home and uncharacterized efficacy in institutional settings [14]. As described above, it is apparent that preventing falls in the first place is the best way to keep elderly people from developing a fear of falling.

Our research group is developing devices to prevent falls by informing the wearer when his or her balance suddenly shifts during walking and other dynamic activities. Maeda et al. evaluated postural control in young and elderly people subjected to translational perturbations in four directions (forwards, backwards, left, and right) in the presence of visual and somatosensory disturbances created with translucent goggles and a soft floor mat [15]. The elderly participants required longer than the young participants to return to an upright standing position after perturbation cessation (i.e., to achieve center of pressure [COP] recovery) after the perturbation had stopped. When an elderly person with poor plantar sensory performance encounters a large deviation in the COP position from a stable position during a dynamic activity, encouraging return of the COP to a stable position by providing COP location information helps prevent falls.

In the present study, we used vibrating tactors to amplify changes in pressure acting on the plantar surfaces following postural changes and to transmit associated signals to the soles. We evaluated changes in dynamic postural control that standing participants subjected to translational perturbations under different conditions experienced when given amplified sensory feedback to the soles with the vibrating tactors. Showing such amplified sensory feedback to the soles to be effective in postural control would indicate that it could also be effective in keeping elderly people from falling during walking and other dynamic activities.

II. Methods

A. Subjects

Six elderly people (men, 69.5±4.5 years of age) and five young people (three men and two women 21.8±1.6 years of age) were included in the study. None of the participants had a serious current or previous disease that could have affected balance. All lived without assistance. The study is part of a larger study approved by the Research Ethics Committee of the University of Tokyo. After being informed about the study and its methods orally and in writing, all participants signed the informed consent form.

B. Methods

The objective of the present study was to determine how

Figure. 1 Motion Platform

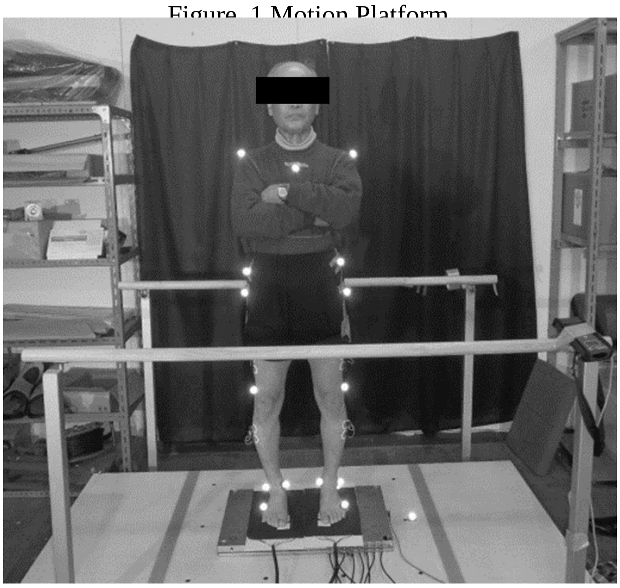


Figure. 2 Experimental Setup

postural control is affected by the provision of plantar feedback to standing participants subjected to translational perturbations in the anteroposterior and mediolateral directions.

During the analysis, the participants stood on a platform with their arms folded and their feet spaced at shoulder width. Translational perturbations were applied with a custom-made motion platform (Kyowa Electronic Instruments Co., Ltd., Tokyo, Japan) (Figures 1 and 2). The platform was set to provide a translational movement (perturbation intensity) of 0.18 m in 1.9 s in one of the four directions of forwards, backwards, left, and right. The platform accelerated at 0.21 m/s^2 over the first 0.7 s, maintained a velocity of 0.15 m/s over the next 0.5 s, and decelerated at 0.21 m/s^2 over the last 0.7 s. The present study focused on postural control following changes in the center of gravity within the support base in association with perturbations. Before analysis, the participants received translational perturbations in each direction to confirm that the perturbation settings achieved the desired result. Hand rails were placed over the platform and two study assistants stood near the participants as safety measures to prevent falls. Plantar vibrational stimuli were provided with small vibrating tactors placed against the plantar surfaces. The vibrating tactors were placed against the great toe, ball, the head of the fifth metatarsal, and heel of each foot (Figure 3). The vibrating tactors were configured to

