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EFFECTS ON BALANCE WHEN INTERFERING WITH PROPRIOCEPTION AT THE KNEE

Christina-Anne Lahiff
Mechanical Engineering Department
University of South Florida
Tampa, Florida 33620
Email: christinaann@mail.usf.edu

Millicent Schlafly*
Mechanical Engineering Department
University of South Florida
Tampa, Florida 33620
mschlafly@mail.usf.edu

Dr. Kyle Reed
Mechanical Engineering Department
University of South Florida
Tampa, Florida 33620
kylereed@usf.edu

ABSTRACT

After experiencing a stroke, 80% of individuals face hemiparesis causing muscle weaknesses, paralysis, and lack of proprioception. This often induces difficulty to perform everyday functions such as balancing. The goal of this project is to determine if stroke-like balance can be induced in healthy individuals. The Proprioceptive Interference Apparatus (PIA) applies vibrations and transcutaneous electrical nerve stimulation (TENS) about the knee joint in different combinations both with and without visual feedback.

Ten subjects stood on one foot for periods of two minutes for each of the eight trial conditions. The root mean squared (RMS) of the position coordinates, the standard deviation of the forces, and the RMS of center of pressure coordinates were analyzed for each trial and subject. Analysis of the variation of position markers and forces showed a statistically significant difference between balance with visual feedback versus without. However, the use of PIA did not have any statistically significant difference on these measures.

INTRODUCTION

The ultimate goal of this research is to aid individuals with asymmetric impairments in balancing with effective balance patterns that counterweigh the dynamics with the resulting forces and torques. In order to do so, it is prudent to first acquire data from able-bodied subjects. To achieve this goal, this paper investigates the utilization of a stroke simulator [1, 2], which is a portable apparatus equipped with four vibration motors and four electronic stimulator applicators, to evaluate the effects of asymmetric impairments on altering the balance patterns of healthy, able-bodied subjects.

The main concept behind the utilization of vibration motors and TENS (via an electronic stimulation pulse massager) is the idea of altering an able-bodied person's proprioception, which translates into "awareness of oneself." Previous studies that utilized vibrations to interfere with proprioception have found that if one vibrates the tendons surrounding a certain joint, one can make a subject misinterpret sensations and distance around the affected area [3, 4].

It is a commonly known fact that those affected by stroke are generally not as mobile or in control of their bodily movements or functions as their able-bodied counterparts. Therefore, it would be better to wait for the technologies to be more refined before testing on those individuals who are affected by stroke. Techniques in the early stages can put physical duress or stress on the individual to obtain data on how the stroke affected them, but the rehabilitation methods that are in the early stages of testing may not have clear benefits to the individual. Using healthy subjects with simulated impairments for the early testing allows for a reduction of error and uncertainty that would be associated with the variability of disabled individuals. This testing apparatus, once optimized, could pose to be a useful instrument when it comes to early research on balance asymmetries induced by stroke and speed the development of rehabilitation therapies.

*Address all correspondence to this author.

BACKGROUND

Due to the fact that stroke is nondiscriminatory by its very nature, it can affect anyone regardless of gender, age, or health [5]. Stroke survivors often have a difficult time adapting to their new life, especially if they have the exceedingly common side effect of hemiparesis, which is partial neuromuscular paralysis allocated to one side of the body. Hemiparesis most often results in asymmetric balance and gait that requires the utilization of various forms of rehabilitation techniques and devices [6, 7].

