STUDY OF THE EFFECT OF DISTANCE-BASED PLANTAR CUTANEOUS ELECTROTACTILE FEEDBACK ON LATERAL BALANCE

A Thesis

by

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ABSTRACT

Our sense of balance and body movement heavily rely upon sensory feedback from our lower limbs, as well as other sensory modalities including visual and vestibular feedback. If the sensory feedback from the lower limb is affected by problems such as diabetes or nerve impairments, it often results in falling and unnecessary cognitive engagement even during simple walking. To address this problem, various approaches of sensory augmentation have been investigated, using visual, auditory, tactile sensory pathway. However, the efficacy of these sensory augmentation approaches is still controversial. One of the important reasons is that these sensory augmentations are often applied to the area not directly associated with the target motor task, resulting in a detour of the sensory pathway via prefrontal cortex and requiring additional cognitive efforts to process the afferent signal.

To address the current limitations, we propose a novel method of evoking distance-based electrotactile feedback on the foot sole. The distance-based electrotactile feedback will inform the subjects via the intrinsic sensory pathway for balancing as a compensatory sensory feedback for proprioception. We hypothesize that the distance-based electrotactile feedback will improve the lateral balance at challenging ground condition. We also hypothesize that the distance-based electrotactile feedback will be more effective than the discrete electrotactile feedback in improving lateral balance. Three subjects have so far participated in this experiment. We first identified the most effective location to apply electrical stimulation (E-stim), then we identified the optimal amplitude and range of frequency required for the E-stim, and finally tested the balancing ability on the balance board with a challenging sensory condition. Our results from 10 subjects showed that the distance-based proportional E-stim significantly increased balancing time compared to that with the distance-based discrete E-stim or the control condition (no E-stim). This result suggests that the distance-based proportional E-stim can be an effective way of augmenting sensory feedback to enhance balance in challenging sensory condition and proves a vital concept for improving human-computer interaction.

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Contributors

This work was supervised by a thesis committee consisting of Dr. Yoonsuck Choe (committee chair) of the CSCE department, Dr. Hangue Park (Committee co-chair) of the ECEN department, Dr. Dylan Shell of the CSCE department, and Dr. Duncan Walker of the CSCE department.

All work conducted for the thesis was completed by the student independently.

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NOMENCLATURE

E-Stim	Electrical Stimulation
HCI	Human-Computer Interface
TENS	Transcutaneous Electrical Nerve Stimulation
FES	Functional Electrical Stimulation
CNS	Central Nervous System
BCI	Brain-Computer Interface

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1. INTRODUCTION

Peripheral neuropathy is one of the prevailing reasons of balance loss in the elderly people. About 8% of the elderly people, ~60% of the people with diabetes, and ~30% of the people who received chemotherapy are suffering from peripheral neuropathy and sensory loss at the foot[1]. The compromised sensory feedback from the foot degrades the ability to self-regulate balance which may cause falling and long-term hospitalizations. Balance rehabilitation is a very important issue for those people to sustain independent walking capability and their quality of life. Multiple sensorimotor augmentation approaches have been applied for balance rehabilitation, including visual augmentation, auditory augmentation, tactile augmentation using transcutaneous electrical nerve stimulation (TENS) or vibration, and motor augmentation like exoskeleton or functional electrical stimulation (FES)[2].

Sensory augmentation is a promising approach in human-computer interfaces for balance rehabilitation because providing motion-dependent sensory feedback is a key for motor rehabilitation[3,4]. Note that, motion-dependent sensory feedback is sufficient to engage the plasticity within the central nervous system (CNS)[5], with reactivating dormant interneurons[6]. Also, sensory augmentation engages the CNS actively in the loop, while the motor augmentation engages the CNS passively via the change in motor outcome. However, the potential of sensory augmentation on improving balance rehabilitation has been investigated very limitedly, while motor augmentation has been investigated extensively with exoskeleton and FES[7,8]. Sensory augmentation has been relatively well investigated in gait rehabilitation after spinal cord injury. For example, body weight supported treadmill training with robotic exoskeletons repetitively move paralyzed lower limbs according to a designated walking pattern, in turn generating motion-dependent sensory feedback[9,10]. Epidural stimulation applies electrical stimulation onto the dura mater and increases the excitability of interneurons to sensory feedback, as well as directly augmenting the sensory feedback[6,11]. Indeed, there is a strong need to investigate the potential of sensory augmentation in balance rehabilitation. We can guide balance rehabilitation towards the right direction by sensory augmentation[12, 13].

As balance is a result of the process of combined sensory feedback including visual, vestibular, and somatosensory feedback, multiple sensory modalities can be used for sensory augmentation to improve the balance. Visual and auditory feedback are common concurrent feedback mechanisms used in balance rehabilitation which enhance performance in the acquisition phase, but those gains are not retained after therapy ends[12,14]. But these methods neither provide nor help in augmenting the dynamic integration of the sensorimotor systems. The lack of the intrinsic sensory feedback for balance still increases dependency on assistive devices and causes asymmetric gaits[15]. Haptic sensory feedback, usually through wearable devices on the arm or the chest, showed promising results in improving balance[16,17]. However, they often have limitations in providing sensory feedback to the location not associated with the balancing motor task, resulting in limited efficacy in cognitively challenging situations[18].

