Plantar or Palmar Tactile Augmentation Improves Lateral Postural Balance With Significant Influence from Cognitive Load

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***Abstract*—Although it seems intuitive to address the issue of reduced plantar cutaneous feedback by augmenting it, many approaches have adopted compensatory sensory cues, such as tactile input from another part of the body, for multiple reasons including easiness and accessibility. The efficacy of the compensatory approaches might be limited due to the cognitive involvement to interpret such compensatory sensory cues. The objective of this study is to test the hypothesis that the plantar cutaneous augmentation is more effective than providing compensatory sensory cues on improving postural regulation, when plantar cutaneous feedback is reduced. In our experiments, six healthy human subjects were asked to maintain their balance on a lateral balance board for as long as possible, until the balance board contacted the ground, for 240 trials with five interventions. During these experiments, subjects were instructed to close their eyes to increase dependency on plantar cutaneous feedback for balancing. Foam pad was also added on the board to emulate the condition of reduced plantar cutaneous feedback. The effects of tactile augmentation from the foot sole or the palm on standing balance were tested by applying transcutaneous electrical stimulation on calcaneal or ulnar nerve during the balance board tests, with and without a cognitively-challenging counting task. Experimental results indicate that the plantar cutaneous augmentation was effective on improving balance only with cognitive load, while the palmar cutaneous augmentation was effective only without cognitive load. This result suggests that the location of sensory augmentation should be carefully determined according to the attentional demands.**

***Index Terms*—Sensory augmentation, transcutaneous electrical nerve stimulation, cognitive load, peripheral neuropathy, postural regulation, lateral balance.**

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I. Introduction

In THE US alone, falls result in more than 2.8 million injuries treated in emergency departments annually, including over 800,000 hospitalizations and more than 27,000 deaths [1]. Many of these falls are caused by balance deficit, which is the diminished ability to self-regulated balance. Aside from falls, balance deficit may also result in asymmetric loading of intact musculoskeletal structures during walking and may be followed by undesirable compensation by the body to maintain balance and stability, which often leads to secondary complications, such as osteoarthritis and lower back pain. Furthermore, balance deficit can signal the beginning of a decline in function and independence because it can limit the amount of exercise an individual is able to partake in, which cascades into further health issues. One disorder that leads to a balance deficit is peripheral neuropathy (PN), which is a condition in which periphery sensorimotor neurons are damaged or diseased such that their ability to transmit signals to and from the brain is limited. PN can be caused by a number of issues, such as aging, diabetes, chemotherapy, hereditary disorders, inflammatory infections, autoimmune diseases, protein abnormalities, exposure to toxic chemicals, poor nutrition, kidney failure, chronic alcoholism, and certain medications – especially those used to treat cancer and HIV/AIDS [2]. PN can result in seriously diminished sensory feedback on the plantar surface of the foot, and this sensory loss can induce detrimental changes in postural balance regulation, even in simple routine tasks, such as walking or standing, which can lead to dangerous falls [3]–[5]. Thus, decreased plantar cutaneous feedback due to PN is a serious issue that needs to be addressed to ensure the safety and quality of life for those who are affected by it.

In addressing the balance deficit caused by decreased plantar cutaneous feedback, several compensatory approaches have been introduced. These compensatory approaches provide indirect sensory cues instead of directly addressing the sensory deficit at the plantar surface. These indirect sensory cues can be visual, vestibular, or proprioceptive feedback, which are known to contribute to balance, or a haptic feedback applied to another part of the body [3], [6]. For example,

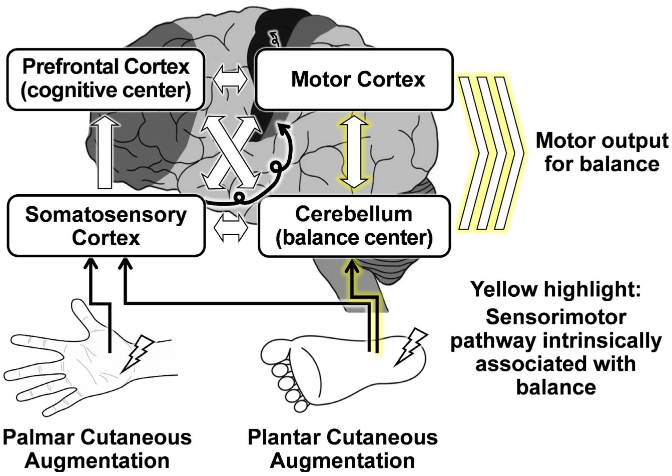

Fig. 1. Hypothetical diagram of the pathways for plantar and palmar cutaneous augmentations to change motor output for balance. Augmented plantar cutaneous feedback is mainly processed in the cerebellum as it is originally associated with balancing, while augmented palmar cutaneous feedback is mainly processed in the prefrontal cortex as a compensatory sensory cue, not originally associated with balancing. Due to this discrepancy, we expect that the plantar cutaneous augmentation is less dependent on cognitive load than the palmar cutaneous augmentation in postural regulation.

Sihvonen and colleagues demonstrated that balance training with a computerized force platform and a visual feedback screen could improve the balance of elderly women [7]. Visual feedback is generally accepted as a compensatory sensory modality for individuals who have a deficit in sensory feedback from the foot or vestibular system, with its effective and intuitive information delivery. Vibrotactile feedback, being applied to the sides of the trunk or shoulders to augment center-of-pressure (CoP) displacement, also showed its efficacy on reducing displacement of CoP during standing posture [8]. As a similar approach, vibrotactile feedback, being provided around the waist to augment CoP displacement, could reduce the anterior-posterior movement of trunk during quiet standing in individuals with vestibular deficits [9], [10]. The underlying principle of the compensatory approaches on improving poor balance is that compensatory feedback can be interpreted in the central nervous system in order to adjust and control motor output to improve balance [11], [12]. However, the efficacy of these compensatory approaches can be limited due to their reliance on an associated cognitive load, which may decrease consistency of motor output and increase response time and fatigue [13], [14]. This notion is depicted in Fig. 1. As seen in the figure, cognitive process can be heavily involved in the process of using compensatory sensory cues. In this regard, compensatory approaches may not be the ideal method of improving balance, especially when users are cognitively loaded.