Coordinated limb control during balance and walking is often debilitated after central nervous system damage, such as suffering a stroke or traumatic brain/spinal injury, or physical changes, such as using a cane or a prosthesis. Able-bodied persons generally take equal steps with each leg, with an offset of about 180°. This offset is frequently referred to as "out-of-phase coordination." Individuals who have had a stroke or lower-limb amputation generally deviate from perfectly out of phase walking and have asymmetries in temporal measures, for instance time spent in double-limb support, and spatial measures, including step length [8, 9]. Asymmetric gait and balance patterns are prevalent in amputees and stroke patients, however, are more discernibly obvious in transfemoral amputees, which describes those who have lost their leg above the knee joint [10–12]. The asymmetry provokes wearers to labor so that they may attempt to compensate for undesirable and unmanageable motions [13]. For stroke victims, the nonparetic limb requires a greater propulsive force than the paretic limb. Therefore, the power and work of the paretic plantar flexors are also abated [8, 14]. In turn, vertical ground reaction forces are lessened on the paretic limb with respect to the nonparetic limb [15]. This is imitated in the decreased weight-bearing of the paretic limb.

Previous studies involving vibrations to simulate proprioceptive interference have shown that proprioception is a key factor in implicit body representation. One such study involved vibrating the tendons surrounding the elbow while having subjects perform the task of grasping a digit on the opposite hand. They found that the vibrations induced a proprioceptive interference that made the subject feel as though the distance being traced on the non-affected side felt either lengthened or shortened, depending upon which tendon was being vibrated [3].

Other studies investigated the effect of TENS on hemiparetic knee spasticity. In these studies, the researchers hypothesized that utilization of TENS in thirty minute or more increments over a prolonged period of time may prove to limit the amount of knee spasticity and possibly result in enhanced motor function [16]. It was also observed that the implementation of TENS treatment has the capability to improve the knee flexion torque of those with multiple sclerosis [17].

Another related study that combined the use of vibration and electrically induced muscle contractions addressed the co-activation of muscle spindles. The researchers found that the electrically induced contractions possessed the capacity to reduce the response of the spindles to vibration. However, the paper also acknowledged that the contractions could enhance the spindle's response to vibration when the receptor-bearing muscle was affected [18].

These studies were the basis for the concept of creating and evaluating a proprioception interference apparatus for the knee. It was deduced that such a testing apparatus would be optimal to use on the knee location since, like the elbow, it too is a joint with various tendons that could be stimulated to generate different sensations. However, for this study in particular, the researchers were only concerned with stimulating the entire joint to induce a tingling or partially numb sensation that would have an effect on a subject's balance on one leg. They also wanted to know which type of stimulation, mechanical or electrical, had a greater effect on the balance of the subjects.

The investigation of the effect of visual feedback in combination with the vibratory stimulation and TENS was derived from multiple balance research studies. These studies tested to see whether or not the lack of visual feedback had an effect on one's ability to balance, especially after the lower extremities were fatigued. It was concluded that visual feedback did have an impact on balance [19]. Thus, the researchers involved in this study wanted to expand upon the previous hypothesis to see if stability changed with different combinations of no external stimuli, vibration stimulation, TENS, eyes open, and eyes closed.

This study was conducted on ten able-bodied subjects, all of which were right leg dominant. The topic of limb dominance has been discussed as to whether or not asymmetries are exacerbated more so if the dominant side is paralyzed. However, this topic was not investigated in this study because previous studies have not been able to conclude as to whether a statistically significant difference exists [20].

METHODS

Design of Proprioception Interference Apparatus

The PIA is comprised of four vibration motors connected to a DC portable external power supply that generates a frequency of roughly 220 Hz and a SPT Mini Electronic Pulse Massager with 4 electrode pads, which was utilized for TENS application and has a frequency range of 0-200 Hz. In an attempt to isolate the knee as opposed to create a specific illusion, the frequencies chosen were above those commonly used for creating kinesthetic illusions or managing pain, usually around 100 Hz [21, 22]. The apparatus had to be adjustable so that it could fit a wide range of thigh and calf circumferences. Thus, the vibration motors were given long leads so that they could be easily positioned in the correct locations. In this case, the correct positions were located around the lateral and medial hamstrings behind the knee in order to vibrate the muscle spindle endings. The vibration motors, seen