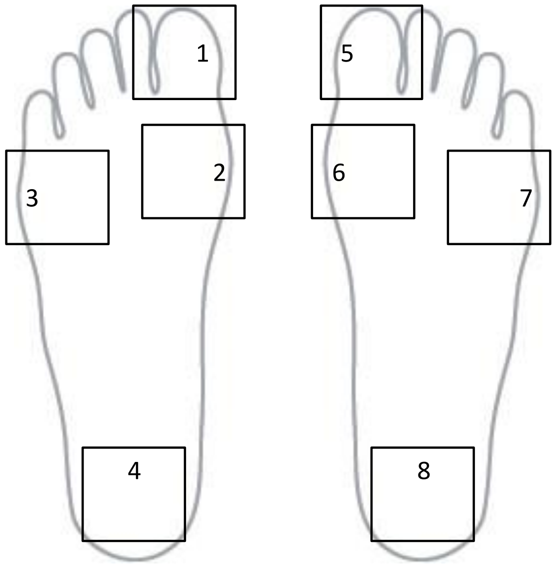


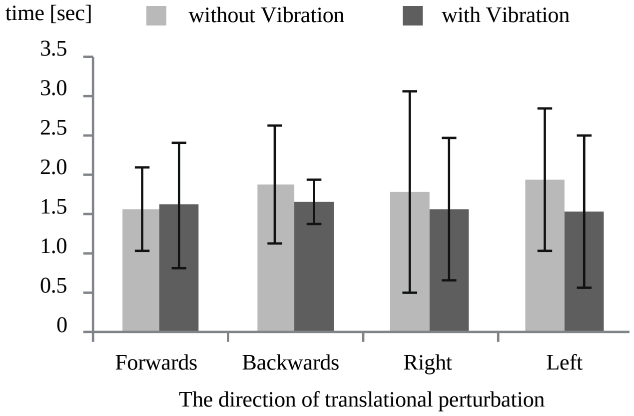
Figure. 3 Arrangement of vibration unit.
1, 5: hallux, 2, 6: hallux area, 3, 7: head of 5th metatarsal 4, 8: heel

activate when pressed against with 10% to 40% of the participant's body weight. The study combined four directions of translational perturbation (forwards, backwards, left, and right) with or without plantar vibrational stimulation for eight different conditions. The conditions were used on the participants in random order, with each condition used twice.

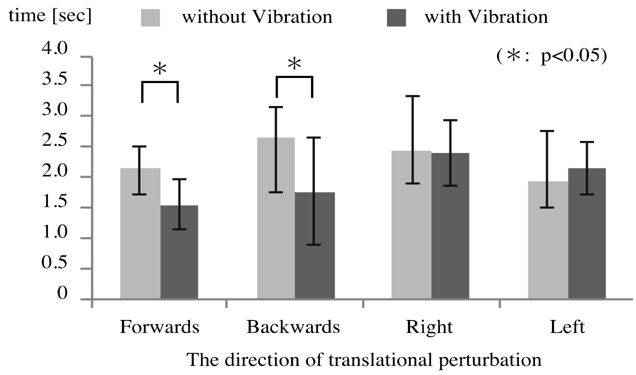
A force plate and electromyograph were used to measure postural changes following perturbations. A force plate (Kyowa Electronic Instruments Co., Ltd.) was placed on the platform to calculate the trajectory of center-of-gravity sway. The sampling frequency of 1000 Hz was converted to 100 Hz for analysis. An electromyograph (NEC Corp, Tokyo, Japan) was used to record muscle activity during postural control. The left and right tibialis anterior, medial head of the gastrocnemius, rectus femoris, biceps femoris, and mesogluteus were analyzed. Wireless electromyography sensors were used so that postural control would not be inhibited. The sampling frequency of the electromyograph was 1000 Hz. Video images of the postural changes the participants experienced were used for qualitative motion analysis.

C. Data Analysis

The force plate was used to determine the distance the COP moved. COP recovery times and COP maxima were also determined. COP recovery time was the time from the end of a translational perturbation to the point at which the participant maintained a COP displacement of no greater than 10 mm for 1 s. COP maxima were the maximum distance that the COP moved in the anteroposterior and mediolateral directions during COP recovery. All electromyography data were normalized according to electromyographic amplitudes during maximal isometric muscle contraction, and muscle activity and latency were calculated. Muscle activity was



(a) The time to recovery of the anteroposterior component of the COP.



