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Simulation of Hemiparetic Function Using a Knee Orthosis with Variable Impedance and a Proprioception Interference Apparatus

by

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A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Mechanical Engineering
Department of Mechanical Engineering
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Abstract

Individuals with stroke have neuromuscular weakness or paralysis on one side of the body caused by some muscles disengaging and overexciting other muscles. Hyperextension of the knee joint and complete lack of plantar flexion of the ankle joint are common symptoms of stroke. This thesis encompasses the simulation of hemiparetic function using both a knee orthosis with variable impedance, specifically in terms of stiffness and damping, and the Proprioception Interference Apparatus.

The section regarding the knee orthosis with variable impedance focuses on the creation and implementation of a small, lightweight, and adjustable orthotic device to be positioned around the knee of an able-bodied person to simulate hemiparetic gait. Force and range of motion data from able-bodied subjects fitted with the orthosis, inducing hemiparetic gait, was collected using the Computer Assisted Rehabilitation ENvironment (CAREN) system. The four parameters that the design focused on are damping, catch, hysteresis, and stiffness. The main goal of the project was to discern whether this device could be utilized as a viable research instrument to simulate hemiparetic gait. It was hypothesized that the device has the potential to be utilized in the future as a research device to be used on able-bodied persons to study asymmetries in gait and eventually quantify the Modified Ashworth Scale. It was also believed that it could serve as a possible rehabilitation device for people with stroke since it has been designed to induce larger knee flexion as an after effect. However, this would require the proper clinical evaluation and experimentation procedures to be successfully concluded. A comparison between how the dominant leg was affected by the orthosis and how the non-dominant leg was affected was investigated as well. The results show that the device affected the velocities, knee angles, and force profiles of the subject's gait.

The second section involving the Proprioception Interference Apparatus involved the creation and implementation of a haptic apparatus that utilizes vibration as well as transcutaneous electrical nerve stimulation (TENS) in various combinations with and without visual feedback to induce a proprioceptive illusion around the knee joint, as if a subject has a version of hemiparesis. The main goal of the project was to discern whether a device of relatively the same design could be utilized as a viable research instrument to simulate stroke-like balance in able-bodied subjects.

Comparison between how the root mean square (RMS) values of each marker location, the average of the standard deviations of the forces, and RMS of the center of pressure affected the various conditions was investigated as well. It was hypothesized and concluded that the RMS values and average of the standard deviations when subjects had no visual feedback would have a significant difference from when they had visual feedback. It was also hypothesized that Proprioceptive Interference Apparatus (PIA) would have a significant effect on the RMS and standard deviation values since it was meant to disrupt the motor control function of the knee, however, this was proved false after data analysis. It was also surmised that the application of the TENS had more of an effect on the RMS and standard deviation values, whether it was used on its own or in combination with the vibrations, than the vibration stimulation alone. However, once again, this was not statistically significant.

Chapter 1: Introduction[1]

This thesis investigates the design and effects of wearing two types of stroke simulators, a stroke gait simulator and a stroke balance simulator. The ultimate goal of this research is to aid individuals with asymmetric impairments in walking and balancing with effective gait and balance patterns that counterweigh the dynamics with the resulting forces and torques. The background information regarding both simulators can be found in the second chapter of this thesis.

The third chapter of this thesis discusses the stroke gait simulator, which is a portable knee orthosis equipped with a spring-damper mechanism to convey variable stiffness and damping as well as to evaluate the effects of asymmetric dynamics of the knee on the gait patterns of healthy, able-bodied subjects. Damping and stiffness of a person affected with stroke have been rated by the Modified Ashworth Scale [1], but it has not been quantified in terms of numerical values for stiffness and damping levels. The concept behind the knee orthosis was to develop a device that could easily and readily induce various levels of the Modified Ashworth Scale on an able-bodied subject via a spring-damper mechanism. The eventual quantification of the Modified Ashworth Scale would allow for a more personalized design of orthotics that could aid rehabilitation. In this preliminary experiment, I studied the effects of one of the various combinations of damping and stiffness on the knee orthosis.

The majority of the walking process is governed by the passive dynamics of the legs and body [9], which generally leads to symmetric walking when both sides of the body are identical. In an asymmetrically impaired individual, asymmetric control effort is necessary to create symmetric motions. These compensatory motions, such as using alternate arm movements along with torso and hip flexion, are commonly used by disabled individuals. These adaptations often lead to back

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[1] Portions of the chapter up to this point were published in [19]. Permission is included in Appendix A.

pain and premature deterioration of joints in individuals with stroke and also cause stresses at the residual limb socket in amputees.

Another intriguing aspect that was investigated in this chapter of the thesis was the idea of limb dominance and whether it plays a significant role in gait asymmetry. Limb dominance is particularly relevant since a stroke is unpredictable and can affect either side of the body. It was surmised that there may exist significant differences in velocities, comfort levels, and sensations between the dominant and non-dominant legs. Some studies regarding motor lateralization have shown that the dominant side may take longer to adapt to a perturbation or hindrance. It is believed that this is due to the tendency of the non-dominant side to react quicker to corrective actions or based on impedance control mechanisms [36].

The fourth chapter investigates the utilization of a stroke balance simulator, 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. 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 that affected area [7].

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 does not prove to be a prudent decision to continually put those persons who are affected by stroke under the physical duress or stress to obtain data on how the stroke affected them. Also, using healthy subjects allows for a reduction of error and uncertainty that would be associated with the variability of disabled individuals. These stroke simulators, once optimized, could pose to be a useful instrument when it comes to researching asymmetries induced by stroke.

The fifth chapter is the conclusion of this thesis. This section evaluates the effectiveness of both stroke simulators and gives recommendations regarding the research. For the stroke gait simulator, testing more subjects with multiple clinicians’ opinions as well as simulating and testing other levels of the Modified Ashworth scale are advised for future works. In regards to the stroke balance simulator, improving the design and placement of the device to enhance the effectiveness of the proprioception interference is recommended.

Chapter 2: Background[2]

This thesis is comprised of various aspects of both engineering and medicine, specifically pertaining to stroke rehabilitation. The specific goals of the stroke gait simulator are to quantify the Modified Ashworth Scale to specific stiffness and damping values, evaluate how the gait patterns change as a function of known stiffness and damping, and to understand how physical asymmetries impact the adaptation of gait. The second half of this chapter pertains to previous research upon which this thesis was derived.

2.1 Modified Ashworth Scale

The Modified Ashworth Scale is a system currently used by clinicians to evaluate the amount of spasticity in a person's knee after a stroke. The level of the scale in regards to the spasticity is correlated to the amount of stiffness and damping felt by the clinician. A table which describes the scale and the relative stroke level associated with each score can be seen in Table 2.1 [1]. As one can deduce from the fact that the level is discerned only through the clinician's evaluation through touch, the scale is very subjective and can vary from clinician to clinician. Due to this somewhat biased interpretation, it was decided that the quantification of the various ratings in regards to stiffness and damping would prove to be beneficial, especially when it comes to designing and implementing corrective devices.

2.2 Hemiparesis

Stroke is nondiscriminatory by its very nature, it can affect anyone regardless of gender, age, or health [22]. Stroke survivors often have a difficult time adapting to their new life,

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[2] Portions of the chapter up to this point were published in [19]. Permission is included in Appendix A.

Table 2.1: Modified Ashworth Scale

Score	Description [1]	Stroke
0	No muscle tone increase	Mild
1	Slight muscle tone increase, manifested by a catch and release, or by minimal resistance toward the end of the movement when the affected part(s) is (are) moved in flexion or extension	Mild
1+	Slight muscle tone increase, manifested by a catch and release, followed by minimal resistance throughout the remainder (less than half) of the ROM	Mild-Moderate
2	More marked increase in the muscle tone through most of the ROM, but affected part(s) easily moved	Moderate
3	Considerable increase in muscle tone, passive movement difficult	Moderate -Severe
4	Affected part(s) rigid in flexion or extension	Severe

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 [33]. About eighty percent of people who have had a stroke have a form of hemiparesis [2]. After a stroke, about 63-77% of survivors are unable to walk without assistance within the first week. However, more than half of all patients are able to walk independently after a time period of about three weeks. This percentage increases to about eighty-five after a time period of six months [24].

The coordinated limb control during balance and walking is frequently impaired following central nervous system damage, such as suffering a stroke or traumatic brain injury, or physical changes, such as utilization of a cane or wearing a prosthesis. Able-bodied adults generally take equal-sized steps with each leg, offset by about 180°. This offset is commonly referred to as out-of-phase coordination. Individuals who have had a stroke or lower-limb amputation often diverge from perfectly out-of-phase walking and have asymmetries in temporal measures, such as time spent in double-limb support, and spatial measures, such as step length, of interlimb coordination [15, 22].

2.3 Asymmetric Patterns

Asymmetric gait and balance patterns are common in those affected by stroke and amputees, but are more noticeably evident in transfemoral amputees, which are amputees that have lost their leg above the knee joint location [3, 6]. The asymmetry causes wearers to exert a large amount of effort in order to try to compensate for unwanted, uncontrollable motions [12]. In the case of stroke victims, the propulsive force of the paretic limb is less than that of the nonparetic limb. Thus, the work and the power of the paretic plantar flexors are in turn also lessened [17, 22]. Vertical ground reaction forces also are decreased on the paretic limb relative to the nonparetic limb [18]. This is emulated in the depreciated weight-bearing of the paretic limb.