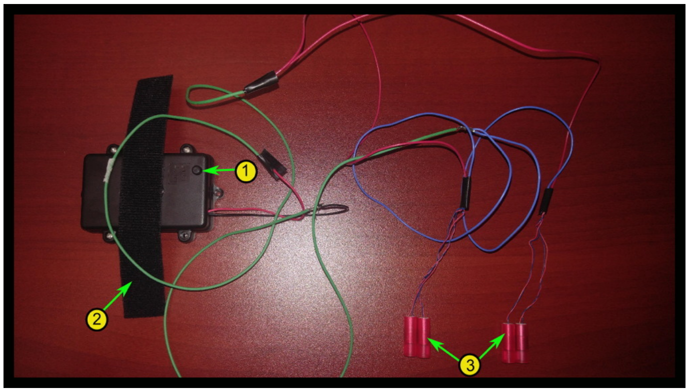

FIGURE 1. **VIBRATION MOTORS** – *COMPONENT 1 IS A POWER BUTTON ON THE BATTERY PACK. COMPONENT 2 IS THE VELCRO STRAP TO HARNESS THE PACK TO THE WAISTLINE. COMPONENT 3 SHOWS THE VIBRATION MOTORS.*

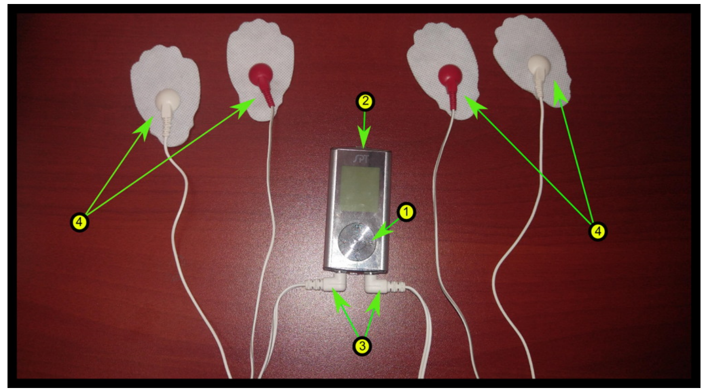

FIGURE 2. **SPT MINI ELECTRONIC PULSE MASSAGER** – *COMPONENT 1 IS THE CONTROLLER. COMPONENT 2 IS THE CHARGER. COMPONENT 3 SHOWS THE LEAD CONNECTION LOCATIONS. COMPONENT 4 SHOWS THE ELECTRODE PADS.*

in Figure 1, were chosen due their small size and capability to produce a noticeable vibration from a portable battery pack.

In contrast to the vibration motors, the pulse massager was used for stimulation on the front of the knee. The electrode pads were placed near the peroneal nerve, tendons of the vastus medialis and lateralis, and the tendon of the rectus femoris. These locations, especially the peroneal nerve, were selected based on previous research that found that muscle spindle fiber endings in this area were sensitive to mechanical stimulation [19]. The pulse massager was chosen since it has an easy to use interface between the motors and the power supply. It also has a variety of alternating frequency modes that have controllable intensity levels. However, for the design of this particular experiment, that characteristic of modes was not utilized due to various constraints. Instead, one mode was selected with a noticeable frequency level and a moderate to high intensity level to ensure consistency between subjects. A description of the electronic stimulation pulse massager and its components can be viewed in Figure 2. The device can be seen attached to an individual's leg in Figure 3.

Subjects

The ten subjects tested were able-bodied persons between 19 and 27 years old and weighed between 50 kg and 95 kg. They volunteered of their own accord to participate in this study after being notified of the design of the device and experimental procedure. The majority of subjects in this study declared themselves as possessing a dominant right leg. However, the testing was not exclusively limited to "right leg dominant" test subjects. And, in contrast to the researchers' conjecture, almost half of the subjects preferred to balance on their nondominant leg. This did not affect the balance data in comparison to those that were balancing on their dominant leg.