Electrical stimulation (E-stim) has a great potential to augment sensory feedback, by exciting voltage-gated ion channels and generating action potential at sensory neurons.

E-stim can be also easily implemented as a small portable or even implantable device and used in daily lives as well as the clinic. Further, E-stim on the plantar cutaneous nerves can augment tactile feedback on the foot sole, which is intrinsically associated with the balancing function[19]. Especially, E-stim applied on the medial malleolus, augmenting plantar cutaneous feedback on the heel, was shown as effective in enhancing the lateral balance[20]. It is because improving plantar sensitivity improves posture control and reduces lateral perturbations in balance[21]. Since plantar cutaneous information regulates the movements for postural stability, augmenting these tactile cues would have therapeutic benefits in balance rehabilitation. Electrotactile feedback through the natural neuronal pathways can also help in improving proprioceptive feedback which is also a factor in retention of motor learning during rehabilitation therapy[22].

In our previous study, we found that E-stim on the medial malleolus was effective on improving lateral balance when it was applied according to the body sway and with a dual-task cognitive distraction[18]. However, we did not investigate the optimal way of applying the E-stim yet. In our previous study, plantar cutaneous augmentation was applied in a discrete fashion (*i.e.*, on/off) based on certain threshold, mainly for simplicity in the proof-of-concept study[18]. It is important to investigate which way of applying the E-stim would be optimal to improve the lateral balance. In this regard, we applied the E-stim in proportion to the distance, with a frequency modulation[23]. As subjects perceive a low-frequency E-stim as a pulsing sensation and differentiate the frequency difference[18,23], a frequency modulation can be used to deliver the analog information like the distance.

In this study, we have implemented a HCI system which provides distance-based electrotactile feedback through transcutaneous E-stim applied on the medial malleolus, specifically in the calcaneal branch of the tibial nerve. This distance-based electrotactile feedback was applied to one side of the foot according to the sway, which would replicate the proprioceptive feedback in the sense that it delivers the spatial information. In our setup, we reduced the cutaneous feedback on the subject's feet by locating foam between the subject's feet and the balance board, and blocked their vision, to make the challenging sensory condition for balance. We compared the effects of distance-based discrete stimulation, distance-based proportional stimulation, and control condition (*i.e.*, no stimulation) on subject's balancing capability.

2. METHODOLOGY

The following subsections describe in detail the experimental setup we developed which is used to perform the experiments and validate our hypotheses.

2.1. Hypothesis

In this study we investigate the best form of plantar cutaneous electrotactile feedback in enhancing lateral balance in challenging sensory condition. Our first hypothesis is that the combination of cognitive load and plantar cutaneous electrotactile feedback promotes lateral balance on challenging ground conditions since the target sensory feedback is intrinsically associated with the balance function. Our second hypothesis is that the distance-based proportional electrotactile feedback will be more effective in improving lateral balance than its discrete (on/off) counterpart.

2.2. Creating a closed-loop system

The body's balance system works through a constant process of position detection, feedback, and communication between the inner ears (vestibular system), eyes (visual cortex), muscles and joints (proprioception), and the brain (cognitive effort). Since our focus is on the proprioceptive system and our goal is to measure and test the brain's natural ability to work with electrotactile sensory augmentation, we created a closed loop system between the tactile sensations from the feet and the CNS's efforts on balance. We asked the subjects to wear a blindfold and perform a cognitive task (counting backwards) to exclude the visual feedback and minimize the engagement of the cognitive function in the balancing task. This concept is visually described in Figure 1.