2.4 Gait Rehabilitation Methods

Current popular asymmetric gait rehabilitation methods include circular treadmill locomotion [13], split-belt treadmills [28, 29], split-motion training [14], rhythmic cuing [27, 30], balance training [5, 15], and others [4]. Treadmill locomotion, split-belt treadmills, and split-motion training are based on the concept that if one was to speed up the hemiparetic patient’s walking, especially on the affected side, symmetry levels can be induced [29]. However, asymmetry may reappear once the patient returns to normal overground walking. In a similar manner of trying to induce symmetry in walking, rhythmic cuing uses auditory stimuli to try to entrain the hemiparetic side so that it becomes more coordinated and symmetrical [27]. Symmetry is sought to be enhanced through the use of balance training as well, which utilizes various devices to aid in correcting gait and balance patterns [15].

Traditional rehabilitation interventions such as locomotive training with and without weight support and physical therapist assistance have aided in speed, control, and endurance. However, these techniques are typically not very effective at restoring symmetry [33]. Recent work investigating gait rehabilitation has had a principal focus on two main outcome measures: velocity and symmetry. Walking velocity is indicative of overall gait performance and can be utilized to discern various levels of disability [5, 21, 26]. Symmetry, in contrast, measures the quality of the gait pattern [8, 25]. Normal gait has been found to be generally symmetric in the kinematics, dynamics, vertical forces, and spatiotemporal parameters between the two legs [16, 32].

2.5 Computer Assisted Rehabilitation Environment

For this thesis, the Computer Assisted Rehabilitation ENvironment (CAREN) system, seen in Figure 2.1, was utilized. The CAREN system is a rehabilitative environment equipped with a splitbelt treadmill system which is mounted on a six degree of freedom motion base with motion capture, utilizing 10 infrared cameras, and force plates. The split-belt treadmill system has two individual moving belts that are able to move at two different velocities. Split-belt treadmills have frequently been used for the rehabilitation of stroke patients that have hemiparesis due to their ability to push one foot at a faster rate than the other, thus assisting in the correction of asymmetric gait patterns [15]. Spatial and temporal asymmetries in gait arise when the step length of one foot is not equivalent to that of the other [23, 24]. While more amplified asymmetries appear in stroke patients and those who possess central nervous system damage, some asymmetries are inherent in able-bodied persons. This was part of the reasoning behind gathering data from the CAREN system of the subject's normal gait pattern prior to being fitted with the orthosis. Also, I was not utilizing the split-belt treadmill system at different velocities, but was instead using its capability as a tied-belt system. This was selected since the primary objective of the studies was to observe asymmetries induced by the devices on able-bodied subjects, not to aid in the correction of asymmetries [15].

2.6 Limb Dominance

Limb dominance refers to the extremity which is most easily and accurately controlled by a person. Often times, handedness and leg dominance are on the same side of the body. However, there are those, such as ambidextrous persons, that have either opposing sides of limb dominance or are unable to accurately determine dominance. The topic of limb dominance has been discussed as to whether or not asymmetries are exacerbated more so if the dominant side is paralyzed. Previous studies have not been able to conclude as to whether a statistically significant difference exists [36]. As a prior point of interest, I conducted a preliminary experiment to see if limb dominance would be a factor when using a proprioception disrupter. The study, which is referred to in Appendix B produced statistically inconclusive results.

2.7 Proprioception Interference

Proprioception translates into "awareness of one’s self." Essentially, it refers to the capability of a person to discern where a part of his/her body is and how to control it both precisely and accurately. For the purposes of this thesis, I am trying to alter a person’s perception of where the knee location is on the body utilizing the stroke balance simulator, which I also refer to as the Proprioception Interference Apparatus (PIA). Therefore, I am simulating the reduced amount or lack of proprioception that a stroke patient has if they have the symptom of neuromuscular paralysis.

Previous studies involving vibrations to simulate a 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 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 on the affected side [7]. These results, along with other studies, therefore suggested that vibration could be used to interfere with a person’s proprioception [7, 11, 31]. Thus, I decided that the utilization of vibration motors in the stroke balance simulator may prove to disrupt the nerve control of the knee location, especially if the vibrations induced a sensation that was both noticeable and distracting.

Other studies have investigated the effect of TENS on hemiparetic knee spasticity. In these studies, the researchers surmised 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 [20]. It was also observed that the implementation of TENS treatment has the capability to improve the knee flexion torque of those with multiple sclerosis [10].

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 [34]. I included a combination of vibration and TENS in my studies involving proprioception interference so as to discern whether the theory was correct, or rather more prevalently founded by my data.

Figure 2.1: Computer Assisted Rehabilitation Environment

Chapter 3: Stroke Gait Simulator

3.1 Main Contribution

This chapter discusses the stroke gait simulator, also referred to as the knee orthosis with variable stiffness and damping. The design and concept of this work was based upon an unfinished project at the Rehabilitation Engineering and Electromechanical Design Lab, which was for a knee orthosis that could simulate a level of the Modified Ashworth Scale using a rotary damper and a musical wire torsional spring. However, information regarding this project had not been previously patented or published before it had been sequestered in the lab due to lack of resources. My main contribution to this project was a redesign of the orthosis which would allow for multiple levels of the Modified Ashworth Scale on able-bodied persons relatively easily while also being lightweight and cost effective.

These goals led me to design and fabricate multiple iterations of the orthosis, on which I conducted preliminary analyses prior to implementing them on able-bodied subjects. Once I had a functional design for the orthosis, I presented it for design review to my engineering professor and clinical evaluation of the Ashworth level simulated to a physical therapist consultant. I was also responsible for the experimental testing of the new design. The experimental procedure consisted of retrieving data from the baseline gait, gait with the orthosis on, and post orthosis gait from 10 able-bodied subjects. My hypothesis that the knee orthosis would elicit trends commonly found in hemiparetic gait in able-bodied subjects was bolstered by the results of my study as it induced longer time spent in stance phase, greater vertical force, decreased pushoff force, higher braking force, and significantly smaller knee angles. Hysteresis effects were observed, but dissipated rather quickly after the orthosis was removed for an extended period of time [19].

3.2 Experimental Design of the Knee Orthosis

The device in this particular experiment was estimated by a physical therapist to simulate about a 1+ on the Modified Ashworth Scale, which usually relates to a moderate to mild stroke. The preferred material used for the frame of the orthosis was Delrin, a plastic that has material properties similar to that of aluminum. The newly designed and fabricated orthosis has a mounting that has slots and an adjustable connector that allows for the rotary damper mechanism to easily be swapped with a different sized rotary damper, c=8898 g-cm-s/$^\circ$. In order to accommodate for variable stiffness, the orthosis was designed so that the connector piece was to be positioned in the center of the circular portion of a torsion spring, K=0.457 kg/mm, with a deflection angle of 90°, and both the upper and lower portions of the orthosis would have two protruding bolts to lock the spring legs into place. Therefore, it would not be difficult to replace the spring with other springs of various stiffnesses for future testing of different stiffness levels. The design can be seen in Figure 3.1. The damping and stiffness allow for the limited flexion at the knee joint to correspond with the limiting ranges of motion of the varying levels of the Modified Ashworth Scale.

Eight plastic military belt buckles were used as fasteners to firmly secure the orthosis onto the thigh and calf of the subject, as well as around the upper and lower portion surrounding the patella. The straps being placed on the top and bottom portion of the orthosis allowed for it to secure on the subject’s knee more accurately than with a previously used device. It helped to reduce the amount of displacement down the leg due to walking that had occurred in a previous study. This device weighed 0.84 kg, which is less than that of the previous design, which weighed 1.14 kg. A comparative table of design iterations can be seen in Table 3.1.

3.3 Subjects

Five subjects volunteered to participate in this study of their own accord after having the experimental procedure and device described. Each subject went through the consenting process following the approved University of South Florida’s IRB participant consenting process. The physical therapist and researchers adjusted the variable damping and stiffness on the orthosis to

Table 3.1: Design Iterations and Modifications to Stroke Gait Simulator

Iteration Number	Description
1	Lightest design by weight, however moment arm was too small to effectively simulate level
2	Larger moment arm to simulate level, however, holsters were easily moved
3	Level simulated, too much internal friction in rotary section
4	Level simulated, friction reduced via use of PTFE washers

simulate the specified level of the Modified Ashworth Scale. All the 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. One subject, the only female, was significantly shorter than the rest, which may have caused the orthosis to affect her gait more than other subjects since it encompassed a larger area of the subject’s leg.

3.4 Experimental Procedure

Able-bodied subjects were first asked to walk a 10 meter distance so an average baseline walking velocity could be obtained. This distance was marked in a hallway and I followed the subject during three trials, maintaining a comfortable distance while keeping time on a stopwatch. Then, I would find the average of these trials to find a baseline velocity.

Then, the Computer Assisted Rehabilitation ENvironment (CAREN) system was used for testing (Figure 3.2). The CAREN system was utilized to collect baseline data, data from when the orthosis was on, and data from immediately after the orthosis was removed from the subject’s knee location.

Baseline symmetry was tested on the CAREN with the treads set at the subject’s baseline velocity prior to being fitted with the orthosis. The subject would be fitted with a harness, positioned with infrared markers on predesignated areas of the body to aid motion capture, transferred to the platform via the ramp, and connected to the rail. The two treads were set to have the same speed, which was set to the subject's measured overground walking velocity.