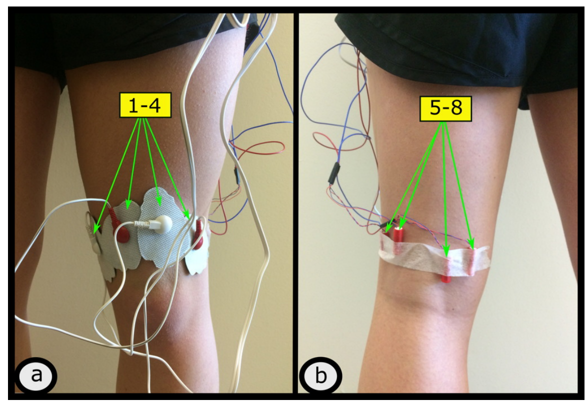

FIGURE 3. **PROPRIOCEPTION INTERFERENCE APPARATUS (PIA) ON SUBJECT** – *(A) FRONT VIEW: COMPONENTS 1-4 ARE THE POSITIONED ELECTRODE PADS (B) BACK VIEW: COMPONENTS 5-8 ARE THE METICULOUSLY PLACED VIBRATION MOTORS.*

EXPERIMENTAL PROCEDURE

The Computer Assisted Rehabilitation ENvironment (CAREN) system, shown in Figure 4, was used for experimental testing. The CAREN system is a rehabilitative environment with a split-belt treadmill system mounted onto a six-degree of freedom motion base. The split-belt treadmill system has two individual belts that are able to move at two different velocities. For the purpose of this study, the researchers only used the CAREN system to determine the RMS values of each marker position, standard deviation of the forces, and the RMS values of the center of pressure over the duration of each trial.

Able-bodied subjects were informed of the testing procedure and signed the appropriate IRB release form prior to experiment commencement. After the subjects' initial processing, the

FIGURE 4. **COMPUTER ASSISTED REHABILITATION ENVIRONMENT (CAREN)**

subjects had markers placed on their extremities and back so that the correct motion tracking could be calibrated by the CAREN system. Then, the PIA was placed on the leg on which each subject chose to balance on without any assistance. However, they were instructed to hold onto the CAREN's safety bars as a precautionary measure if they felt as though they would fall, in which case, the researchers would note the occurrence and account for it in the data analysis.

An initial relative comfort level for the mode intensity of the electronic stimulation was taken at this time for each subject since the desired effect was to stimulate the affected area without harming the subject. It was determined that a moderate intensity level of 5/10 was selected for most subjects, with a ± 1 being allowed for those that felt that the intensity was too low or too high. After the comfort level assessment and instruction on how and when to turn on the PIA, subjects were asked to balance for two minutes with eyes open so that baseline balance with visual feedback could be obtained by the researchers. The same process for balancing was performed for baseline with eyes closed. After baseline data was collected, the following two minute trials were conducted in a randomized order for each subject:

1. vibration with eyes open
2. vibration with eyes closed
3. pulse with eyes open
4. pulse with eyes closed
5. vibration and pulse with eyes open
6. vibration and pulse with eyes closed

Including the two baseline trials, eight conditions were evaluated. Resting periods of about 5 minutes between trials were offered to the subjects, but were left to be taken at the discretion of the subject.

RESULTS AND DISCUSSION

For this data, the subjects' RMS values of marker positions, average of the standard deviations of the forces, and the RMS of the COP in the x, y, and z directions for each trial were analyzed using MATLAB. Two-way repeated measures with each of the three parameters as the dependent measure and independent factors of eyes open/closed and perturbation (four levels: vibration, TENS, both, and none) were conducted to test for statistical significance. The graphs of the comparative results between subjects for each experimental parameter can be seen in Figures 5, 6, and 7. From this analysis, previous research was reaffirmed that eyes closed has a greater effect on balance than eyes open in all parameters except RMS of center of pressure [19]. There was not a statistically significant difference for perturbation.