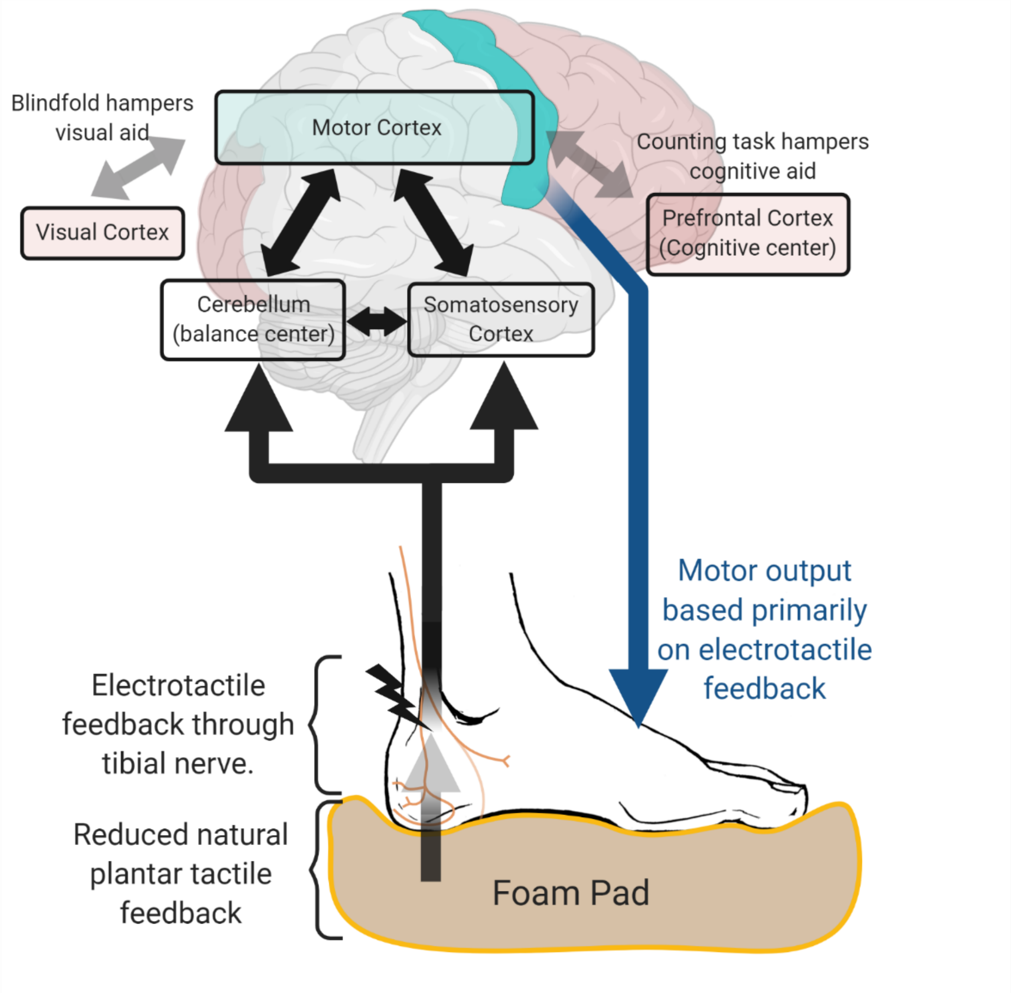


Figure 1: Hypothetical diagram to explain the effect of electrotactile feedback in augmenting proprioceptive feedback under challenging ground conditions without the explicit need of visual and cognitive aid.

2.3. Experimental Setup

2.3.1. The Human-Computer Interface

To measure the lateral balance under challenging ground condition, we used a lateral balance board (3B Scientific W15075 Eucalyptus Wood Lateral Balance Rocker Board) fitted with 4-inch foam padding to reduce the plantar cutaneous feedback the subjects have on their bare foot. The board was also fitted with two custom-made force sensors on either side of the board which is used to detect when the board touches the floor. The distance sensor fitted on the left edge of the balance board recorded the board-to-floor distance information. We also installed a safety handrail in front of the balance board and installed the custom-made force sensors onto the handrail to detect the timing when the subject's hand left the handrails. A computer and 2 Arduino Nano microcontrollers performed all the necessary computations for data collection and stimulation. The experimental setup is described in Figure 2. The computer system will interact with subject through the sensors and implement the closed loop system of obtaining information from the subject (through sensors) and providing E-stim feedback (through electrodes).