The pathway for plantar cutaneous feedback can be more independent of the pre-frontal cortex than compensatory approaches, as plantar cutaneous feedback is originally involved in balancing operation. Augmenting plantar cutaneous feedback, as a direct approach to address the decreased plantar cutaneous feedback, would reduce the issue of the cognitive involvement that plagues compensatory approaches. Note that, plantar cutaneous feedback plays an important role in balance regulation, especially in a challenging condition. Human and animal experiments have shown that plantar cutaneous feedback becomes more critical in regulating balance with postural perturbations or during challenging locomotor behavior [5], [15]–[17]. Considering that postural regulation is a challenging task for individuals with reduced plantar cutaneous feedback, tactile augmentation on the foot sole has a great potential to improve balance for them.

A pair of related studies showed that electrical stimulation applied on the plantar area could improve the balance of people with diabetic neuropathy, potentially by increasing the sensitivity of plantar cutaneous receptors [18], [19]. In another study, vibrating insoles could enhance balance for elderly subjects and subjects with diabetic neuropathy, and the result was interpreted as white noise enhancing sensorimotor function by stochastic resonance [20], [21]. Although the plantar sensation was modulated, these prior studies did not augment plantar cutaneous feedback, because the stimulation or vibration was not timed with the original plantar sensation. To augment plantar cutaneous feedback and directly compensate for the decreased sensation, closed-loop operation is necessary. In other words, the plantar cutaneous augmentation should be applied based on the lateral sway of the body or the pressure on the foot, to be timed with the original plantar sensation.

Another aspect to consider is that direct intervention onto the foot sole would not be effective for elderly people or diabetic neuropathy patients because they have often lost sensitivity of the plantar nerves by several pathophysiological problems. Furthermore, direct intervention onto the foot sole can provide discomfort to the user because actuators or electrodes need to be placed onto the foot sole. Instead, we can augment plantar cutaneous feedback by stimulating the distal-tibial nerve and its branches, which can be accessed at the caudal aspect of the medial malleolus and are located close to the skin [22], [23]. The distal-tibial nerve is innervated onto the foot sole and is mainly composed of cutaneous axons [24], [22]. It is highly likely that the transcutaneous electrical stimulation, applied onto the skin along the path of the distal-tibial nerve, can selectively elicit plantar cutaneous feedback [25]–[29]. Therefore, transcutaneous distal-tibial nerve stimulation is a promising approach for tactile augmentation from the foot sole and could allow for improvement in postural regulation for individuals with reduced plantar sensation.

In this paper, we present a novel closed-loop transcutaneous distal-tibial nerve stimulation methodology as an approach to direct plantar cutaneous augmentation. The overall research goal of this study is to determine the efficacy of closed-loop transcutaneous distal-tibial nerve stimulation on improving postural regulation in conditions of compromised plantar cutaneous feedback [28], [29]. We have two hypotheses regarding the effect of the plantar cutaneous augmentation on the balance. First, we *hypothesize* that the closed-loop plantar cutaneous augmentation, on the swayed side of the body, will improve lateral balance for people standing in a challenging condition for balance. The rationale of this hypothesis is that, the plantar pressure would naturally change in the opposite direction to the sway, as the plantar pressure on the swayed side would be reduced by the subject swaying to the other side, especially in a challenging ground condition like the balance board. Therefore, if plantar cutaneous feedback on the swayed side is augmented, the balancing system would be alarmed as the system is not functioning well and the corrective behavior would be triggered. Second, we *hypothesize* that cognitively-challenging task will not affect the efficacy of the plantar augmentation on the balance. We believe that a cognitively-challenging task will not diminish the ability of the balance center (*e.g.,* cerebellum) to process intrinsic balance-related sensory feedback such as the plantar cutaneous augmentation.

In this study, we also investigated the effect of the palmar cutaneous augmentation on balance, as a representative example of using a compensatory sensory cue. In this regard, we have the third *hypothesis* that closed-loop plantar cutaneous augmentation will be more effective at improving lateral balance than providing the palmar cutaneous augmentation. Note that, plantar cutaneous feedback is intrinsically associated with sway and postural balance, while palmar cutaneous feedback provides only an auxiliary sensory cue in regards to balance [30]. Additionally, we have our fourth *hypothesis* that a cognitively-challenging task will be detrimental to the efficacy of palmar augmentation. This is because compensatory cues, such as palmar augmentation, heavily involves cognitive process in its interpretation.

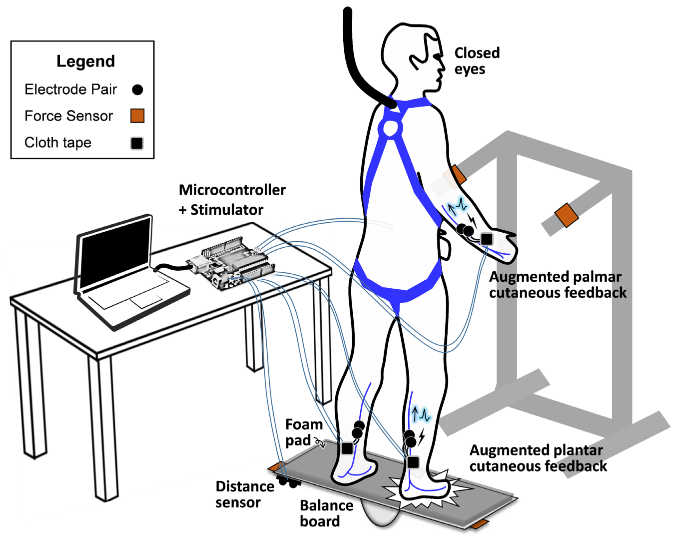

Fig. 2. Diagram of the lateral balance board with closed-loop transcutaneous electrical stimulation system. Each subject initially obtained a balanced position with the help of the handrail. Once balance was achieved, the subject closed his or her eyes and released the handrail. In the experiment, the subject received plantar or palmar cutaneous augmentation of the side they were leaning towards. A distance sensor relays the balance board's distance from the ground to an Arduino Nano microcontroller. The microcontroller then activates a stimulator to apply electrical stimulus to subjects via gel electrodes. The stimulator consists of an H-bridge that converts DC supply voltage to biphasic stimulus with control signals from the microcontroller.