For the position RMS values in Figure 5, it was hypothesized that the trials with visual feedback, which had a combination of pulse and vibration, improved some of the subjects' balance with visual feedback more so than the trials in which they had no external stimuli applied with visual feedback. This may be due to

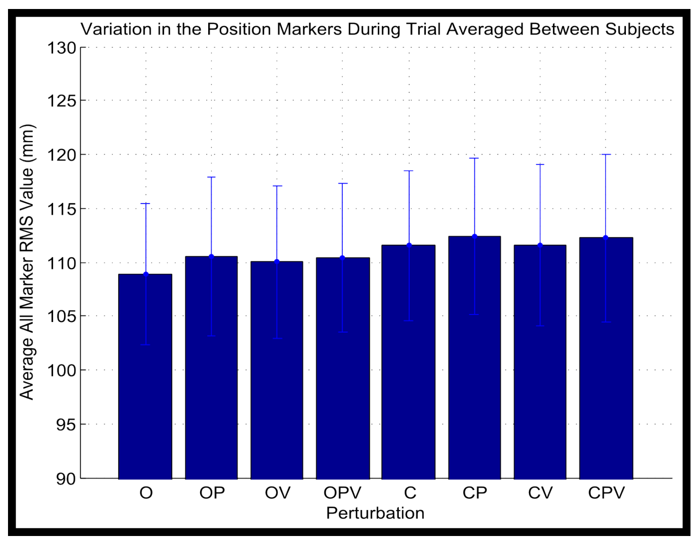

FIGURE 5. **GRAPH OF RMS OF MARKER POSITION** – *EXPLANATION OF ACRONYMS: **O**-OPEN EYES, **C**-CLOSED EYES, **P**-PULSE MASSAGER FOR TENS, **V**-VIBRATION. THE ERROR BARS REPRESENT THE STANDARD DEVIATION BETWEEN THE SUBJECTS. POSITION POINTS WHERE THE VALUE WAS EQUAL TO ZERO OR GREATER THAN 3 STANDARD DEVIATIONS FROM THE MEAN WERE REMOVED.*

the fact that the combination of the two different stimuli made the majority of subjects more able to compensate than in other trials. In a related study, the researchers found that the application of vibration and electronic stimuli to muscle spindles resulted in the electric pulses enhancing the muscular spindle fibers' response to vibration when the "receptor-bearing muscle" was affected [18]. In that same study, they also claimed that the response of the spindle to vibration effects could be reduced if both types of stimuli were applied, which seems to be the case in the eyes closed condition where both stimuli are applied since vibration enhanced the majority of the subjects' balance, and electronic stimulation reduced it. The results of this study may bolster their conclusions, but there was still not a statistically significant difference between any of the trials with the exception of eyes open versus eyes closed. This was discerned via a two-way repeated measures test with RMS of positions of markers as the dependent measure and independent factors of eyes open/closed and perturbation (four levels: vibration, TENS, both, and none). The results showed a statistically significant difference for eyes ($F(1,9) = 19.5$, $p < .05$). There was not a statistically significant difference for perturbation. In regards to the effects of the pulse massager on its own, it appears as though the pulse massager enhanced the balance of some subjects under the eyes open condition while disturbing the majority of the subjects' balance while eyes were closed. In comparison, the vibration on its own enhanced the balance of some subjects in the case of eyes open and the majority of subjects while eyes were closed.

In regards to the standard deviations of the forces, the results were similar to the results previously discussed in the position RMS locations in the sense that there was not a significant difference between any perturbation parameter. Once again, a two-way repeated measures ANOVA was performed, this time with standard deviation of force as the dependent measure and independent factors of eyes open/closed and perturbation (four levels: vibration, TENS, both, and none). The results showed a statistically significant difference for eyes in the y-direction ($F(1,9) = 18.4$, $p < 0.05$) and in the xz-plane ($F(1,9) = 6.0$, $p < .05$). There was not a statistically significant difference for perturbation. This can viewed in Figure 6, which contains the variation of the vertical forces (in the y-direction) as well as the variation of the planar forces (combined x and z directions) normalized by the weight of each subject.