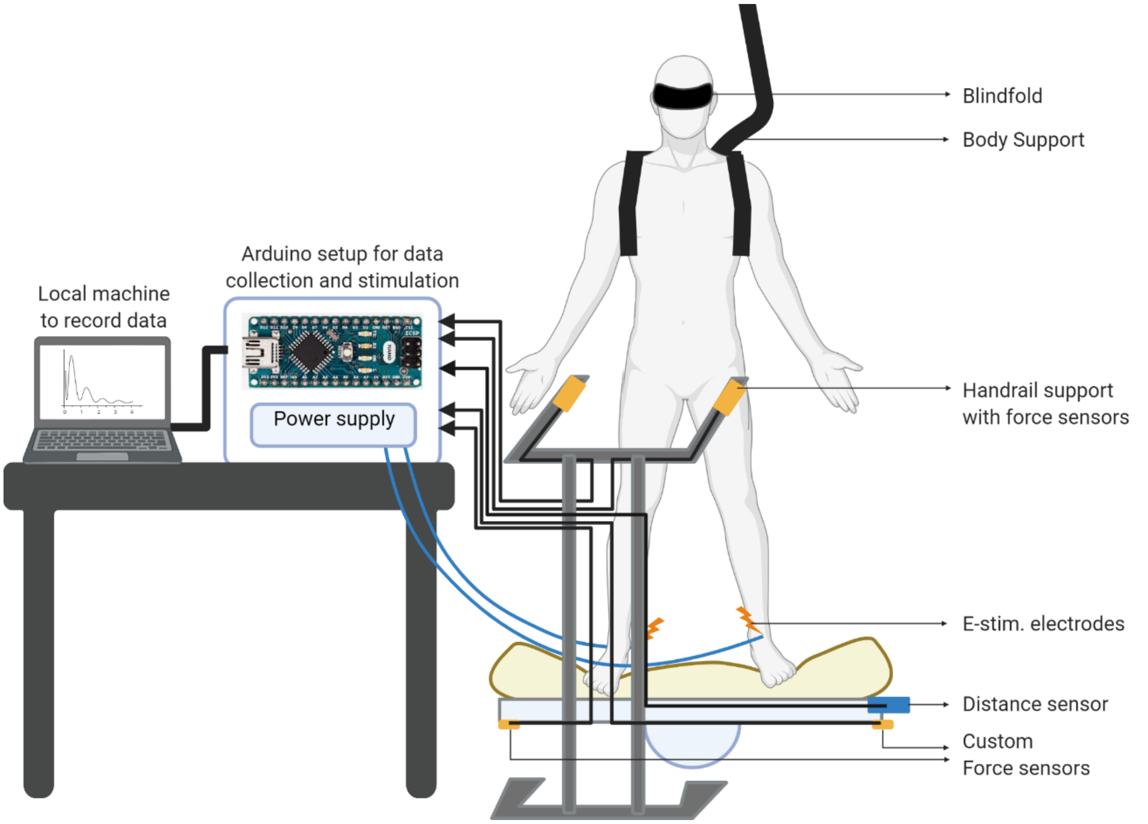


Figure 2: Experimental Setup

2.3.2. Software Setup

The software for this human-computer system was split into 2 components. The Arduino component which handles the closed-loop system and the Python (local machine) component which oversaw the experiment, recorded data, and analyzed it.

The Arduino Component: The 2 microcontrollers had dedicated processes to handle. *The first micro-controller* was set to handle only the stimulation frequency sent through the electrodes. This allowed us to have much more control over the stimulation since real human subjects are involved. *The second micro-controller* was implemented as a state machine dedicated to collecting the sensor data and determining the stimulation frequency based on the trial and sensor data. The process flow diagram of the second microcontroller is given in Figure 3.

The Python Component: There were 2 python scripts written to automate the entire experimental process. *The first script* was dedicated to overseeing the entire experimental process. This includes collecting data, organizing data, and verifying that the correct stimulation mode was being implemented at every trial. At the end of the experiment (150 trials), this script calls upon the second script. *The second script* is dedicated to graphing the data collected and compiling the data into a spreadsheet which graphs the overall results and statistical averages.

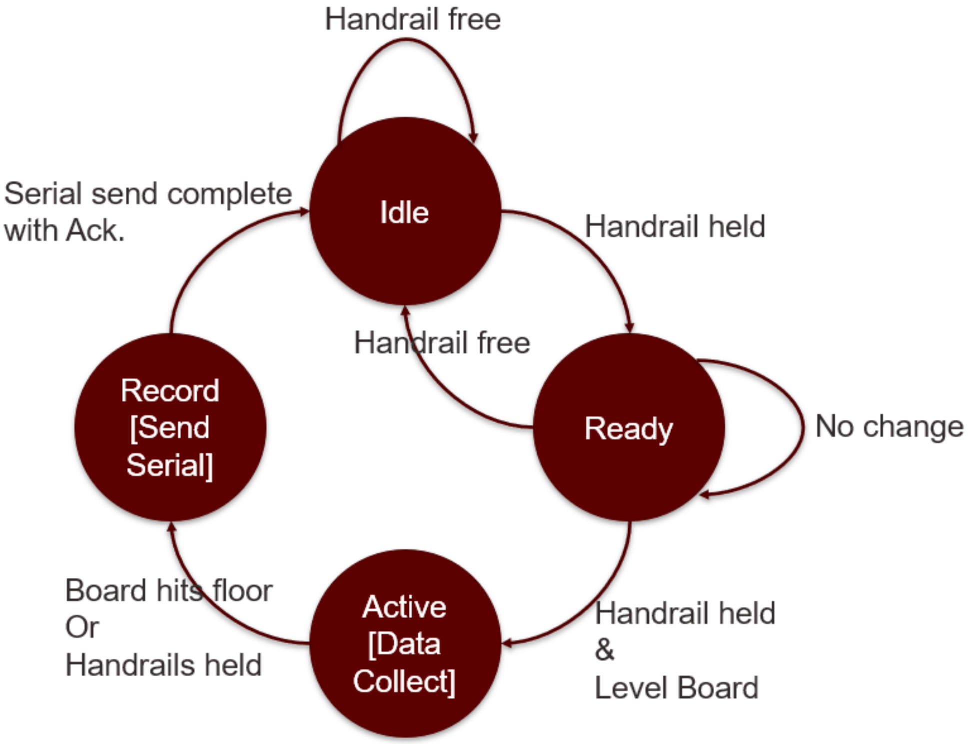


Figure 3: The second microcontroller's state machine diagram

2.3.3. Identifying the site of stimulation.

The first task that needs to be done was determining the proper site of stimulation on the subject’s feet. We picked the medial malleolus region where the posterior tibial nerve branches into calcaneal nerves and plantar nerves. This gives us the ability to stimulate a specific region of the foot. The stimulation used for identifying the site of stimulation was a bi-phasic voltage stimulus with a 1 millisecond pulse-width at 100Hz frequency (i.e., 20% duty cycle) passing through a pair of electrodes. One of the electrodes was placed over the branching point of the medial calcaneal nerve from the inferior tibial nerve while the other electrode was placed near the end of the medial calcaneal nerve. These electrode positions are shown in Figure 4.