II. Methods

A. Human Subject Recruitment

The experiments in this study were performed in accordance with relevant guidelines and regulations, according to the procedure described in the protocol approved by the Institutional Review Board of Texas A&M University in 2018 (IRB2018-1511F). Informed consent was collected from all subjects. Six healthy human subjects with no history of neurological disorders participated in the experiments in this study. The subject group consisted of one female and five males. All subjects were over the age of 18, and the mean age of subjects was 25.

B. Lateral Balance Board, Handrail, and Force Sensors

To measure the lateral balance in a challenging environment, the lateral balance board (3B Scientific W15075 Eucalyptus Wood Lateral Balance Rocker Board) was located on the ground with a stationary handrail affixed to the ground in front of the balance board (see Fig. 2). During the experiments, data was collected to measure the time duration that subjects could stay balanced on the balance board. This duration was defined as the time between the subject releasing the handrail and the moment that either side of the balance board contacted the ground (*i.e.,* balance time). In order to record this time duration, custom-made force sensors were placed on the handles of the handrail and on the bottom edges of the balance board to detect both the release of a subject's hand from the handrail and the contact between the balance board and the ground.

C. Closed-Loop Plantar/Palmar Cutaneous Augmentation System

To augment the tactile feedback from the foot sole or the palm, we designed a system that operates as a real-time closed-loop monitoring and stimulation system. First, we measured the distance between each side of the balance board and the ground using an ultrasonic distance sensor (HC-SR04), which provides high-accuracy distance output from 2 to 25 cm. The distance sensor was placed on the left end of the lateral balance board (from the subject's perspective) facing downwards towards the ground. The sensor was installed to measure 3 cm when the board was touching the ground on the left side (where the sensor is located), and 17 cm when the board was touching the ground on the right side. The board was evenly balanced when the sensor measured 10 cm.

The distance data from the sensor was delivered to an Arduino Nano microcontroller, which then sent a signal to a stimulator to provide electrical stimulus to subjects. The stimulus were provided only after a subject was deemed off balance by the system. This occurred when the balance board is deviated more than 1.5 cm vertically from the perfectly balanced position. The electrical stimulus was applied to either calcaneal nerve (branch of distal-tibial nerve) or ulnar nerve to augment the plantar or palmar cutaneous feedback, respectively [28]. Stimulation was provided to the foot sole or the palm on the leaned side of the subject. As a result, a larger tactile sensation was evoked on the side that is closer to the ground (*i.e.,* the side that the subject is leaning towards). Although the balance board is not a familiar environment for subjects, we expect that the stronger tactile feedback on the foot sole of the leaned side would be intuitively used by subjects' balancing system as a cue to sway to the other side. Note that the plantar pressure on the swayed side should be reduced by the subject swaying to the other side. Stimulation was turned off when the board was balanced, with a hysteresis of ±1.5 cm (when the sensor output was between 8.5 and 11.5 cm).

The stimulator circuit consisted of an H-bridge to produce biphasic stimulus from the control signal given by the micro-controller, which is level shifted to the desired stimulation voltage before reaching the H-bridge. Each H-bridge in the stimulator circuit consists of a CD4007 CMOS transistors (Texas Instruments, TX, USA), and each level shifter consists of two 2N3904 transistors. The biphasic voltage stimulus was provided at 100 Hz with 1-ms pulse width (*i.e.,* 20% duty factor), and the stimulation voltage amplitude was adjusted for each subject to attain appropriate sensation on the desired area of the body. The maximum stimulation current was limited to 20 mA. The output of the stimulator was transmitted to gel electrode pairs (Patients Choice®Silver 0.8" Round Tan Tricot Electrode), which were placed on the subjects' skin along calcaneal or ulnar nerve that innervates onto the foot sole or the palm, respectively. The stimulation was applied while the subjects remained outside of the balanced region, and the stimulation ended once the subjects either returned to the balanced region or the balance board touched the ground. A diagram of the entire experimental system is shown in Fig. 2.

D. Selection of Locations and Parameters for Transcutaneous Electrical Stimulation to Augment Plantar or Palmar Cutaneous Feedback

We established the location of electrodes and the stimulation voltage for both the plantar and palmar cutaneous augmentation via transcutaneous electrical stimulation, for each subject. First, the subject's skin was cleaned around the targeted electrode location with sterile alcohol prep pads to reduce the skin impedance. Then, the bipolar gel electrodes were placed along the expected pathways of target nerves on either the plantar or palmar surface (i.e., calcaneal nerve for plantar surface and ulnar nerve for palmar surface). Once the electrodes were in place, the voltage across the electrodes was raised from 0 V incrementally by 0.1 V until the subject reported that the stimulation evoked electrotactile feedback on the plantar or palmar surface. When the electrodes were not placed along the correct nerve, subjects reported electrotactile sensation around the electrodes instead of the plantar/palmar areas. We accordingly adjusted the location of electrodes until subjects reported plantar/palmar tactile feedback. Subjects reported the level of sensation on a scale of 1 to 5, with 1 being minimal sensation and 5 being strong sensation that causes discomfort. We established the stimulation voltage to be utilized in experiments when subjects reported 3 on the scale of 1 to 5. This process was completed for both feet and both hands for each subject because the location and threshold of stimulation can vary between two sides of the body.