(b) The time to recovery of the mediolateral component of the COP.

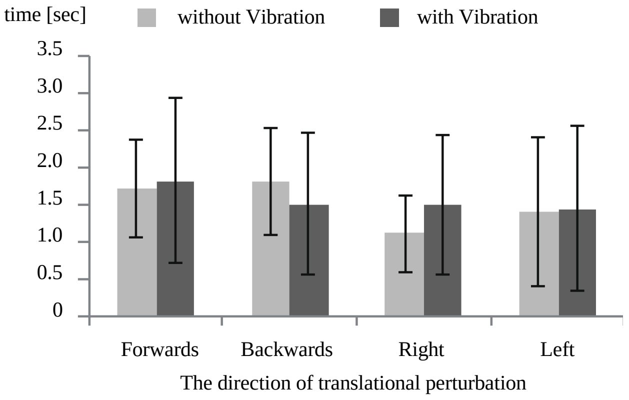
Figure. 4 The time to recovery of the COP in the young participants.

defined as the integral of the muscle discharge during the perturbation (1.9 s following the start of measurement). Muscle latency was defined as the time from the start of a perturbation to the start of muscle activity. The start of muscle activity was in turn defined as the point when the signal exceeded three standard deviations of the baseline waveforms during static muscle activity.

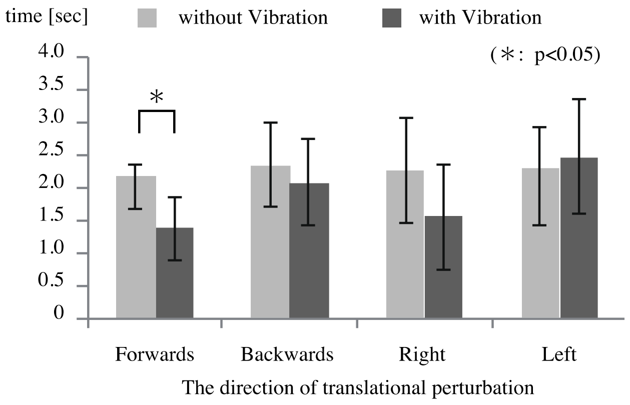
SPSS version 20.0 was used for statistical analysis. A paired t-test was used to compare data obtained under the presence and absence of vibrational stimuli. An unpaired t-test was used to compare the data of the young and elderly participants. A level of significance of 5% was used for all comparisons.

III. RESULTS

The COP results are shown in Figures 4 and 5. Following forwards or backwards translational perturbation, the time to recovery of the mediolateral component of the COP in the young participants was significantly shorter when vibrational stimuli were provided (Figure 4). Following forwards translational perturbation, the time to recovery of the mediolateral component of the COP in the elderly participants was significantly shorter when vibrational stimuli were provided (Figure 5). COP maxima did not significantly differ in the presence and absence of vibrational



(a) The time to recovery of the anteroposterior component of the COP.



(b) The time to recovery of the mediolateral component of the COP.

Figure. 5 The time to recovery of the COP in the elderly participants.

Table. 1 Muscle activity during translational perturbations.