In reference to the RMS values of the center of pressure, a two-way repeated measures was conducted, this time with RMS of center of pressure as the dependent measure and independent factors of eyes open/closed and perturbation (four levels: vibration, TENS, both, and none). No statistical significance was found. As shown in Figure 7, the COP values did not significantly differ, even in regards to visual feedback versus no visual feedback.

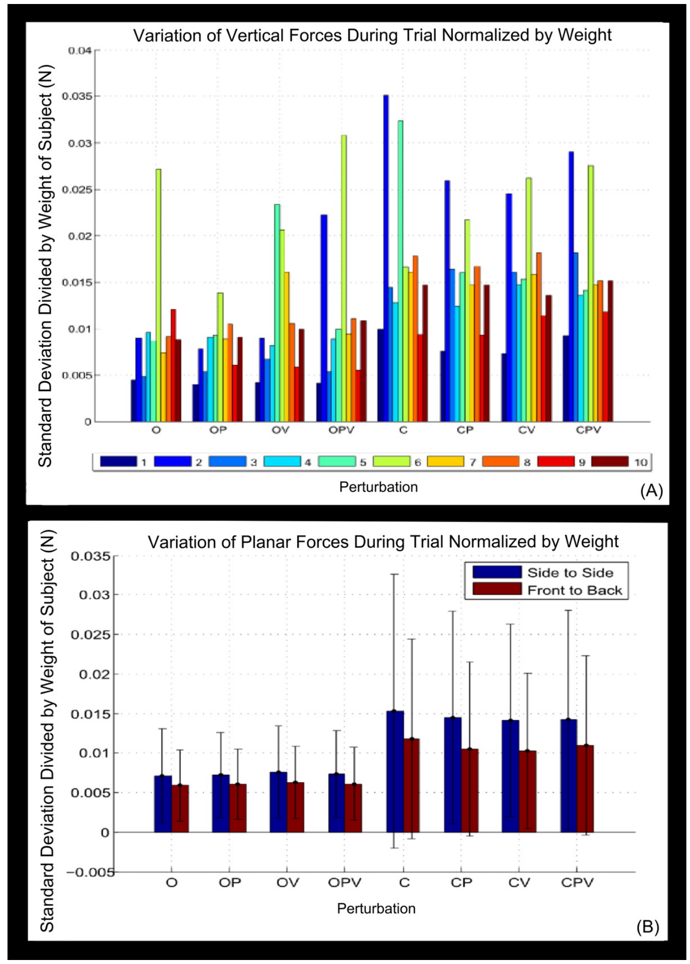

FIGURE 6. GRAPHS OF STANDARD DEVIATION OF FORCES – *EXPLANATION OF ACRONYMS: **O**-OPEN EYES, **C**-CLOSED EYES, **P**-PULSE MASSAGER FOR TENS, **V**-VIBRATION (A) STANDARD DEVIATION OF VERTICAL FORCES FOR EACH SUBJECT/PARAMETER DIVIDED BY THE WEIGHT OF THE SUBJECT (N). (B) STANDARD DEVIATION OF X/Z FORCES FOR EACH SUBJECT/PARAMETER DIVIDED BY THE WEIGHT OF THE SUBJECT (N) AND THEN COMBINED WITH THE MEAN.*

FUTURE WORKS

There are multiple steps that can be taken to improve and expand upon this study. First, the design of the PIA needs to be enhanced. It needs be designed in such a way that it can be easily and more accurately positioned on the optimal knee locations in order to isolate the entire knee. The current design, while it allows the researchers to place the external stimuli in an accurate manner on the subject, is not what one may consider easy. While the TENS application is rather easy to position and secure, the vibration motors must be held in the correct manner and taped onto the skin of the subject.