E. Sensory Deficit During the Balance Board Test

During the whole experiment, we introduced two kinds of sensory deficit. First, a piece of 10 cm-thick medium-density foam was placed between each subject's feet and the balance board to attenuate the plantar cutaneous feedback. This was done to emulate the condition of reduced plantar cutaneous feedback that is experienced by individuals with PN and elderly people. Second, subjects were asked to close their eyes to remove visual feedback, which adds a further challenge for subjects to balance on the balance board and increases the subjects' dependency on tactile information during the experiments. With the attenuated plantar cutaneous feedback and the lack of visual feedback, we expected that the balance board would be a challenging environment, although subjects were healthy and young.

F. Cognitive Dual-Task Interference on the Balance Board Test

To determine the effect of cognitive distraction on the efficacy of sensory augmentation, we employed cognitive dual-task interference in the experiment. As a cognitive dual-task interference, subjects were asked to continuously count backwards by 7 from a random two-digit number that was given by the operator at the beginning of each balance board trial (right before subjects released their hands from the handrail). Subjects were asked to perform the subtraction as accurately and as quickly as possible. Subjects didn't have any practice trial regarding the counting task, to maximize the effect of cognitive dual-task interference.

G. Balance Test on the Balance Board With Closed-Loop Tactile Augmentation on Either the Foot Sole or the Palm

With all preparations of balance board, handrail, closed-loop tactile augmentation system, sensory interventions, and cognitive dual-task interference, subjects participated in the balance board experiment. During the participation in the experiment, subjects didn't have any practice trial regarding the balance board task. Each subject was instructed to stand on the lateral balance board barefoot with both feet equidistant from the center of the board and at shoulder width apart (see Fig. 2). Once correctly positioned on the board, subjects then gained their balance with the help of a stationary handrail affixed to the ground in front of the balance board. Subjects were then asked to close their eyes and release the handrail, move their hands to the sides of their body, and remain balanced on the board for as long as possible. The duration of time that a subject was able to maintain balance on the board without the board touching the ground was termed the balance time for this study.

Subjects participated in the balance board test through two separate visits on two different days. During the first visit, half of the subjects were given the following three different conditions: 1) no stimulation (control), 2) stimulation onto the medial calcaneal nerve (tactile augmentation from the foot sole), and 3) stimulation onto the medial calcaneal nerve plus a cognitive task (counting backward). At the second

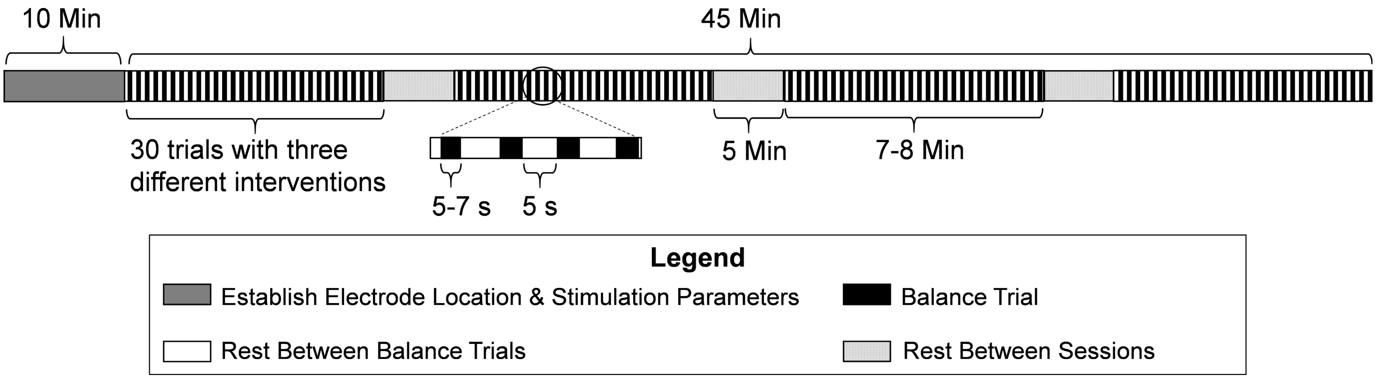

Fig. 3. Timeline of the palmar and plantar sensory augmentation experiments. The first 10 minutes of either experiment is used to establish the location of the electrodes and the thresholds of stimulation for the subject, for tactile feedback to be augmented via transcutaneous electrical stimulation on either the palmar or plantar surface. The experiments are broken up into 4 sessions that each contain 30 balance trials (10 trial with each of three conditions of intervention, in a random order). After each trial, the subject rests for 5 seconds to avoid fatigue. The subject also rests by sitting down for 5 minutes between each session. Each trial can last approximately 5 to 7 seconds, which incorporates time for the subject to gain his or her balance with the use of the handrail, receive a verbal cue to release the rail and begin the trial, and the time they are able to keep their balance.

visit, they were given the following three different conditions: 1) no stimulation (control), 2) stimulation onto the ulnar nerve (tactile augmentation from the palm), and 3) stimulation onto the ulnar nerve plus a cognitive task (counting backward). The other half of the subjects were given the augmentation in a reverse order (palmar augmentation during the first visit and plantar augmentation during the second visit).

During each visit, subjects participated in four sessions, each composed of 30 trials. Subjects were instructed to rest for five seconds between trials in order to minimize the effect of fatigue on the test results. Between each session of the experiment, subjects were also given five minutes to sit and rest. In each trial, each of the three conditions were given in a random order (10 trials for each condition) to eliminate any learning effect. The timeline for the experimental design of each visit is summarized in Fig. 3.

H. Balance Analysis Using the Balance Board Movement

Balance was evaluated by three output parameters of the balance board, including the balance time: 1) *Balance time* is the basic parameter showing how long subjects could maintain balance; 2) We also calculated the *deviation magnitude*, as the average distance outside the balanced region, while the distance exceeded the threshold (*i.e.,* >1.5cm deviation), per each trial. It was calculated by dividing the deviation area by the deviation time, with all deviations in each trial, as detailed in Eq. 1. A smaller deviation magnitude indicates the better resilience, as it means that subjects deviated less before they regained their balance; 3) Third, we calculated the *deviation time*, as how long it takes for subjects to recover balance (*i.e.,* return to the predefined balanced region), per each deviation during each trial. If there were multiple deviations in each trial, we averaged the deviation time within each trial. The smaller deviation time indicates the quicker subjects could return to a balanced position (*i.e.,* distance within the balanced region). Note that deviation time is minimally affected by system delay, which is composed of <0.2-ms triggering delay, 0.5-ms echo delay (for sound travel), and 16-ms processing delay at the Arduino (by the execution of command lines).