2.3.4. Identifying the parameters of stimulation – Amplitude and Frequency

Once the site of stimulation and location of electrodes have been fixed, the parameters for the E-stim were decided. The amplitude of E-stim was decided using the voltage level. The frequency was set as 100Hz based on prior success[18,20]. The voltage level was slowly increased from zero while the subject was asked to provide verbal confirmation when they first feel the sensation (V_{min}) as well as when the E-stim becomes uncomfortable (V_{max}). The two-thirds point of this range is set as the voltage for the experiment. i.e.

$$\mathrm{V}_{\mathrm{experiment}} = V_{min} + \frac{2}{3} * (V_{max} - V_{min})$$

We also decided the frequency range which can be used for the proportional E-stim part of the experiment. For this, we measured a range of frequency which the subject can differentiate easily. First, we set the minimum frequency as 10Hz (F_{min}) because frequency lower than 10 Hz can be hardly used for the sub-second-level decision in balancing task. We then slowly increased the frequency by 10Hz steps, until the subject was unable to differentiate between two steps in the frequency range. We set this maximal differentiable frequency (with 10-Hz step) as the maximum frequency (F_{max}). This range of frequency from F_{min} to F_{max} was mapped to the balance board in such a way that the frequency of stimulation for each foot increases as each side of the board approaches to the ground. In the case of discrete stimulation, the frequency was set to fixed 100Hz when the board was not level and no E-stim was applied when the board was level (*i.e.,* below threshold).

2.3.5. Discrete Stimulation vs Distance-based stimulation

While the experiment was in progress, subjects were given one of the 3 different types of stimulation. The first type was the control where no stimulation was given. The second type was the discrete stimulation where the subject was given a constant 100Hz E-stim on the side of foot leaning towards the ground (left foot if the board is leaning left, right foot if leaning right, and no E-stim when the board sway is below threshold). The third type was distance-based stimulation where the frequency of stimulation varies proportional to the distance of the side of the balance board from the floor. The frequency of E-stim increased when the side of the board approaches to the floor, decreased when the board is closer to being level, and E-stim was stopped when the board leans to the other side. This method mimics the natural sensation of foot pressure when we sway from one side to the other.

2.3.6. The balancing task

Once the site of stimulation and parameters were set, subjects were then blindfolded and asked to stand on the foam-clad balance board. They had to hold onto the hand rail in front of them and make sure the board was level. At this point they let go of the hand rails and tried to balance for as long as possible while focusing on the backwards counting task. Each attempt at balancing was considered a trial. There was a total of 150 trials with a 5-second break between each trial and a 3-minute break between every 50 trials, to counteract fatigue. The stimulation type for each trial was selected at random order but the 3 types of stimulation were distributed evenly and equally over the 150 trials.

3. EXPERIMENTAL RESULTS

3.1. Region of stimulation and natural differences in the nerve pattern

Our goal was to have the same region and strength of E-stim in both feet of a subject. We also required the region to be as close to the heel as possible. The experiment was conducted among 10 test subjects and they reported 2 different regions of stimulations (dubbed A and B) as shown in Figure 4.

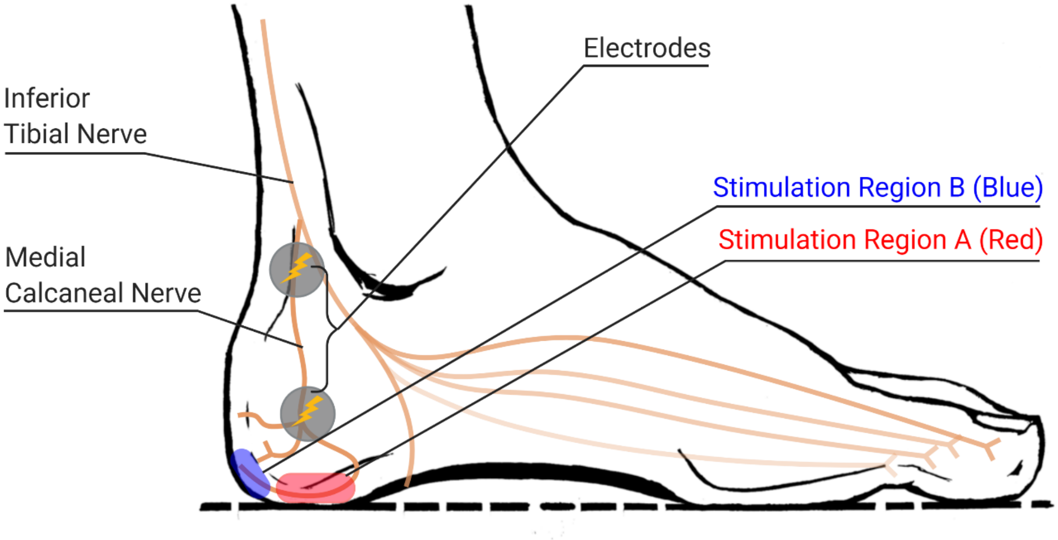


Figure 4: Regions A and B used for stimulations with electrode sites.

It is interesting to note here that only one subject (Subject 3) had sensation in region B (blue) whereas the other 9 subjects reported sensation in region A (red). From Figure 4, we can see that both regions are part of the same nerve, but at different positions. The tibial nerve and the medial calcaneal nerve, which is used for stimulation here, have been reported to have variations in branch positions, number of terminals, and nerve lengths[24,25]. Given this common anatomical variation, both regions of stimulations were accepted for this experiment.