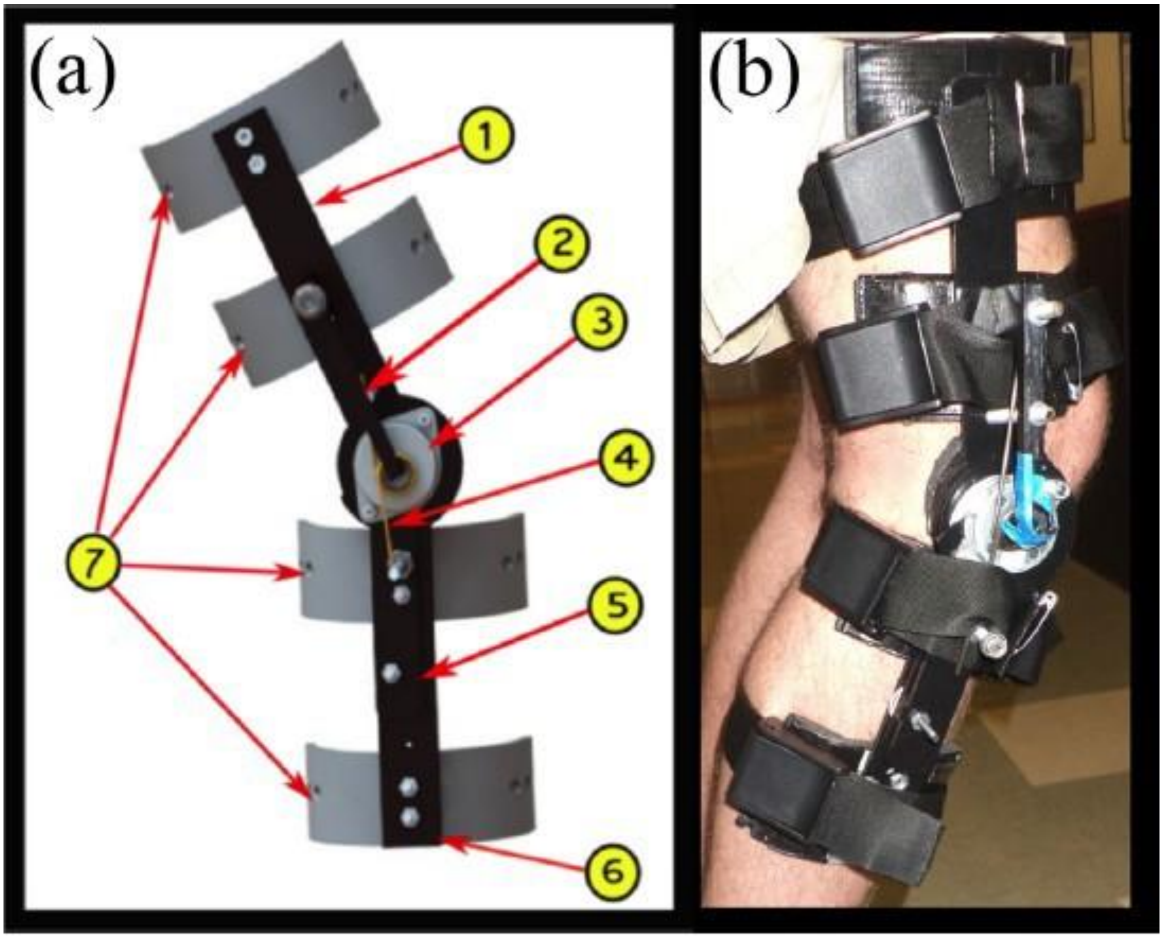

Figure 3.1: Design of Knee Orthosis.(a) SolidWorks Rendering of Knee Orthosis: (1) Upper Rotational Piece of Orthosis, (2) Connector Piece, (3) Rotary Damper, (4) Spring, (5) Damper/Spring Mount, (6) Lower Rotational Piece of Orthosis, (7) Holsters for Calf, Thigh, and Straps. (b) Knee Orthosis on a Subject

The treadmill would begin to move and the subject would be allowed a couple of minutes to get acclimated to the system and make any adjustments prior to data collection. Then, I, as the researcher would be able to collect data on any pre-existing spatial or temporal asymmetries, knee flexion angles, and ground reaction forces over a period of 5 minutes.

After this "baseline walking" data had been collected, the orthosis would be fitted onto the subject's non-dominant leg, and markers were placed on designated locations on the body. A depiction of the device positioned on the subject can be viewed in Figure 3.1. The evaluation

Figure 3.2: Subject on the Computer Assisted Rehabilitation Environment

continued by placing the subject on the CAREN system, harnessing and transferring him to the platform. The system would be programmed to have the split belt treadmill velocities tied together and set at the subject's previously measured baseline velocity. Once the treadmill begins to move, the kinematic and kinetic data are collected and processed to find any spatial or temporal asymmetries, knee flexion angles, and ground reaction forces induced by the orthosis averaged over the period of 10 minutes.

Immediately following the trial with the orthosis on, myself and another researcher would pause the system and remove the orthosis while the subject was still on the treadmill. Post orthosis data would be obtained by having the subject walk on the system for a period of 5 minutes. The expected after effect was an increase in knee flexion of the affected knee and increased force profile that would dissipate within the first minute. Thus, I could begin to discern if asymmetry was being induced through the use of the knee orthosis. This process of obtaining data from the orthosis placed on the non-dominant leg was to be repeated for the orthosis being placed on the dominant leg. Both legs were tested for the purpose of analyzing if limb dominance was a factor to be considered in gait symmetry. The collected data from both legs was then analyzed to determine if the orthosis is a viable device to induce stroke-like gait patterns and asymmetries, which was the hypothesis.

3.5 Results

The results are summarized in Figure 3.3. The measured parameters include step length (SL), step time (ST), average vertical force during stance phase (VF), pushoff force (PF), braking force (BF), and knee angle (KA). Each of these parameters are evaluated at baseline (i.e., when not wearing the stroke simulator), with the stroke simulator on the left leg, and with the stroke simulator on the right leg. The data can be viewed as the first bar of each color representing the baseline asymmetry for that parameter, the second bar representing the asymmetry for the orthosis on the non-dominant left leg, and the third bar being the asymmetry corresponding to the dominant right leg. The percent asymmetry left or right means an increased asymmetry toward that side of the body. Although the data obtained varied from subject to subject due to the fact that each person has an inherent asymmetry, the averages for all subjects are presented to demonstrate the trends associated with wearing the stroke simulator.

The results show that the side with the stroke simulator had more time in stance phase, more vertical force, lower pushoff force, higher braking force, and much smaller knee angles. These are similar characteristics of stroke gait. It can also be seen in Figure 3.3 that the direction of asymmetry for step length, push off, and braking forces are consistent. This may be the sign that the device has no effect on these parameters with respect to the direction of asymmetry. We hypothesize that the reason may be due to limb dominance amongst the subjects.

During the experiment, it was noticed that some subjects tended to extend the knee that was wearing the stroke simulator, especially when it was worn on the non-dominant knee, and there were some hysteresis effects that were observed in the after effect trials. However, there did not appear to be a very large change in the step time and step length. This may have been due to the subjects adapting their gait to accommodate for the hindrances and acclimating to the velocity of the treadmill [19].