The direction of translational perturbation	Muscle	Young without Vibration Mean±SD	Young with Vibration Mean±SD		Elderly without Vibration Mean±SD	Elderly with Vibration Mean±SD	Young vs Elderly without Vibration	Young vs Elderly with Vibration
Forwards	Anterior Tibialis (Lt)	25.6 ±15.2	34.5±20.2		28.8±4.8	36.3±11.3		
	Anterior Tibialis (Rt)	42.3±33.7	51.1±30.5		34.1±8.8	40.7±4.3		
	Gastrocnemius (Lt)	29.2±23.3	35.0±20.4		57.4±68.9	53.7±49.2		
	Gastrocnemius (Rt)	44. 3 ±44.4	38.3±26.2		24.7±12.9	19.6±8.2		
	Rectus Femoris (Lt)	15.3±9.3	18.5±9.1		48.0±13.5	52.1±15.9	*	*
	Rectus Femoris (Rt)	20.2±11.6	19.8±9.7		56.3±6.5	61.6±13.5	*	*
	Biceps Femoris (Lt)	6.6±5.6	7.3±4.4		12.3±3.6	10.4±4.6		
	Biceps Femoris (Rt)	4.7±2.9	5.7±2.3		14.0±6.4	16.5±7.7		*
	Gluteus Medius (Lt)	6.8±3.9	9.6±5.5	*	15.5±1.3	19.3±4.4	*	
	Gluteus Medius (Rt)	7.8±7.7	6.7±4.8		16.2±4.5	17.9±5.0		
Backwards	Anterior Tibialis (Lt)	13.5±17.8	15.5±12.9		17.9±2.3	22.9±7.7		
	Anterior Tibialis (Rt)	36.0±55.9	36.1±31.3		25.8±5.9	33.6±5.8		
	Gastrocnemius (Lt)	48.1±47.8	49.5±49.2		55.8±50.5	61.1±51.4		
	Gastrocnemius (Rt)	45.6±43.0	40.3±28.4		21.7±7.9	22.3±9.5		
	Rectus Femoris (Lt)	10.5±13.6	13.5±11.7		47.1±9.1	46.9±16.0	*	*
	Rectus Femoris (Rt)	20.0±20.6	17.1±13.3		54.3±16.0	67.0±32.6		
	Biceps Femoris (Lt)	7.0±6.4	7.3±6.4		12.2±1.8	9.4±6.9		
	Biceps Femoris (Rt)	5.6±4.0	5.1±1.9		14.4±7.4	15.8±8.5		*
	Gluteus Medius (Lt)	6.5±6.6	8.2±5.6		18.9±2.3	19.5±2.1		
	Gluteus Medius (Rt)	8.9±12.1	8.6±10.0		16.6±7.4	17.4±6.2		
Right	Anterior Tibialis (Lt)	9.4±6.4	14.1±11.3		7.4±3.8	9.4±1.3		
	Anterior Tibialis (Rt)	13.1±6.6	20.1±15.8		6.5±2.5	11.4±7.2		
	Gastrocnemius (Lt)	25.5±17.3	25.9±14.4		49.5±63.9	38.8±44.3		
	Gastrocnemius (Rt)	19.3±14.5	21.1±16.0		13.4±7.3	12.1±4.6		
	Rectus Femoris (Lt)	8.4±6.7	10.4±6.6		22.3±20.9	21.4±18.1		
	Rectus Femoris (Rt)	9.4±7.5	11.3±8.0	*	19.5±11.8	19.4±11.7		
	Biceps Femoris (Lt)	5.2±6.6	4.9±5.5		12.3±2.5	9.4±6.7		
	Biceps Femoris (Rt)	3.8±3.1	4.0±2.2		11.8±6.7	13.7±8.3		
	Gluteus Medius (Lt)	12.1±10.5	14.0±10.9		16.9±4.7	23.5±8.2		
	Gluteus Medius (Rt)	7.8±10.8	10.1±13.2		15.1±5.1	20.2±8.3		
Left	Anterior Tibialis (Lt)	4.8±3.8	8.2±6.3		3.3±0.9	4.5±0.7		
	Anterior Tibialis (Rt)	11.1±7.8	19.8±20.8	*	9.2±3.6	12.9±5.4		
	Gastrocnemius (Lt)	12.4±7.1	17.0±10.2		33.4±45.9	28.4±27.3		
	Gastrocnemius (Rt)	27.2±11.0	32.3±12.7		12.7±4.0	15.8±7.1		
	Rectus Femoris (Lt)	5.6±3.3	10.1±5.6	*	22.0±18.7	20.4±16.6		
	Rectus Femoris (Rt)	7.7±6.0	10.5±9.0		23.5±17.0	20.4±12.3		
	Biceps Femoris (Lt)	5.6±5.4	4.8±4.2		8.2±5.0	7.5±5.3		
	Biceps Femoris (Rt)	4.3±3.1	4.2±3.6		13.2±8.8	14.5±9.7		
	Gluteus Medius (Lt)	7.7±6.7	8.8±9.4		19.1±5.1	21.5±3.0		
	Gluteus Medius (Rt)	8.6±9.6	12.0±17.4		19.3±9.3	21.9±11.5		

(*: p<0.05)

stimuli or between the young and elderly participants.