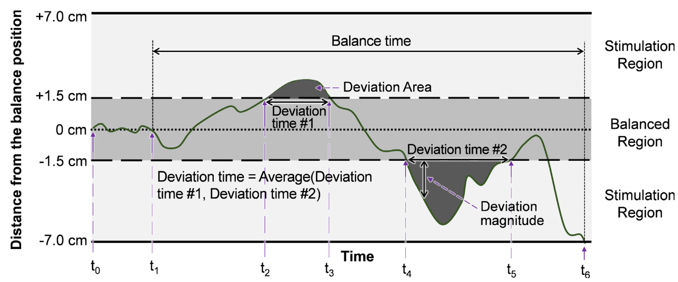

Fig. 4. Exemplary distance change curve during the balance board experiments. The graph shows an exemplary output of the distance sensor on the balance board in the vertical direction. We utilized this data to evaluate how well each subject was able to regulate their balance during each trial throughout the experiments. The five points in time axis were defined as follows: t_0 occurs when the subject gains their balance with the help of the handrail, t_1 occurs when the subject releases the handrail to begin the trial, t_2 and t_4 occurs when the deviation exceeds the balanced region (one side of board high and the other side low) and stimulation is turned on (except during control trials), t_3 and t_5 occurs when the subject returns to the balanced region and stimulation is turned off, t_6 occurs when the balance board touches the ground to conclude the trial, t_6 - t_1 is the balance time, and $\{(t_3 - t_2) + (t_5 - t_4)\}/2$ is the deviation time.

Stimulator delay was negligible as the sum of the rising time of the transistors was <0.01ms. The total system delay of $\sim$16.7 ms was less than 3% of the whole deviation time, which was $\sim$700 ms for all cases.

$$Deviation\ magnitude = \frac{\sum_1^n \int_{t,crossing}^{t,return} (deviation\ over\ threshold)dt}{\sum_1^n (t.return - t.crossing)} \quad (1)$$

The balance metrics, selected in this study to evaluate the balance on the balance board, are depicted in Fig. 4. In this figure, an example of the actual distance change curve that we recorded during the balance trial is shown, as well as indicators for key moments during the exemplary trial.

I. Statistical Test Used to Determine the Difference Between the Data

To determine the efficacy of the two independent factors (electrical stimulation and dual-task cognitive distraction) on

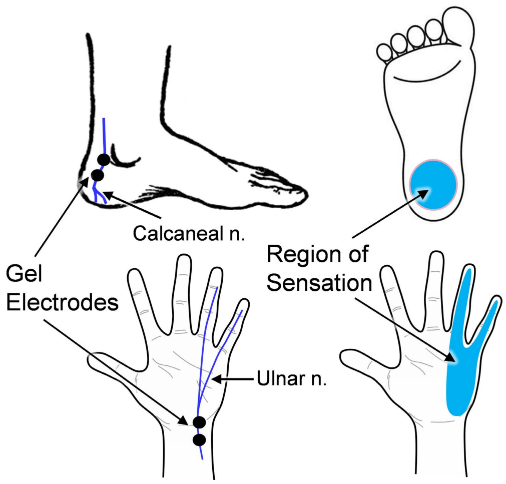

Fig. 5. Depiction of electrical stimulation through gel electrodes along the calcaneal and ulnar nerves: (a) location of gel electrodes and (b) area where the artificial sensory feedback was evoked.

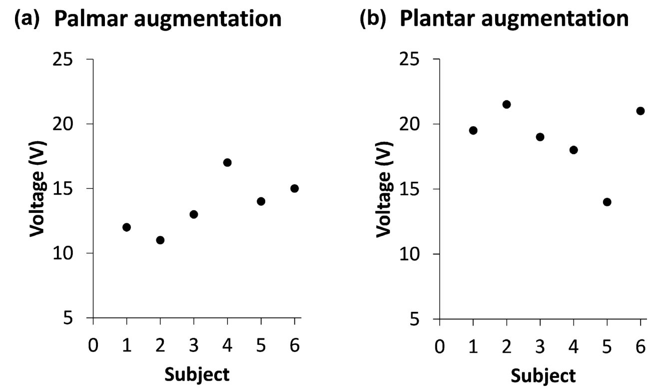

Fig. 6. Voltage levels required to produce electrotactile feedback a) on the palm of the hand and b) on the foot sole, according to the subjective sensation reported by each subject.

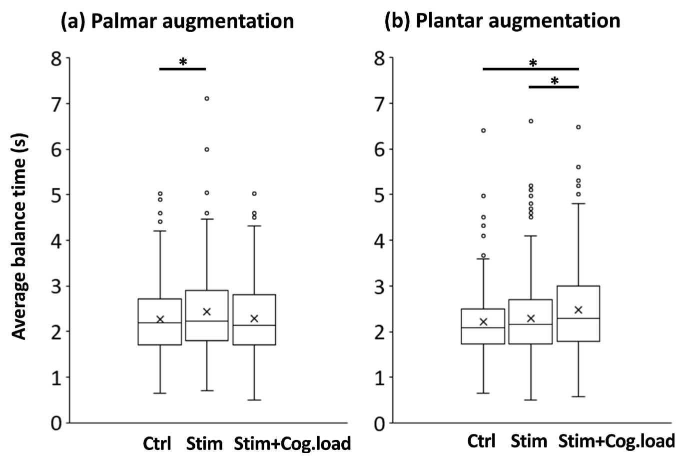

Fig. 7. Average balance time per trial, on the (a) palm and (b) foot sole, for three different interventions: control, stimulation, stimulation with cognitive load. Data points are shown by Box plot (x: mean), * <0.05.

dependent variables, and to account for both within-subject and across-subject variability, we performed a linear mixed model analysis (SPSS, IBM, Chicago, IL, USA). Both subjects and trials were set as random factors. The analysis was done with three dependent variables: average balance time, average deviation magnitude per trial, and average deviation time per trial. For the two independent factors (electrical stimulation and dual-task cognitive distraction), their effects on dependent variables were determined as both independently and in combination. The significance level was set at 0.05.