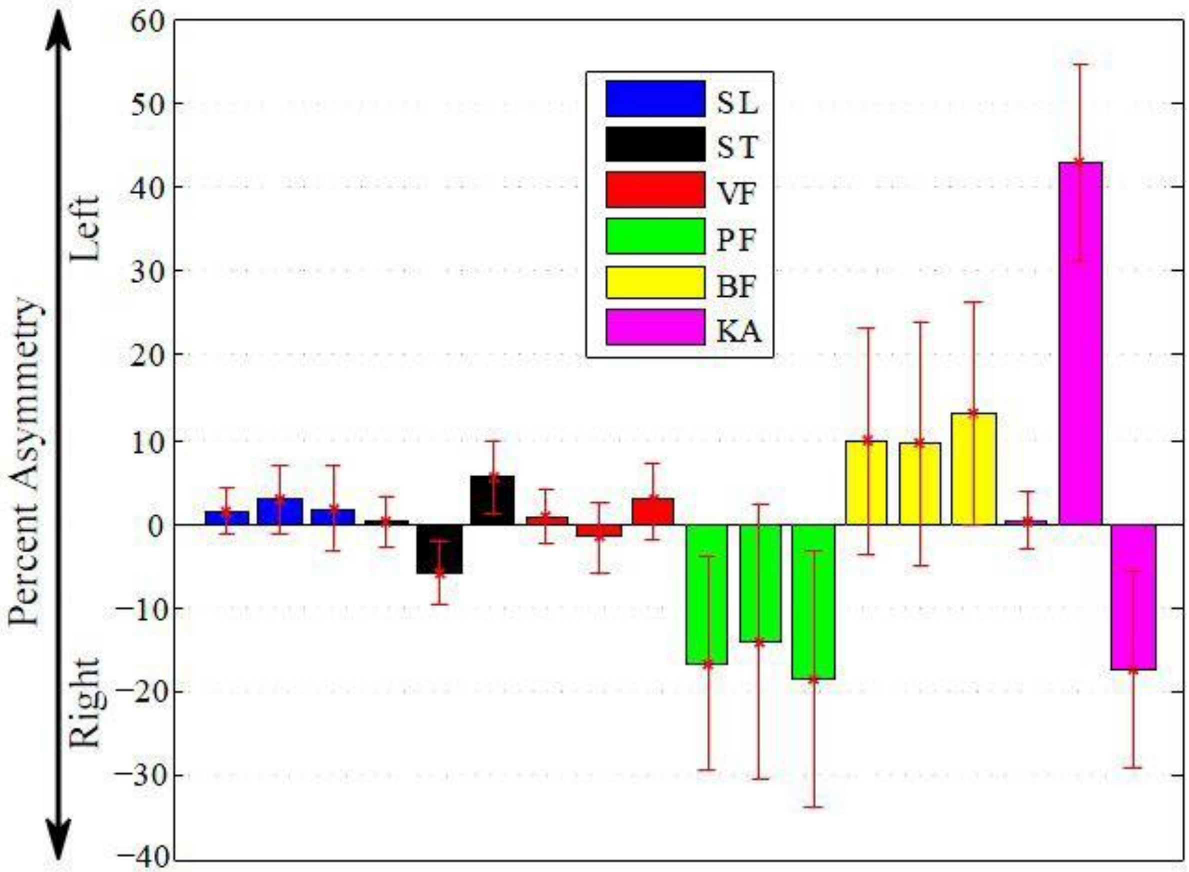

Figure 3.3: Bar Graphs Comparing Asymmetries in Gait Parameters. Among Baseline (lst bars of each color), Simulator on Left Knee (2nd bars of each color), and Simulator on Right Knee Gait Parameters (3rd bars of each color) vs. Left/Right Asymmetries: Step Length (SL), Step Time (ST), Vertical Forces (VF), Pushoff Forces (PF), Braking Forces (BF), and Knee Angles (KA)

Chapter 4: Stroke Balance Simulator

4.1 Main Contribution

This chapter discusses the stroke balance simulator, also referred to as the Proprioception Interference Apparatus (PIA). The design and concept behind this work was based upon a prior project of mine in the graduate level elective course, Haptics. In that course, I developed the Proprioception Illusionistc Haptic Device (PIHD) to be used during walking. The results of the PIHD were not promising for two main reasons. The first cause for concern was the fact that the able-bodied subjects were susceptible to overcoming the interferences while walking. Thus, the results showed that there must have existed a design or placement error with the PIHD as it should not have been that easily overcome. Secondly, there were multiple subjects in that study that believed that the utilization of a knee brace to house the vibration motors had actually caused them to be more aware of their knee location than if the vibration motors had been taped onto them.

The results and critiques from the PIHD led to the design and implementation of the PIA. Firstly, I decided with aid from my major professor that the use of the PIA should be on single leg balance rather than walking, as the mechanics of walking would cause the wearer to overcome the effects of the proprioception disrupter. Secondly, I had discerned that the use of vibration motors may not prove to be sufficient enough to induce a proprioceptive disruption, so I conducted research and decided to utilize both TENS and vibration motors. With the aid of my colleagues as preliminary test subjects, I designed and developed the PIA. After a brief anatomical and physiological research endeavor, I determined what I believed was the optimal arrangement, mode of operation, and position for the PIA.

The goal of the project was to disrupt proprioception while not causing exorbitant amounts of physical pain to the subjects. My undergraduate research assistant and I decided to investigate the following parameters for the various experimental conditions described while balancing: RMS of the position, standard deviations of the forces, and the RMS of the center of pressure. While I was able to visually witness a certain amount of balance disruption, myself and my colleague decided to test for statistical significance for each case via two-way repeated measures with each parameter as the dependent measure and independent factors of eyes open/closed and perturbation (four levels: vibration, TENS, both, and none). The results bolstered prior research that stated visual feedback had a statistical significance in regards to the RMS of positions and standard deviation of forces.

4.2 Design of Proprioception Interference Apparatus (PIA)

The predecessor to the PIA, the Proprioception Illusionistic Haptic Device (PIHD), was used to interfere with proprioception during walking. It utilized a neoprene knee brace, 6 miniature vibration motors, a 5 V DC portable external power supply, and a 8/8/8 Phidget interface kit which can be seen in more detail in Appendix B. Due to design critiques, such as the implementation of a brace causing increased proprioception rather than sensation interference, and subjective results, the device was redesigned in to the PIA. This new design was determined to only be used for balance related studies, as it appeared relatively easy for subjects to overcome any sensation interference in the gait study.

The PIA is comprised of 4 vibration motors connected to a DC portable external power supply which 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. 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, relatively similar locations to those used in the vibration studies [7]. The vibration motors, seen in Figure 4.1, 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 [34]. Since the device is meant to be mobile, it has a portable and rechargeable power supply with a control pad and display. 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 descriptive depiction of the electronic stimulation pulse massager and its components can be viewed in Figure 4.2. The device can be seen attached to an individual’s leg in Figure 4.3.

4.3 Subjects

The sampling size of the experimental group was ten subjects. Subjects were able-bodied persons that varied in size, age, and gender. 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 the 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 my previous conjecture, three of the ten 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.

4.4 Experimental Procedure

The Computer Assisted Rehabilitation ENvironment (CAREN) system, shown in Figure 2.1, was used for experimental testing. 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 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

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.

4.5 Results

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 tested for statistical significance. The graphs of the comparative results between subjects for each experimental parameter can be seen in Figure 4.4, Figure 4.5, and Figure 4.6. 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 [34].

For the position RMS values in Figure 4.4, which depicts the average of the RMS values of all position markers for each subject and trial measured in millimeters, it was surmised 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 the fact that the combination of the two different stimuli made the majority of subjects more able to compensate than in previous 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 effected [34]. 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 as vibration enhanced the majority of the subjects' balance and electronic stimulation reduced it. The results of this study may bolster these conclusions, but there was still not a statistically significant difference between any of the trials with the exception of eyes open versus eyes closed. 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 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 closed. This was discerned via two-way repeated measures 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 statistical difference for eyes (F(1,9)=19.5, p<.05). There was not a statistically significant difference for perturbation.

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 conducted, 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 statistical difference for eyes in the y-direction (F(1,9)=18.4, p<.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 4.5, 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, yet again, a two-way repeated measures, 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), was conducted. No statistical significance was found. As shown in Figure 4.6, the COP values did not significantly differ, even in regards to visual feedback versus no visual feedback.

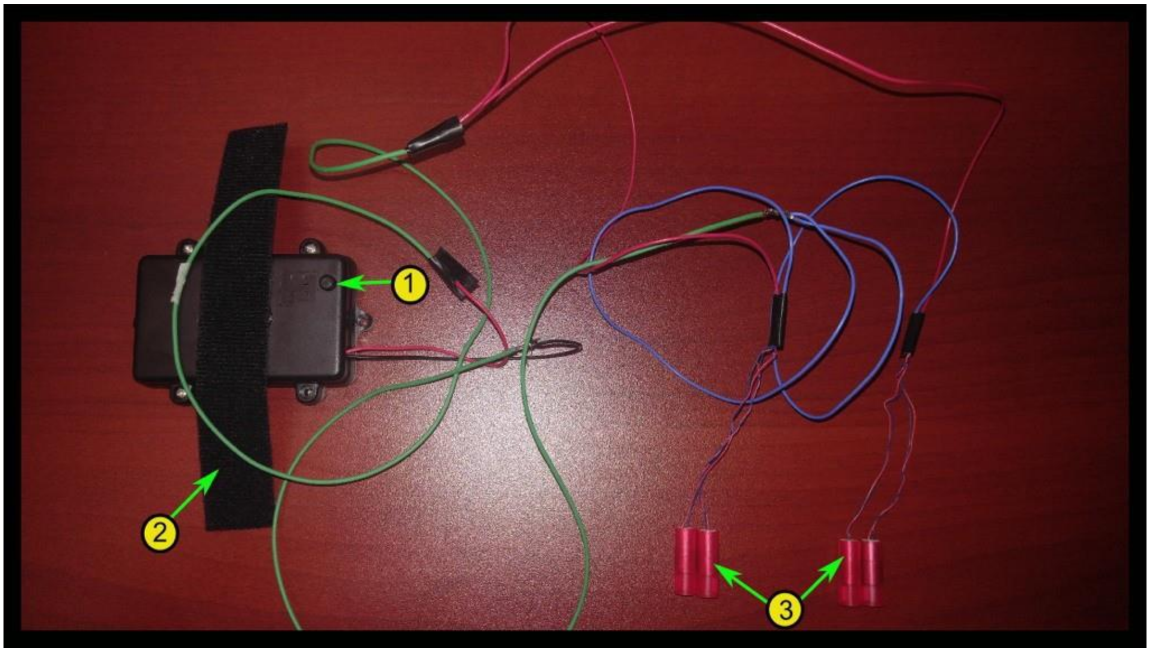

Figure 4.1: Vibration Motor. Component 1 is power button on battery pack. Component 2 is the velcro strap to harness pack to subject's waistline. Component 3 shows the vibration motors.