3.2. Parameters of E-stim

The voltage levels of E-stim for the 10 subjects were in the range of 11.7V and 23.5V with an average of 18.5V, median of 18V, and standard deviation of 3.24V. The voltage value used is the two-thirds level between the voltage at which they started noticing the E-stim (i.e., perception threshold) and the voltage at which the E-stim became very uncomfortable (i.e., discomfort threshold). The frequency of E-stim was identified by asking the subjects if they notice a difference in change at every 10Hz frequency step from 10Hz to 100Hz. All 10 subjects reported that they were not able to differentiate between 70-Hz and 80-Hz frequency. Thus, the distance-based stimulations for all 10 subjects have been conducted with a frequency range of 10 Hz to 70 Hz. The discrete stimulation always had a fixed frequency of 100 Hz, based on previous success with this frequency[18].

3.3. Balance time comparison between 3 stimulation types

The experiment was conducted with 10 subjects and the statistical average across all subjects is shown in Figure 5. We can see that the control (no stimulation) trials have an average balance time of 1.76s. Discrete stimulation has a balance time of 1.81s which is 2.47% more than no stimulation. Proportional stimulation has an average of 1.89s which is 4.86% more than discrete stimulation and 7.46% more than no stimulation. This shows a significant increase in balance time when using distance-based proportional stimulation compared distance-based discrete stimulation. This supports our hypothesis that distance-based proportional E-stim is better than its discrete counterpart since it mimics the natural tactile sensation of foot pressure. The individual balance times of all 10 subjects is shown in Figure 6 (each error bar shows the standard error).

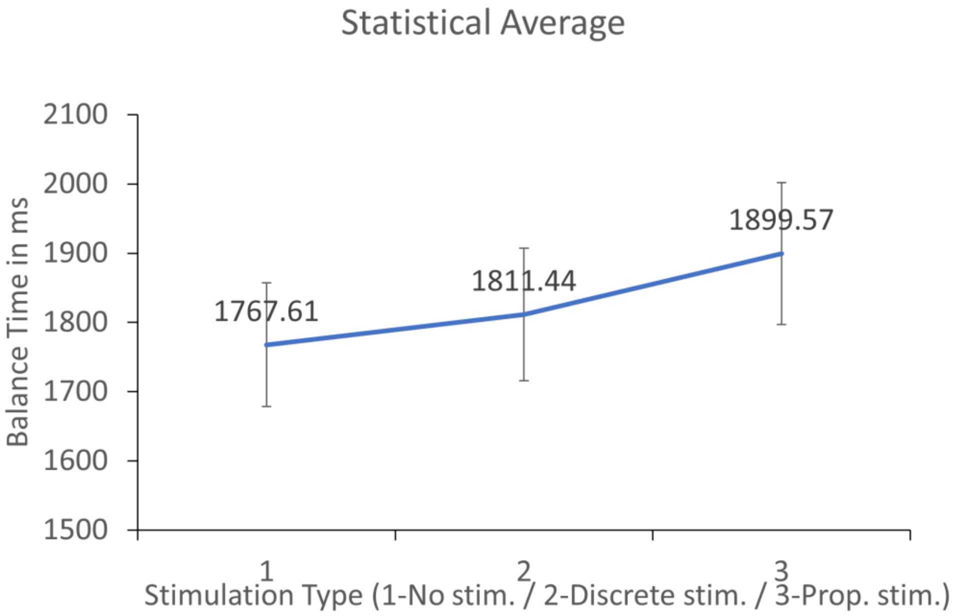


Figure 5: Statistical average of balance times of 3 stimulation types (10 subjects)