III. Experimental Results

A. Location and Amplitude of Transcutaneous Electrical Stimulation for Plantar or Palmar Cutaneous Augmentation

The locations of the gel electrodes used for tactile augmentation on the foot sole or the palm are depicted in Fig. 5a. Electrical stimulation applied onto the posterior and inferior side of the medial malleolus, where the medial calcaneal nerve is located, augmented tactile feedback from the heel of the foot sole. Electrical stimulation applied onto the lateral and anterior side of the wrist, where the ulnar nerve is located, augmented tactile feedback from the lateral side of the palm on the ring and pinky fingers (fourth and fifth fingers). The electrotactile feedback was evoked onto the areas depicted in Fig. 5b, for the foot sole and the palm, respectively. The stimulation voltages required to evoke electrotactile feedback, at a level of 3 out of 5 (as reported by each subject), are shown in Figs. 6a and 6b for hand and foot stimulation, respectively. No subject reported any feeling of discomfort by the stimulation at the selected voltage.

B. Balance Time

The average balance times per trial, for both plantar and palmar cutaneous augmentation experiments, are graphically represented in Figs. 7a and 7b. In Fig. 7a, the average balance times, for all subjects who participated in the hand stimulation experiment, are shown for each of the three intervention methods. The statistical test demonstrates that there is an increase in the average balance time when the subjects were given sensory augmentation on the palmar surface as a compensatory sensory cue, when compared to the control setting (*i.e.,* no stimulation) ($p = 0.025$). As a baseline (no intervention), the balance time was 2.27 s, which was increased to 2.44 s with electrotactile feedback on the palm. When dual-task cognitive distraction was given in conjunction with the palmar augmentation, the balance time was decreased to 2.28 s, which is nearly identical to the control setting. The effect of dual-task cognitive distraction was statistically significant ($p = 0.041$), which means that the balance time was decreased by the cognitive distraction. The balance time was not different between the cases of control setting and the combination of hand stimulation and cognitive distraction ($p = 0.834$), which means that the balance time was decreased back to the level at control setting by the cognitive distraction.

Fig. 7b depicts the balance time for the foot stimulation experiment. The baseline values of balance times, when no stimulation was given, was the lowest of the three cases at 2.20 s. When stimulation was applied to augment the plantar

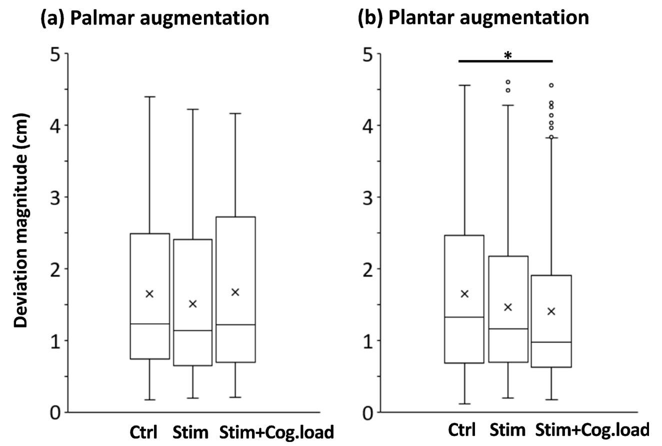

Fig. 8. Average deviation magnitude per trial, on the (a) palm and (b) foot sole, for three different interventions: control, stimulation, stimulation with cognitive load. Data points are shown by Box plot (x: mean), * <0.05.

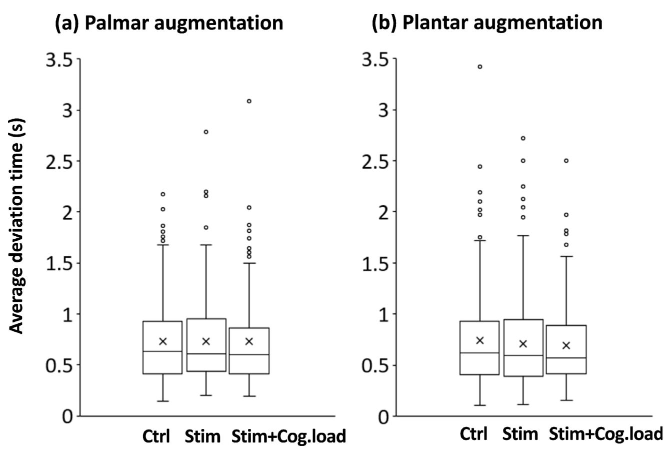

Fig. 9. Average deviation time per trial, on the (a) palm and (b) foot sole, for three different interventions: control, stimulation, stimulation with cognitive load. Data points are shown by Box plot (x: mean), * <0.05.

cutaneous feedback, the average balance time was slightly increased to 2.29 s but without statistical significance (p = 0.688). When dual-task cognitive distraction was given in conjunction with the plantar augmentation, the balance time was increased to 2.48 s with statistical significance (p = 0.002), which means that the balance time was increased by the cognitive distraction. The balance time with the combination of foot stimulation and cognitive distraction was also longer than the balance time at control setting (p = 0.007).

C. Deviation Magnitude

Fig. 8 describes the deviation magnitude for all three cases in the hand stimulation and the foot stimulation experiments. In the palmar augmentation experiment, the average deviation magnitude was 1.63 cm as a baseline, which did not change statistically with stimulation. The average deviation magnitude did not change either, with application of cognitive task. In the plantar augmentation experiment, the average deviation magnitude was 1.61 cm as a baseline, which did not change statistically with stimulation. When stimulation was applied along with cognitive task, the average deviation magnitude was decreased to 1.41 cm compared to the baseline value (p = 0.023).