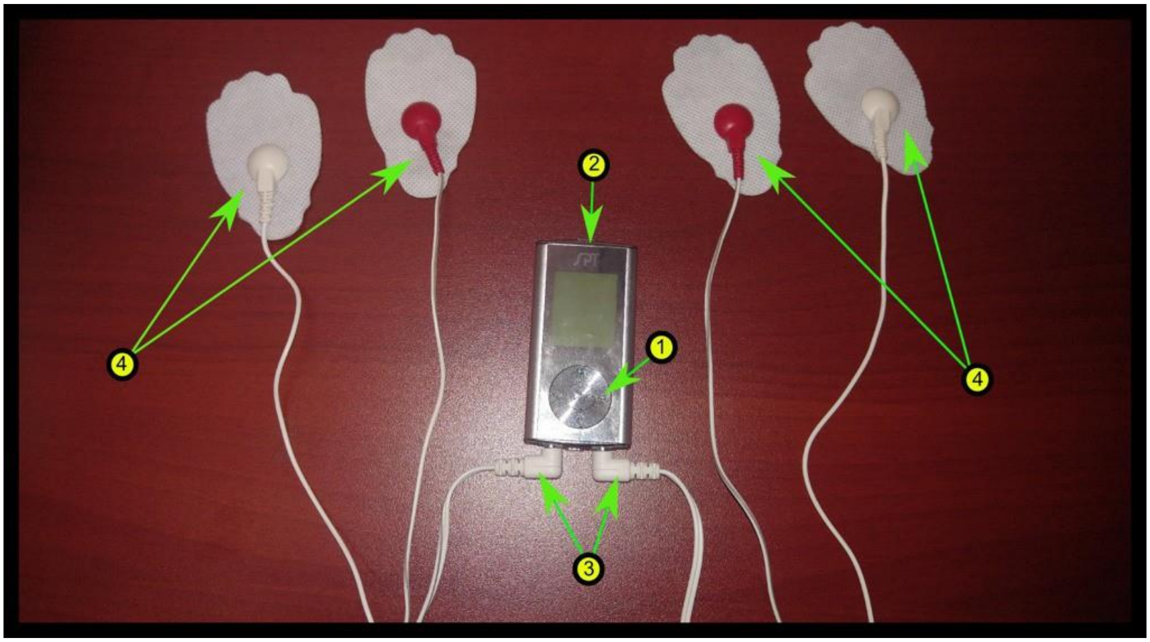

Figure 4.2: SPT Mini Electronic Pulse Massager. Component 1 is the controller. Component 2 is the charger location. Component 3 shows the lead connection locations. Component 4 shows the electrode pads.

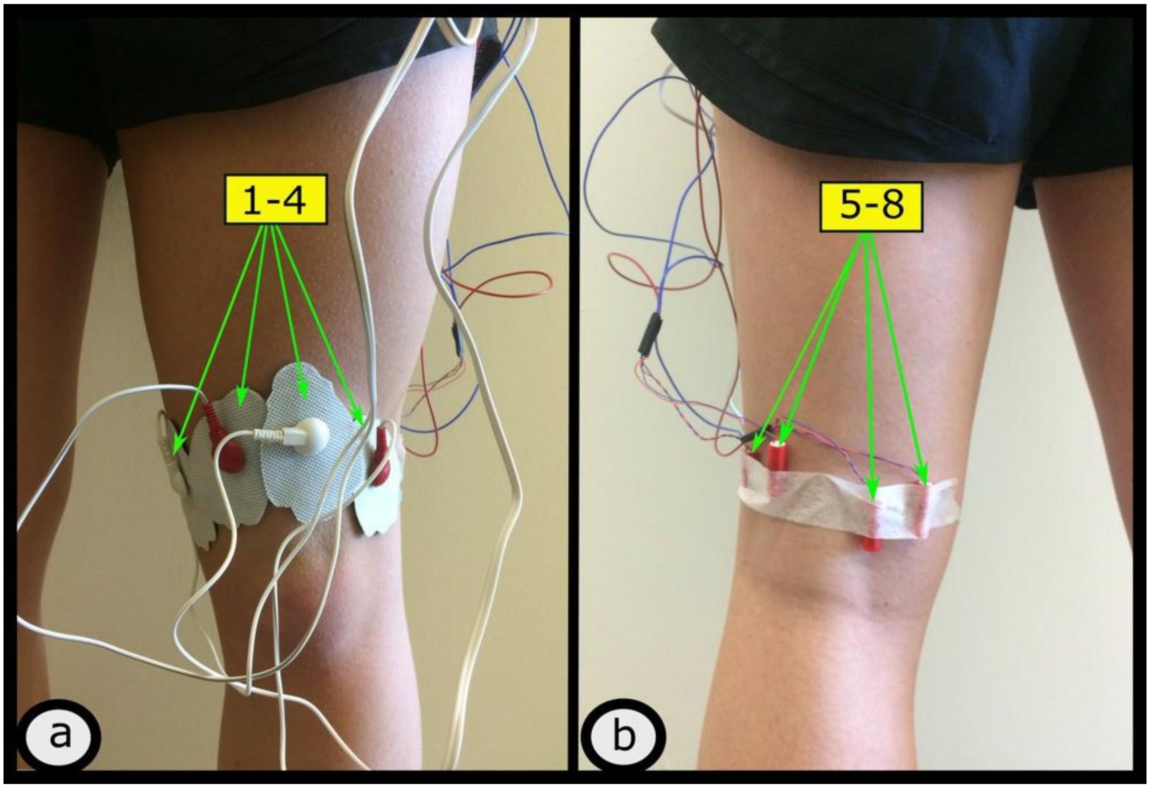

Figure 4.3: Proprioception Interference Apparatus (PIA) on Subject. (a) Front View: Components 1-4 are the positioned electrode pads (b) Back View: Components 5-8 are the meticulously placed vibration motors.

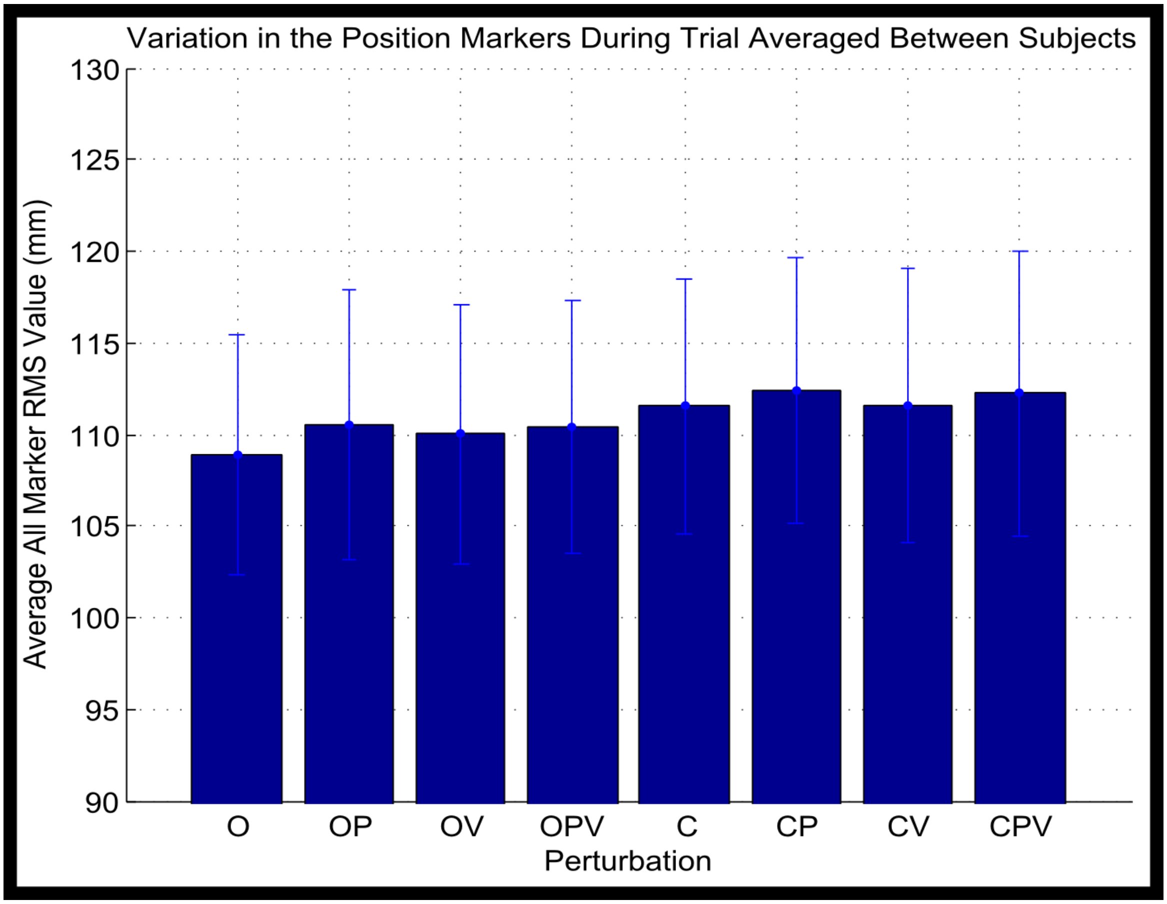

Figure 4.4: Graph of RMS of Marker Position. Explanation of Acronyms: O – Open Eyes, C – Closed Eyes, P – Pulse Massager for TENS, V – Vibration. The error bars represent the standard deviation between the position markers. Position points where the value was equal to zero or greater than 3 standard deviations from the mean were removed. The graph depicts the average of the RMS values of all position markers for each subject and trial measured in millimeters.