Muscle activity results are shown in Table 1. Muscle activity in the elderly participants did not differ in the presence and absence of vibrational stimuli. During anteroposterior translational perturbations, muscle activity of the rectus femoris was significantly larger in the elderly participants compared with the young participants. Muscle latency did not differ significantly in the presence and absence of vibrational stimuli or in the young and elderly participants.

Qualitative motion analysis revealed a tendency for an overall larger change in joint angles in the presence of vibrational stimuli following perturbations. In reaction to anteroposterior perturbations, the young participants changed their posture primarily with the ankles, while the elderly participants did so with the knees and hips. In reaction to mediolateral translational perturbations, the young participants bent the trunk, hips, and ankles at comparable angles, while the elderly participants tended to bend the trunk less than the hips and ankles.

IV. DISCUSSIONS

The plantar vibrational feedback provided to the young and elderly participants in our study in accordance with the load acting on the soles following translational perturbations in the anteroposterior direction was a factor behind the significantly shorter time to recovery of the mediolateral component of the COP. Providing plantar vibrational stimuli appears to effectively help people return their center of gravity to a stable position when it shifts during dynamic activities.

The effects of vibrating tactors placed against the soles of the feet on balance were previously studied. Simenov et al. evaluated the effects on balance of three randomly activating vibrating tactors placed against the plantar surface of the feet and found that randomly providing perceptible vibrational stimuli disrupted sensory information provided from the plantar surface of the feet, reducing postural stability[16]. In our study, plantar vibrating tactors were configured to activate in response to load shifts. Their vibrational stimuli informed the participants of load changes (i.e., shifts in the center of gravity) rather than disrupting the sensory information provided from the plantar surface of the feet. The participants were able to recognize postural shifts and control their posture accordingly based on these vibrational inputs. Similar findings were made in a previous study. Priplata et al. found that statically standing elderly individuals showed less postural sway when vibrational stimuli were provided to the soles of the feet. They state that supplementing age-related reduced plantar sensory ability in elderly people could improve balance [17].

In our study, plantar sensory feedback reduced center-of-gravity sway in the mediolateral direction following perturbations in the anteroposterior direction. In a previous study, Okubo et al. found that plantar sensory feedback changed center-of-gravity swaying in the mediolateral direction. Participants in their study, when standing still, exhibited less sway when given tactile and pressure information, and this information reduced sway more in the mediolateral direction than the anteroposterior direction [18]. The shortened recovery time in the mediolateral direction that our participants achieved agrees with the findings of Okubo et al., although their participants stood still while ours faced dynamic perturbations in postural control. Shortening the time to recover the center of gravity in the mediolateral direction during dynamic activities is an effective way to prevent falls. This is because the supportive base the foot forms during dynamic activities such as walking and running is narrower in the mediolateral direction than the anteroposterior direction. People experiencing a sudden mediolateral shift in the center of gravity keep from falling by quickly returning the COP to a stable position. Providing vibrational sensory feedback to the soles appears to be an effective approach to facilitate recovery.

COP maxima in all directions did not differ significantly according to whether or not the participants received vibrational stimuli. Stimuli, however, significantly reduced COP recovery times. This indicates that plantar sensory feedback does not reduce the maxima of center-of-gravity shifts but rather informs the participants of center-of-gravity shifts over time. In people experiencing recurring perturbations, the center of gravity moves less and less as they act to regain a stable posture. These smaller movements reduce the load acting on the plantar surfaces. Changes in the center of gravity therefore become harder to detect, which may explain why people take longer to return to a stable posture. Increasing the amount of information the plantar surface senses with vibrational stimuli allows people to detect even slight changes in the center of gravity. This appears to be why the participants were able to quickly return to a stable posture.

Our study showed that vibrational sensory feedback provided to the soles shortened COP recovery. This same feedback, however, did not have a marked effect on muscle activity or latency. We will continue our research by quantitatively analyzing changes over time in muscle activity and joint movement to determine how plantar sensory feedback affects people's strategies for controlling posture.

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