D. Deviation Time

In Fig. 9a, the deviation time is plotted for all three cases in the hand stimulation experiment, and the corresponding data for the foot stimulation is plotted in Fig. 9b. In the hand and the foot experiments, the average deviation time was 0.73 s and 0.71 s as a baseline, respectively. For both palmar and plantar augmentation experiments, stimulation did not change the deviation time, with and without cognitive task.

IV. Discussion

A. For All Subjects, Transcutaneous Electrical Nerve Stimulation Could Successfully Evoke Electrotactile Feedback on the Palm or the Foot Sole

We confirmed that electrotactile feedback on the plantar and palmar surface could be evoked by stimulation along the calcaneal and ulnar nerve, respectively, in a safe, non-invasive, unobtrusive, and accurate manner. These results suggest that transcutaneous electrical nerve stimulation on the ankle and the wrist may work as an effective intervention for individuals with peripheral neuropathy to sense better on their feet and hands, respectively. As the ankle and wrist mostly are accessible as a bare skin and remain untouched, while feet and hands are mostly occupied and interacting with external objects, access through the ankle and wrist would be a practical approach. Also, wearable version of the stimulators can be worn on the ankle and wrist.

B. Lateral Balance Was Improved by the Plantar Cutaneous Augmentation, Only With Cognitive Task

The closed-loop plantar cutaneous augmentation itself did not increase the balance time. It also decreased neither the deviation magnitude nor the deviation time. Indeed, all three parameters we measured showed that lateral balance was not enhanced by the closed-loop plantar cutaneous augmentation, without cognitive dual-task interference. Therefore, this result *rejects our first hypothesis* that the closed-loop plantar cutaneous augmentation, based on the lateral sway of the body, will improve lateral balance for people standing in a challenging condition for balance. This result agrees with the reinvestment theory suggesting that the automated motor process can be degraded by conscious control [31]. On the other hand, when a cognitively-challenging task was given to the subjects along with the closed-loop plantar cutaneous augmentation (*i.e.,* cognitive dual-task interference), two of three parameters indicated the improvement of lateral balance: Balance time was increased and deviation magnitude was decreased. This result *supports our first hypothesis*, although conditionally with the presence of cognitively-challenging task. This result *rejects our second hypothesis* that cognitively-challenging task will not affect the efficacy of the plantar cutaneous augmentation.

C. Lateral Balance Was Improved by the Palmar Cutaneous Augmentation, but Not With Cognitive Task

An improvement in lateral balance on the balance board was achieved with the closed-loop palmar cutaneous augmentation itself, suggested by the increased balance time, while the closed-loop plantar cutaneous augmentation itself was not effective. This result *rejects our third hypothesis* that the plantar cutaneous augmentation will be more effective at improving lateral balance than the palmar cutaneous augmentation. Rather, this result suggests that the closed-loop palmar cutaneous augmentation can be more effective than the closed-loop plantar cutaneous augmentation. However, when cognitive counting task was given to the subjects along with the closed-loop palmar cutaneous augmentation, the improvement in balance was cancelled, suggested by the balance time. This result *supports our fourth hypothesis* that a cognitively-challenging task will be detrimental to the efficacy of palmar augmentation. It also agrees with prior reports that an overt sensory cue allows for individuals with limited postural feedback to cognitively interpret the cue and react appropriately to improve their balance [7]–[10].

D. Different Effects of Cognitive Task on Plantar and Palmar Cutaneous Augmentations Suggest That the Two Cutaneous Augmentations Have Different Mechanisms of Operation

Plantar cutaneous augmentation becomes effective on enhancing balance with a cognitive dual-task interference, while it was ineffective without a cognitive dual-task interference. This result implies that cognitive involvement may not be desirable in interpreting the plantar cutaneous augmentation for balance. This is perhaps because the plantar cutaneous augmentation is intrinsically involved in the sensorimotor loop operation for the balancing activity and conscious drive is in dissonance with the unconscious control, as suggested by the reinvestment theory [31]. Note that the notion of cognitive distraction as a means to enhancing the postural stability has been investigated before, but not with the plantar cutaneous augmentation [32]. Palmar cutaneous augmentation becomes ineffective on enhancing balance with a cognitive dual-task interference. This result implies that cognitive headroom is important for effectively using compensatory sensory cues for balancing. This is what we expected because cognitive effort is needed to interpret and use the compensatory sensory cues for balancing [7]–[10]. We speculate that subjects consciously manipulated their muscle activity on top of the subconscious balance control, to shift their weight to the other side of the board than the leaned side.

E. Plantar Cutaneous Augmentation, if Applied With Cognitive Task, Decreased Magnitude of Deviation, Which May Have Contributed to Longer Balance Time, But Caused no Change in Deviation Time

A reduction in the average magnitude of deviation is an indication that subjects remained closer to the balanced region before and after they counteracted to the sway of the ground. This result suggests that, subjects could react either more sensitively with less deviation or more softly with less reaction force, or the combination of the two. The reduction in deviation magnitude can partially explain the increase in balance time. However, deviation time was not changed by the plantar cutaneous augmentation with cognitive task, which suggests that reaction did not become faster by the augmentation. Overall, the plantar cutaneous augmentation, if applied with cognitive task, could enhance the resilience of the balance to lateral ground sway but not the reaction speed.

F. Palmar Cutaneous Augmentation Changed Neither Deviation Magnitude nor Deviation Time, Which Suggests Another Mechanism That Contributed Longer Balance Time

In case of the palmar cutaneous augmentation, without cognitive task, we could not find a clue of what increased the balance time. Even though there was the same trend of decreased deviation magnitude, as the case of the plantar cutaneous augmentation, the decrease was not statistically significant ($p = 0.112$). Deviation time did not change either. It is perhaps because subjects were asked to keep the board off the ground as long as possible, instead of keeping it level. We speculate that, considering the clear increase in balance time, the palmar cutaneous augmentation may change other important balance parameters that we could not observe by the balance board movement. In the following studies, we expect to find more details behind this balance time increase, by investigating the kinematic and kinetic variables of the subjects during the balance board trials.