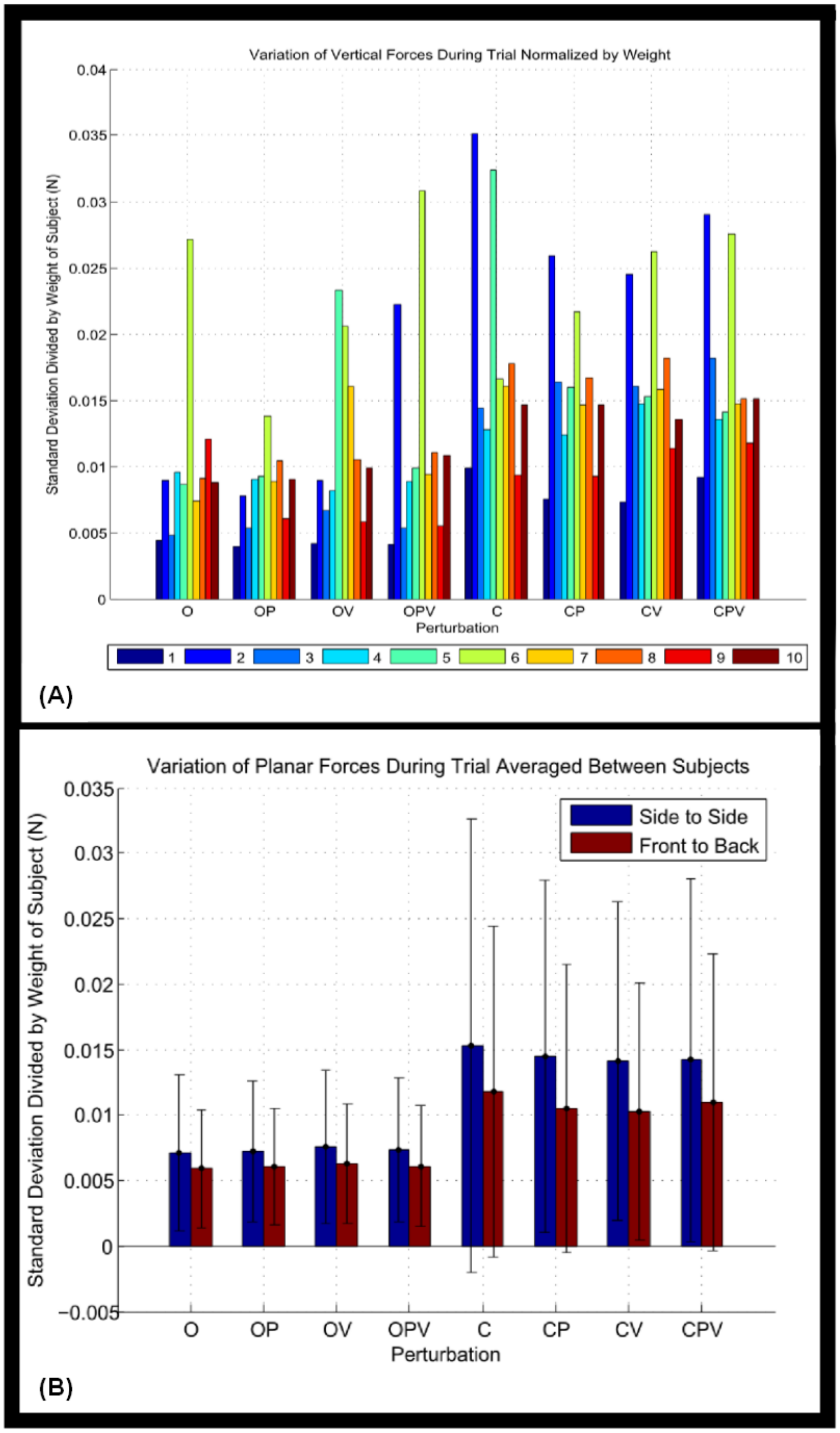

Figure 4.5: Graphs of Standard Deviation of Forces. Explanation of Acronyms: O – Open Eyes, C – Closed Eyes, P – Pulse Massager for TENS, V – Vibration. (A) Standard deviation of vertical forces for each subject/parameter divided by the weight of the subject (N). (B) Standard deviation of x/z forces for each subject/parameter divided by the weight of the subject (N) and then combined with the mean.

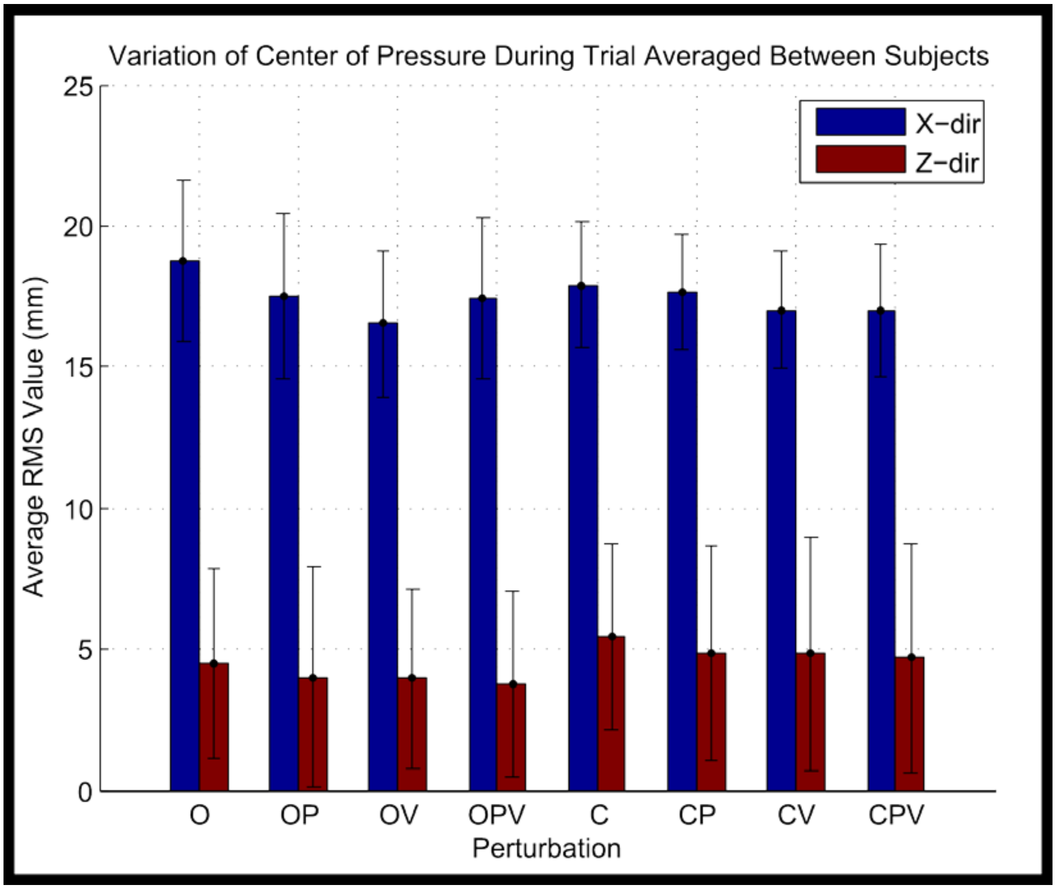

Figure 4.6: Graphs of Centers of Pressure. Explanation of Acronyms: O-Open Eyes, C-Closed Eyes, P-Pulse Massager for TENS, V-Vibration. Depicts the RMS of all x and z COP.

Chapter 5: Conclusions

In conclusion, it appears as though this knee orthosis with variable stiffness and damping may prove to be a viable research device in the study of stroke gait. This is based on the results that showed in multiple cases that it has the capability to alter an able-bodied person's gait, especially in the parameters of vertical forces, pushoff forces, braking forces, and knee angles. It also was able to induce some asymmetries for a short period of no more than a minute immediately after the orthosis was removed.

One possible advancement would be to test these subjects at other levels of the Ashworth Scale. Recently, I have altered the stiffness and damping of the orthosis to generate what I believe would be a 2 rating on the scale. Preliminary evaluation has concurred that the alteration has the potential to be closer to a 2+ or 3, but further modification and evaluation is necessary prior to the commencement of a new set of experimental procedures. The study could be further expanded upon via testing a larger number of subjects with varying dominant legs. It was actually somewhat surprising that not a single subject in the current study claimed to have a dominant left leg. It would be interesting to see if and how data from such a subject would differ from that of a right leg dominant person.

In regards to the stroke balance simulator, there are multiple steps that can be taken to improve and expand upon this study. First, the design of the P. I.A. 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.

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. This hypothesis is bolstered by a related TENS study on the hand, the researchers determined that the Pacinian corpuscles were actively disrupting proprioception when the stimuli was closer to 300 Hz [35].

Another way to enhance the sensation could be the implementation of larger, more powerful vibration motors or stronger TENS modes. These would most definitely cause the sensations on the tendons surrounding the knee to be more noticeable. These applicators could once again be meticulously placed on possibly more sensitive locations 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.