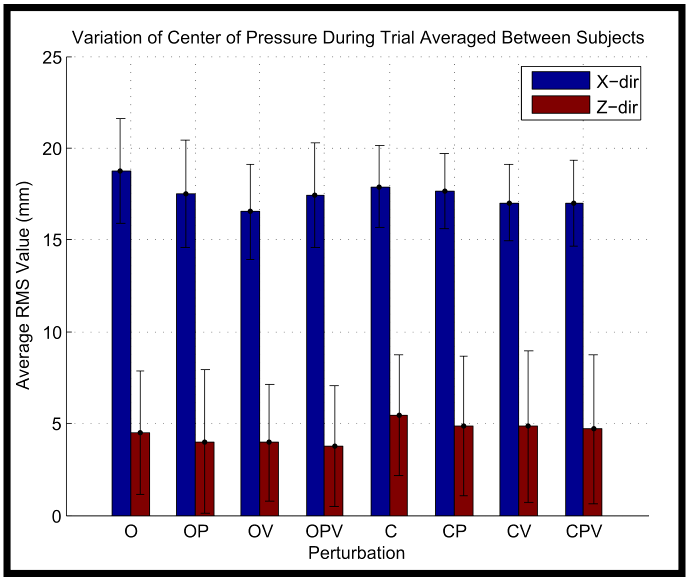

FIGURE 7. **GRAPHS OF CENTERS OF PRESSURE-** *EXPLANATION OF ACRONYMS:* ***O****-OPEN EYES,* ***C****-CLOSED EYES,* ***P****-PULSE MASSAGER FOR TENS,* ***V****-VIBRATION. DEPICTS THE RMS OF ALL X AND Z COP.*

Secondly, the sensation induced by the apparatus may need to be significantly heightened. As the results showed, only a few of the subjects experienced sensations that somewhat aligned with those experienced by subjects in related studies. Also, it is possible that the frequency at which the vibration motors are firing could be altered in such a manner that it enhances the effect of the vibration on the muscle spindles.

Another way to enhance the sensation could be the implementation of larger, more powerful vibration motors. These would most definitely cause the vibrations on the tendons surrounding the knee to be more noticeable. These motors could once again be meticulously placed on the subject to isolate the knee from the rest of the leg.

A third way of improving and expanding on this study could be the incorporation of more electrode pads for the pulse massager and more vibration motors as well as more subjects. Thus, more locations on the knee with sensitive muscle fibers could be targeted. The addition of not only these applications, but also subjects could lead to more results and possibly a definitive conclusion as to which perturbation or combination thereof leads to physical imbalance.

REFERENCES

[1] Lahiff, C.-A., Ramakrishnan, T., Kim, S. H., and Reed, K. B, 2016. "Knee orthosis with variable stiffness and damping that simulates hemiparetic gait". IEEE 38th Annual International Conference of the Engineering in Medicine and Biology Society (EMBC), pp. 2218–2221.

[2] Lahiff, C.-A., 2017. "Simulation of hemiparetic function using a knee orthosis with variable impedance and a proprioception interference apparatus". Master's thesis, University of South Florida.

[3] De Vignemont, F., Ehrsson, H. H., and Haggard, P., 2005. "Bodily illusions modulate tactile perception". *Current Biology,* ***15***(14), pp. 1286–1290.

[4] Roll, J., Vedel, J., and Ribot, E., 1989. "Alteration of proprioceptive messages induced by tendon vibration in man: a microneurographic study". *Experimental brain research,* ***76***(1), pp. 213–222.

[5] McIntosh, J., 2015. "What is stroke? what causes strokes?". *Medical News Today,* ***4***.

[6] Handzic, I., and Reed, K. B., 2013. "Comparison of the passive dynamics of walking on ground, tied-belt and split-belt treadmills, and via the gait enhancing mobile shoe (gems)". In Rehabilitation Robotics (ICORR), 2013 IEEE International Conference on, IEEE, pp. 1–6.

[7] Reed, K. B., Handžić, I., and McAmis, S., 2014. "Home-based rehabilitation: enabling frequent and effective training". In *Neuro-Robotics*. Springer, pp. 379–403.