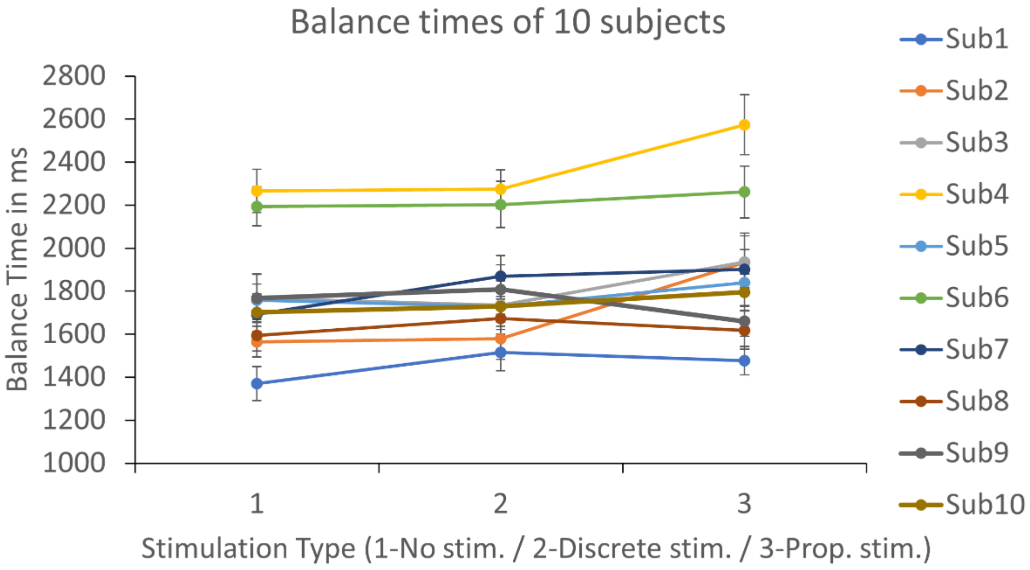


Figure 6: Balance times of all 10 subjects over the 3 stim. modes

4. DISCUSSION

4.1. Distance-based proportional E-stim improved lateral balance but distance-based discrete E-stim did not.

As shown in Figure 5, the balance time of subjects with distance-based proportional E-stim was higher than that of the discrete E-stim, which supports our hypothesis. However, we noticed that discrete stimulation has lesser effect on improving lateral balance compared to the result in our prior work[18]. We believe that this discrepancy may be due to a combination of 2 reasons. First, it may be due to the 0.5cm threshold used to start the E-stim. The threshold of 0.5cm means that the stimulation is applied only when the board sways more than 0.5cm from the level. We used 1.5cm threshold for our prior work. The second reason may be due to the fact that the region of stimulation used in this experiment was different from the region used in our last study[18,20]. We mainly evoked sensation on the region A (9 of 10 subjects) while our prior work evoked sensation on the heel.

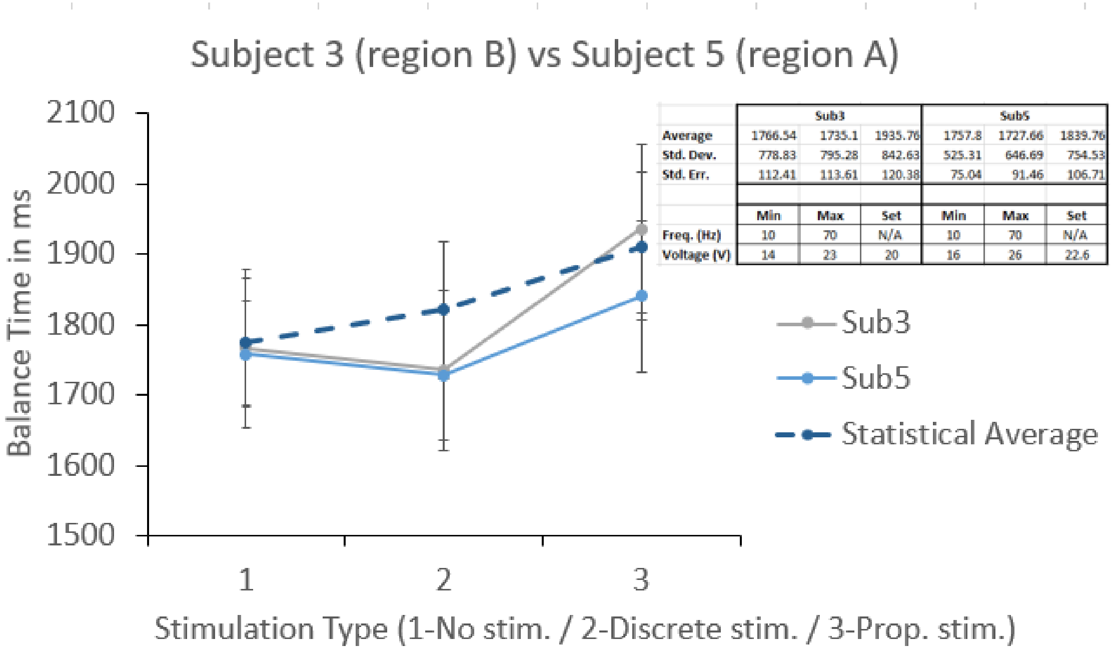
4.2. Sensation should be evoked around the heel not on the foot sole.

We initially thought to augment the sensation on the heel of the foot, which is innervated by the inferior calcaneal nerves. Although stimulating this region would be the closest to the natural tactile sensation, subjects reported that the electrotactile sensation reduced drastically when pressure was applied onto this region. Our next option was to move forward in the sole and evoke sensation on the anterior part of the heel. As expected, this region was not affected as much by pressure (standing on floor) but was affected when subjects stand on the foam. This is perhaps because a foam was deformed and in contact with the anterior part of the sole. It is possible that even if the subject does not perceive the sensation, the electrotactile feedback could play a role in proprioception, but this needs further study and experimentation.

The next viable region of stimulation is the part closest to the heel but just above it, specifically regions A and B shown in Figure 4. These regions are innervated by the medial calcaneal nerve which branches from the inferior tibial nerve near the ankle. Thus, we placed one electrode at the branching point of the medial calcaneal nerve and the second electrode about 1.5-inches below the first one over the branching point of the specific nerve which innervates regions A and B (shown in Figure 4). It is important to note here that the stimulation region was determined based on the individual variation caused by differences in shape of each person's foot.