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Appendix B: Unpublished Research Paper

Proprioception Illusionistic Haptic Device for the Knee

Christina-Anne Lahiff[1]

***Abstract*— Individuals with stroke have neuromuscular weakness or paralysis on one side of the body caused by some muscles disengaging and overexciting other muscles. Hyperextension of the knee joint and complete lack of plantar flexion of the ankle joint are common symptoms of stroke. This project involved the creation and implementation of a haptic device that utilizes vibration to induce a proprioceptive illusion around the knee joint, as if a subject has a version of hemiparesis. The main goal of the project was to discern whether a device of relatively the same design could be utilized as a viable research instrument to simulate stroke-like gait in able-bodied subjects.**

A comparison between how the dominant leg was affected by the haptic device versus how the non-dominant leg was affected was investigated as well. It was concluded that the device did have a significant effect on the velocities of the gait of the subjects, but it could not be surmised if it had significantly different effect on the dominant leg versus the non-dominant leg. A qualitative analysis regarding the sensations experienced by the subjects and their levels of comfort between the trials was also conducted.

I. INTRODUCTION

The ultimate goal of this research is to aid individuals with asymmetric impairments in walking with effective gait patterns that balance the gait 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, which is a portable knee orthosis that equipped with six miniature vibration motors, to evaluate the effects of asymmetric impairments on altering the gait patterns of healthy, able-bodied subjects.

The main concept behind the utilization of vibration motors is the idea of altering an able-bodied person’s proprioception, which translates into ”awareness of oneself.” 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 does not prove to be a prudent decision on behalf of a researcher to continually put those persons who are affected by stroke under the physical duress or stress to obtain data on how the stroke effected them. Also, using healthy subjects allows for a reduction of error and uncertainty that would be associated with the variability of disabled individuals. This device, once optimized, could pose to be a useful instrument when it comes to researching gait asymmetries induced by stroke.

Another intriguing aspect that was investigated via this study was the idea of limb dominance and whether it plays a significant role in the research of stroke-like gait asymmetry. This was deemed to be an interesting avenue to research since stroke is unpredictable and can affect either side of the body. It was surmised that there may exist significant differences in velocities, comfort levels, and sensations between the dominant and non-dominant legs. It was hypothesized that the dominant leg would be less affected than the non-dominant since that is the side of the body that has been determined to be the most easily and accurately controllable by the central nervous system. However, it cannot be confidently assumed that this side would adapt to and overcome a perturbation or hindrance in a more timely manner than that of the non-dominant side. As a matter of fact, some studies regarding motor lateralization have shown that the opposite was true in certain cases. They believed that this was due to the tendency of the non- dominant side to react quicker to corrective or impedance control mechanisms [1].

II. BACKGROUND

Since stroke is a nondiscriminatory occurrence, it can affect anyone at any time [2]. Stroke survivors have a hard time adapting to their new life, especially if they have the side effect of hemiparesis, which is partial neuromuscular paralysis which occurs most generally on one side of the body. Hemiparesis often results in asymmetric gait that requires the utilization of various forms of rehabilitation techniques and devices [3].

The coordinated limb control during walking is frequently impaired following central nervous system damage, such as suffering a stroke or traumatic brain injury, or physical changes, such as utilization of a cane or wearing a prosthesis. Able-bodied adults generally take equal-sized steps with each leg, offset by about 180 degrees. This offset is commonly referred to as out-of-phase coordination. Individuals who have had a stroke or lower-limb amputation often diverge from perfectly out-of-phase walking and have asymmetries in temporal measure, such as time spent in double-limb support, and spatial measures, such as step length, of interlimb coordination [4], [5]. Asymmetric gait patterns are common in stroke victims and amputees, but are more noticeably evident in transfemoral amputees, which are amputees that have lost their leg above the knee joint location [6], [7]. The asymmetry causes wearers to exert a large amount of effort in order to try to compensate for unwanted, uncontrollable motions [8]. In the case of stroke victims, the propulsive force of the paretic limb is less than that of the nonpareticlimb. Thus, the work and the power of the paretic plantar flexors are in turn also lessened [4], [9]. Vertical ground re- action forces also are decreased on the paretic limb relative to the nonparetic limb [10]. This is emulated in the depreciated weight-bearing of the paretic limb.

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*This work was not supported by any organization

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Previous studies involving vibrations to simulate a proprioceptive illusion 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 that induced a proprioceptive illusion 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 on the affected side [11]. This was the basis for the concept of creating the Proprioception Illusionistic Haptic Device for the knee. It was deduced that such a device would be optimal to use on the knee location since, like the elbow, it too is a joint with various tendons that could be vibrated to generate different sensations. However, for this study in particular, the researcher was only concerned with vibrating the entire joint to induce a tingling or partially numb sensation. It is unclear whether simulating stroke-like gait by vibrating different tendons in different sequences would provide intriguing results.

III. METHODS

A. Experimental Design of Propioception Illusionistic Hap- tic Device (PIHD)

The device is comprised of a neoprene knee brace with adjustable velcro straps, 6 miniature vibration motors, a 5 V DC portable external power supply, and a 8/8/8 Phidget interface kit. The knee brace had to be adjustable so that it could fit a wide range of thigh and calf circumferences. The material properties of the neoprene allow for the brace to be relatively comfortable, flexible, lightweight, and breathable. However, it also has the tendency to accumulate sweat, in which case, it can be sanitized easily. A similar brace to the one utilized can be seen in an unaltered state in Figure 1. The miniature vibration motors, seen in Figure 2, were chosen due their small size and capability to produce a small, yet noticeable vibration from a portable battery pack. Since the device is meant to be mobile, a portable and rechargeable 5 V DC battery pack was selected to be the power supply. The Phidget was chosen to act as an interface between the motors and the power supply. Phidgets, like Arduinos, are typically used to program and control different electronically powered devices. However, for the design of this particular device, that characteristic of programming was not utilized due to various constraints. A descriptive depiction of the PIHD and its components can be viewed in Figure 3.

B. Subjects

The sampling size of the experimental group was limited to nine subjects due to time constraints. Subjects were able- bodied persons that varied in size, age, and gender. They volunteered of their own accord to participate in this study after being notified of the design of the device and experi- mental procedure. It just so happened that all the 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. Only one subject had qualms coming to this conclusion since he was ambidextrous, but believed that he was capable enough to discern between his leg dominance. In contrast, one aspect in which the subjects differed was in the type of clothing that they were wearing at the time of the experiment. Four of the subjects wore shorts above the knee in length and 5 wore pants that extended below the knee. Clothing was noted as part of the qualitative

Fig. 1. Unaltered Neoprene Knee Brace from McDavid

Fig. 2. Miniature Vibration Motor

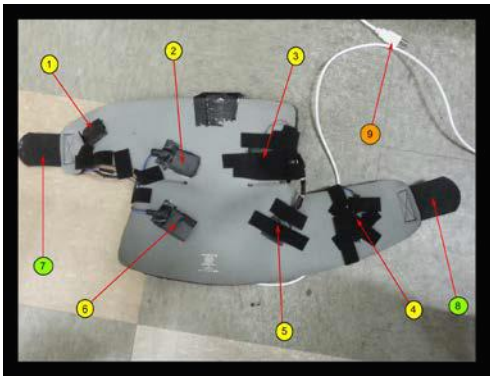


Fig. 3. Depiction of Proprioception Illusionistic Haptic Device (PIHD)- Components 1-6 are the meticulously placed miniature vibration motors. Components 7 and 8 show the adjustable velcro straps. Component 9 shows the adapter of the device to connect to the power supply.

Fig. 4. Depiction of Proprioception Illusionistic Haptic Device (PIHD) On Subject- (a) Front View of PIHD On Subject (b) Side View of PIHD On Subject

data acquisition since it was deemed by the author to be a concern, especially if it were found to decrease the affect or sensation caused by the PIHD. In further regards to the acquisition of sensation and comfort levels, one subject had noted a prior knee injury. However, it was determined by both the subject and the researcher that this would not affect the results of this study because it had occurred multiple years prior and the subject had been almost entirely rehabilitated without any symptoms surfacing from the injury since then.

C. *Experimental Procedure*

Able-bodied subjects were first asked to walk a 10 meter distance three times so that a baseline walking velocity could be obtained by the researcher. This distance was marked in a hallway and the researcher followed the subject during trials, maintaining a comfortable distance while keeping time on a stopwatch. Following the retrieval of the baseline velocity, the subject had the haptic device positioned on the knee location of the subject's dominant leg by the researcher and performed the same task of walking a 10 meter distance three times so that average velocity for the PIHD on the dominant limb could be obtained. A depiction of the device positioned on the subject can be viewed in Figure 4. This procedure was again repeated for the device being positioned on the non-dominant leg. Following the active portion of the experiment, subjects filled out a qualitative survey created on SurveyMonkey on a laptop in the room adjacent to the testing hallway. The survey consisted of seven multiple choice questions and additional comment boxes to be analyzed after the experimental data retrieval had concluded.