[8] Balasubramanian, C. K., Bowden, M. G., Neptune, R. R., and Kautz, S. A., 2007. "Relationship between step length asymmetry and walking performance in subjects with chronic hemiparesis". *Archives of physical medicine and rehabilitation,* ***88***(1), pp. 43–49.

[9] Brandstater, M., De Bruin, H., Gowland, C., and Clark, B., 1983. "Hemiplegic gait: analysis of temporal variables.". *Archives of physical medicine and rehabilitation,* ***64***(12), pp. 583–587.

[10] Gitter, A., Czerniecki, J., and Weaver, K., 1995. "A reassessment of center-of-mass dynamics as a determinate of the metabolic inefficiency of above-knee amputee ambulation.". *American journal of physical medicine & rehabilitation,* ***74***(5), pp. 337–338.

[11] Hoffman, M. D., Sheldahl, L. M., Buley, K. J., and Sandford, P. R., 1997. "Physiological comparison of walking among bilateral above-knee amputee and able-bodied subjects, and a model to account for the differences in metabolic cost". *Archives of physical medicine and rehabilitation,* ***78***(4), pp. 385–392.

[12] Handžić, I., and Reed, K. B., 2015. "Perception of gait patterns that deviate from normal and symmetric biped locomotion". *Frontiers in psychology,* ***6***.

[13] Huang, C., Jackson, J., Moore, N., Fine, P., Kuhlemeier, K., Traugh, G., and PT, S., 1979. "Amputation: energy cost of ambulation". *Arch Phys Med Rehabil,* ***60***(1), pp. 18–24.

[14] Bowden, M. G., Balasubramanian, C. K., Neptune, R. R., and Kautz, S. A., 2006. "Anterior-posterior ground reaction forces as a measure of paretic leg contribution in hemiparetic walking". *Stroke,* ***37***(3), pp. 872–876.

[15] Kim, C. M., and Eng, J. J., 2003. “Symmetry in vertical ground reaction force is accompanied by symmetry in temporal but not distance variables of gait in persons with stroke”. *Gait & posture,* ***18***(1), pp. 23–28.
[16] Levin, M. F., and Hui-Chan, C. W., 1992. “Relief of hemiparetic spasticity by tens is associated with improvement in reflex and voluntary motor functions”. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section,* ***85***(2), pp. 131–142.
[17] Fredriksen, T., Bergmann, S., Hesselberg, J., Stolt-Nielsen, A., Ringkjøb, R., and Sjaastad, O., 1986. “Electrical stimulation in multiple sclerosis”. *Stereotactic and Functional Neurosurgery,* ***49***(1-2), pp. 4–24.
[18] Burke, D., Hagbarth, K.-E., Löfstedt, L., and Wallin, B. G., 1976. “The responses of human muscle spindle endings to vibration during isometric contraction.”. *The Journal of Physiology,* ***261***(3), p. 695.
[19] Vuillerme, N., Nougier, V., and Prieur, J.-M., 2001. “Can vision compensate for a lower limbs muscular fatigue for controlling posture in humans?”. *Neuroscience letters,* ***308***(2), pp. 103–106.
[20] Yadav, V., and Sainburg, R. L., 2014. “Limb dominance results from asymmetries in predictive and impedance control mechanisms”. *PloS one,* ***9***(4), p. e93892.
[21] Goodwin, G. M., McCloskey, D. I., and Matthews, P. B., 1972. “Proprioceptive illusions induced by muscle vibration: contribution by muscle spindles to perception?”. *Science,* ***175***(4028), pp. 1382–1384.
[22] Chao, A.-S., Chao, A., Wang, T.-H., Chang, Y.-C., Peng, H.-H., Chang, S.-D., Chao, A., Chang, C.-J., Lai, C.-H., and Wong, A. M., 2007. “Pain relief by applying transcutaneous electrical nerve stimulation (tens) on acupuncture points during the first stage of labor: a randomized double-blind placebo-controlled trial”. *Pain,* ***127***(3), pp. 214–220.