4.3. Difference between region A and region B in balance times

Out of the 10 subjects, only 1 subject reported sensation in region B while 9 others reported sensation in region A (see Figure 4). From Figure 7, we see that the discrete E-stim balance time was lower than control (no E-stim.) balance time for subject 3. This trend was seen in only one other participant, subject 5, who had sensation in region A. The voltages used for both these subjects were also similar in range (20V vs 22.6V). Since only 1 subject had sensation in region B, we can conclude with certainty that the 2 regions do not affect balance times. But since we have 2 subjects with comparable results and different regions of stimulation, we do not see any reason to exclude subject 3's data from our data set.



	Sub3			Sub5		
Average	1766.54	1735.1	1935.76	1757.8	1727.66	1839.76
Std. Dev.	778.83	795.28	842.63	525.31	646.69	754.53
Std. Err.	112.41	113.61	120.38	75.04	91.46	106.71
	Min	Max	Set	Min	Max	Set
Freq. (Hz)	10	70	N/A	10	70	N/A
Voltage (V)	14	23	20	16	26	22.6

Figure 7: Subject 3 with region B sensation vs subject 5 with region A sensation

4.4. Strength and region of stimulation in both feet should be same

We believe that it is important the make sure that both the region and strength of stimulation on both feet should be the same or at least very similar. From some initial experimentation, it does seem to be that most people feel stimulation in either region A or B as shown in Figure 4 and it is the same region in both feet. Apart from the 10 subjects shown in the results, we attempted to get data from 2 more subjects. With both these subjects, we were not able to locate a good region of stimulation in either foot and only reported feeling any sensation under the electrodes itself. One of these subjects reported feeling slight sensation in region B in their right foot, but not on their left. This shows that anatomical variations in the foot plays a role in being able to find the right region of stimulation. We are unsure how the different locations of stimulation and the different perceptions on each foot would change the effect of E-stim on lateral balance. Further research is required to clarify this question.

4.5. Removing erroneous trial data

While the data is being collected during the experiment, there were some erroneous trials or mistrials. Sometimes the subjects accidently triggered a trial while getting down from the board or getting on, or even forgot to release the support before each trial. These trials were noted down by us and removed from the data set before we processed and compared them in Figure 5 through Figure 7. Some of these accidental trials were 54s and 143s long and some mistrials lasted less than 100ms where the subject barely let go off the support before accidently ending the trial. Out of the 150 trials for each subject, there was an average of 4 mistrials per subject, with one subject having 11 mistrials and one subject having none. Since each stim mode has 50 trials randomly and uniformly distributed, we do not expect a few missing points of data to skew our results by a significant margin.

4.6. Human Computer Interaction

Human Computer Interaction (HCI) is the field of study which focuses on the interface between humans and computers. This field of study has been around since 1980’s when the earliest computers started populating offices and homes. As computers expand into various fields and fulfil many use cases, there is a need to improve the interface between the user and the computers as well. Mouse and keyboard for computers, controllers for gaming consoles, hand tracking for VR headsets, voice modalities for home assistants, and visual modalities for robotics are examples of how computers can interact with us.

Neural interfaces are another example which has allowed us to expand the HCI paradigm to medicine, rehabilitation therapy, and even robotic prosthetics. Brain-Computer Interface (BCI) allows us to interpret the brain signals and map them to motor actions or communication modals which then can be used be locked-in patients to communicate[26], paralysis patients to control muscles[27], or even using neuroimaging to track and control robotics devices[28]. Humans are intrinsically designed to perceive the world using multiple sensory systems and HCI expands to provide externals signals to our brain using these systems to compute and make sense of the feedback to perform an action.

Our project focused on using the existing neural pathways to provide electrical stimulation as a feedback mechanism. Using these neural channels reduce the dependency on cognition to interpret the common sensory modalities used in HCI such as visual and auditory feedback. This is a non-invasive method of BCI ideal for short term rehabilitation therapy and for patients who are simply looking to improve their daily life.

5. FUTURE WORK

With these hypotheses proven, the next point of research should be to test whether transcutaneous electrotactile augmentation can be used in learning balance and test if that learning is retained over time. Another interesting metric to measure would be how much the balance time can be improved over time and what metric constitutes to a saturation in the learning curve. Such metrics would pave the way towards the end goal of improving the daily life of peripheral neuropathy patients, and in turn, the life of everyone around them.

This project has also proven itself to be an effective form of HCI using neural pathways. Since it is a noninvasive method, this can be expanded to devices such as massagers or show in-soles which work towards improving your balance without interrupting your daily routine or requiring your full attention.

6. CONCLUSIONS

From the results, we see that there is 7.46% increase in balance time with proportional/distance-based stimulation and a 2.47% increase in balance time with discrete stimulation compared to the control (no stimulation). This supports our first hypothesis that transcutaneous electrotactile feedback applied in the plantar region with cognitive load is beneficial in improving lateral balance under challenging ground conditions. Our second hypothesis that the distance-based proportional electrotactile stimulation is better than its discrete counterpart has also been shown true by the fact than the distance-based proportional stimulation is 4.86% better than the distance-based discrete stimulation.

Acknowledgement

This study has been conducted as per IRB Approval number: IRB2018-1511F

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