IV. RESULTS

A. *Quantitative Results*

As previously mentioned, this study involved the analysis of both quantitative and qualitative data. For the quantitative data, the subjects' velocities for baseline, device on dominant leg, and device on non-dominant were analyzed using ANOVA in MATLAB. From the Probability Table that was generated and can be seen in Table I, one can discern that the F-values were greater than 1 which signifies that there exist differences between velocities, subjects, and the location of the device during each trial. Therefore, post-hoc analysis was conducted to further investigate the significance of the differences. For the velocities, there did exist a significant difference between the velocities and subjects, especially between Subject 8 and Subject 9. As an aside, neither of these two subjects were the subject that had previously noted a prior inconsequential knee injury. The post-hoc analysis graph can be witnessed in Figure 5. There also existed a slight, but not very significant difference between the velocities and the location of the device at the time of the experiment. This correlation can be seen in Figure 6. It was relatively surprising that there was a somewhat noticeable and yet not significant difference between the trials with and without the placement of proprioception illusionistic haptic device.

B. *Qualitative Results*

For the qualitative data, the results were analyzed and found to be rather subjective. The subjects were presented this survey in a not pressured and relaxed environment. The multiple choice versions of questions that were posed on the electronic survey can be seen below. The written comments are discussed at a later point in this section.

- Today, I am wearing...
- I have a prior knee injury or physical disability.
- My assumed ”dominant” leg is my...
- On a scale from 0-7, 0 being not affected at all and 7 being extremely affected, I would rate the effect of the device on my ”dominant” leg as...
- On a scale from 0-7, 0 being not affected at all and 7 being extremely affected, I would rate the effect of the device on my ”non-dominant” leg as...
- On a scale from 0-7, 0 being not uncomfortable at all and 7 being extremely uncomfortable, I would rate the

effect of the device on my ”dominant” leg as...

- On a scale from 0-7, 0 being not uncomfortable at all and 7 being extremely uncomfortable, I would rate the effect of the device on my ”non-dominant” leg as...

The statistical results obtained from the survey are displayed below.

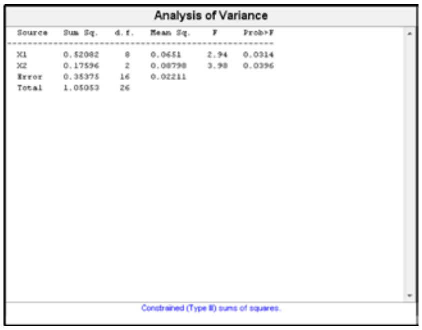
- Five out of the nine subjects wore long pants at the time of the test.
- One subject, as previously noted, had a knee injury.
- All of the subjects had a dominant right leg.
- On a scale from 0-7, 0 being not affected at all and 7 being extremely affected, eight subjects rated that the effect of the device on their ”dominant” leg was between 0 and 3. One subject rated it as 4.
- On a scale from 0-7, 0 being not affected at all and 7 being extremely affected, two subjects would rate the effect of the device on their ”non-dominant” leg as 0. Six subjects rated it between 2 and 6. One subject rated it as 5.
- On a scale from 0-7, 0 being not uncomfortable at all and 7 being extremely uncomfortable, three subjects rated the effect of the device on their ”dominant” leg as 0. One subject rated it as 1. Both ratings of 4 and 5 received one subject vote each. The highest rating for this question, a raating of 5, received three subject votes.
- On a scale from 0-7, 0 being not uncomfortable at all and 7 being extremely uncomfortable, three subjects rated the effect of the device on their ”non-dominant” leg as between 0 and 1. Five subjects rated it between 4 and 5, and one subject rated it as 6.

From these responses, one can see that the results proved to be very subjective. Many subjects noted that they felt very little or no effect of the device on their gait at all. However, during testing, the researcher visually noticed that many subjects had the tendency to limit their knee flexion and take quicker steps when certain subjects were wearing the device. However, a single person noting slight changes in knee spasticity based on visual stimuli is not a valid source. There are multiple considerations that must be taken into account when analyzing these results. One in particular that should be mentioned was that during a few trials with subjects, the device’s connection to the battery would be lost at times due to the Phidget board bending with the gait induced movement of the leg. This would cause the device to hault its vibrations until either the Phidget board returned to a flattened state while the subject took another step, or it was repositioned by the researcher. This may have resulted in lower ratings regarding how each leg how each person felt their leg was affected.

Another concern which should be addressed was that in the comment portion of the survey, many subjects,especially those that wore shorts, noted that the device induced a slight tingling sensation. This sensation is associated with the type of reaction that the researcher had wanted to simulate, which shows that the device shows some promise in that respect. However, a few of those participants that wore shorts also noted that the device itself was somewhat uncomfortable due to the velcro rubbing against their skin, which may have affected their ratings.

TABLE I

ANOVA PROBABILITY TABLE: HERE, X1 SIGNIFIES THE SUBJECT NUMBER AND X2 SIGNIFIES THE LOCATION OF THE PIHD AT THE TIME OF THE TRIAL



Analysis of Variance

```
Source   Sum Sq.   d.f.   Mean Sq.     F     Prob>F
-----------------------------------------------------
X1       0.52082     8    0.0651     2.94   0.0314
X2       0.17596     2    0.08798    3.98   0.0396
Error    0.35375    16    0.02211
Total    1.05053    26
```

Constrained (Type III) sums of squares.

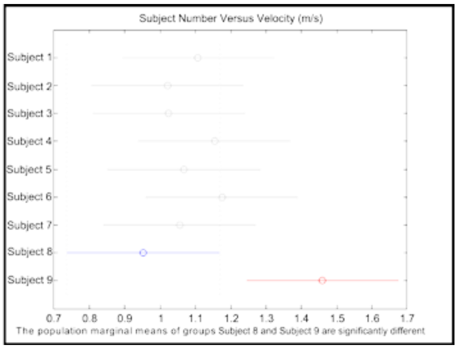


Fig. 5. Post-hoc Graphical Analysis of Subjects

V. FUTURE WORKS

There are multiple steps that can be taken to improve and expand upon this study. First, the design of the Proprioception Illusionistic Haptic Device needs to be enhanced. It needs to have the rather large 8/8/8 Phidget Interface replaced by another, smaller interface or it needs to be secured properly to the neoprene knee brace. This would help to eliminate the issue regarding a loss of power to the vibration motors that occurred multiple times during testing. It would also further reduce the weight of the device slighlty. Secondly, the sensation induced by the device needs to significantly heightened. As the results showed, only a few of the subjects experienced the desired tingling or numbing sensation. This sensation can be heightened in a number of ways. One that immediately comes to mind is the utilization of a higher voltage, portable power source. The current design with the 5 V DC motors was just enough to power the six motors that were utilized. This resulted in continually recharging batteries in between subjects, which

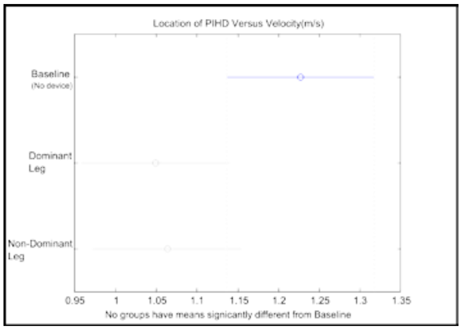


Fig. 6. Post-hoc Graphical Analysis of Location of PIHD

was not energy or time efficient. Also, a larger power source would provide the researcher with more confidence that the participants in the study were being subjected to the same strength of vibrations. This was not the case during testing since the researcher was unsure if the subjects experienced different strengths of vibrations depending on how much life was left in the battery pack.

Another way to enhance the sensation would most likely 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 neoprene brace to isolate the knee from the rest of the leg.

A third way of improving and expanding on this study would be to conduct it in the Computer Assisted Rehabil- itation ENvironment, also known as the CAREN system. The CAREN system is a rehabilitative environment that has a split-belt treadmill system mounted on a six-degree of freedom motion base with motion capture and force plates. This system would allow the researcher to collect force and range of motion data of the asymmetric gait of the subjects, as well as control and monitor their velocities. This system has been utilized in previous stroke-like gait simulations as depicted in Figure 7, and therefore will most likely prove to be beneficial for testing this device.

Finally, the study could be further expanded upon via testing larger number of subjects with varying dominant legs. It was actually somewhat surprising that not a single subject in the current study claimed to have a dominant left leg. It would be interesting to see if data from such a subject would differ from that of a right leg dominant person and how.

ACKNOWLEDGMENT

I would like to thank Dr. Reed for commissioning this work and aiding in its completion.

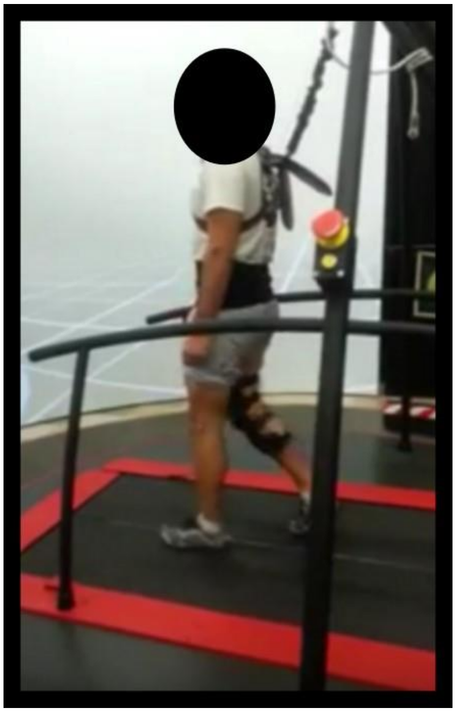


Fig. 7. Related Stroke-Like Gait Study Subject on CAREN

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