G. Plantar and Palmar Cutaneous Augmentation May Need to Be Processed in Different Parts of the Brain

As discussed in Fig. 1, both plantar and palmar cutaneous augmentations can be processed by the pre-frontal cortex to influence motor output, because subjects could clearly perceive them. Considering that the plantar augmentation did not enhance balance without cognitive distraction, the plantar augmentation might not be processed effectively in the pre-frontal cortex as a sensory cue. On the other hand, as the plantar augmentation became effective with cognitive distraction, the plantar augmentation might be more effective on improving balance when it is handled subconsciously by the intrinsic sensorimotor pathway for balance through the balance regulation system (*e.g.,* cerebellum). As the palmar cutaneous augmentation had a positive effect on balance without cognitive distraction but the effect was cancelled with cognitive distraction, the palmar augmentation may be processed effectively at the pre-frontal cortex but not be effectively incorporated into the balance regulation system. This result also reinforces the idea of resource sharing between motor and cognitive functions, that is, the complex motor control necessitating cognitive involvement can be hindered when subjects focused on the cognitive task [33].

H. Plantar and Palmar Cutaneous Augmentation Need to Be Used in Different Circumstances of Improving Balance

Experimental result showing balance enhancement under the condition of cognitive dual-task interference suggests that subjects were able to subconsciously incorporate the plantar cutaneous augmentation to better control their balance. Therefore, the plantar cutaneous augmentation may be used in the controlled setting like a clinic, with a cognitively-challenging task such as the cognitive dual-task interference. On the other hand, the palmar cutaneous augmentation was effective on enhancing balance only without cognitive dual-task interference. The effect of compensatory sensory cues, like the palmar cutaneous augmentation, on balance has been suggested by multiple studies [7]–[10]. However, the effect of cognitive distraction has not been well investigated. The result of this study suggests that the palmar cutaneous augmentation may be used for balance improvement in cases when people are not cognitively loaded. Note that the effectiveness of plantar and palmar cutaneous augmentations would also depend on the individual balancing strategy. For example, palmar cutaneous augmentations would be more effective to people who heavily depend on external focus [34].

I. Subjects' Balance System Adapts to the New Ground Condition on the Balance Board, and Makes it Natural to Respond to the Board Sway Instead of the Body Sway

Another interesting fact that we found by the experimental results is that, the plantar cutaneous augmentation increased balance time with cognitive distraction, even though we did not augment the plantar cutaneous feedback based on the plantar pressure but based on the sway of the balance board. We initially designed the plantar cutaneous augmentation to respond to the board sway instead of plantar pressure, because the board sway indicates the sway of the CoP on the balance board as the body sway indicates the sway of the CoP on the ground. To stay longer on the balance board, the subject should sway in the opposite direction to the board sway. Based on the fact that the plantar cutaneous augmentation was effective with cognitive distraction, the plantar cutaneous augmentation seems more effective when used more subconsciously than consciously. Our interpretation on this observation is that subjects' balance system adapted to the new ground condition on the balance board, by responding to the board sway instead of the body sway.

J. The Results May Be Translated to the Balance Training of People With Peripheral Neuropathy

Even though all experiments have been done with healthy individuals, we expect that the results can be translated to the cases of peripheral neuropathy. Although experiments have been conducted with healthy individuals, the improvement in lateral balance was accomplished in a challenging internal and external conditions with no visual feedback, decreased plantar cutaneous feedback, and a challenging ground condition on a dynamically swaying balance board. Considering that even the normal ground condition can be challenging for people with peripheral neuropathy, the plantar and/or palmar cutaneous augmentation may enhance their balance. However, there is another possibility that the neural adaptation to the plantar and/or palmar cutaneous augmentation may oppose the balance improvement [35]. Also, note that, the balance was improved only with the cognitive dual-task interference, and therefore special setup is necessary to provide the similar effect.

K. Limitations of the Presented Study and Future Direction

This study has several limitations, which can be addressed by the follow-up studies. First, the number of subjects was limited to six, and therefore the experimental results have limited statistical power. In a follow-up study, we plan to recruit larger number of subjects to confirm the result. Second, the presented study did not observe the learning curve and aftereffect, as the interventions were applied in a randomized order. In a follow-up study, we will apply interventions consistently and observe a plateau in both learning curve and aftereffect. Third, changes in attention devoted to the cognitive task between tactile conditions were not quantified through cognitive task performance. Conclusions could be more strongly supported with the addition of these data in future studies.

V. Conclusion

In this paper, we tested the efficacy of the novel plantar cutaneous augmentation approach on balance enhancement, by a closed-loop transcutaneous calcaneal nerve stimulation. The plantar cutaneous augmentation could also enhance resilience of the body in response to the body sway and increase the balance time. The importance of the plantar cutaneous augmentation became noticeable only when subjects were given the cognitive dual-task interference. This new sensory augmentation approach via the transcutaneous calcaneal nerve stimulation will potentially address the lack of plantar cutaneous feedback for those with peripheral neuropathy, as a non-pharmacologic and non-invasive solution.

We also compared between plantar and palmar cutaneous augmentations regarding the efficacy on balance improvement. Both plantar and palmar cutaneous augmentation allowed subjects to maintain their balance on the balance board for a longer period of time, but with different conditions of cognitive involvement. The palmar tactile augmentation improved lateral postural balance but the effect was cancelled with cognitive distraction, suggesting that interpretation of compensatory sensory cue needs cognitive headroom. The plantar tactile augmentation improves lateral postural balance only with cognitive dual-task interference, suggesting that cognitive distraction enhances subconscious process for balancing. These results suggest that cognitive headroom and distraction need to be considered carefully when cutaneous augmentation is employed for balance enhancement. If the cutaneous feedback is originally involved in the process of balance control, like the plantar cutaneous feedback, cognitive involvement would be undesired, and vice versa.

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