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Knee Orthosis with Variable Stiffness and Damping that Simulates Hemiparetic Gait

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Abstract— **Individuals with unilateral stroke have neuromuscular weakness or paralysis on one side of the body caused by some muscles disengaging and others overexciting. Hyperextension of the knee joint and complete lack of plantar flexion of the ankle joint are common symptoms of stroke. This paper 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 rehabilitation device for people with stroke since it has been designed to induce larger knee flexion as an after effect. 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.

I. INTRODUCTION

This paper investigates the design and effects of wearing a stroke simulator. The stroke simulator 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 [12], but it has not been quantified in terms of numerical values for stiffness and damping levels. The eventual quantification of the Modified Ashworth Scale would allow for a more personalized design of orthotics that could aid rehabilitation. Figure 1 shows the knee orthosis prototype design. In this preliminary experiment, we study 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 [13], 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 pain and premature deterioration of joints in individuals with stroke and also cause stresses at the residual limb socket in amputees.

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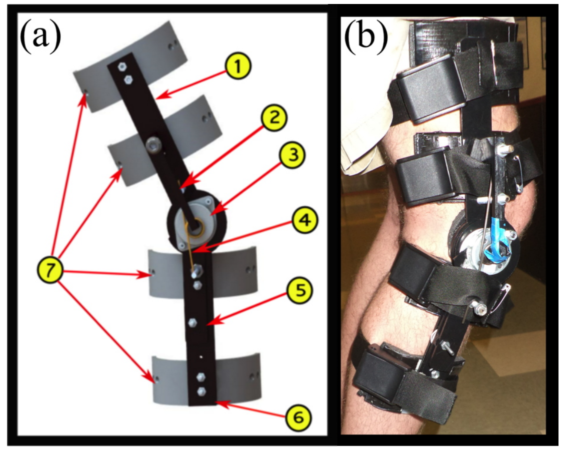

Fig. 1. **(a)** SolidWorks rendering of knee orthosis: (1) Upper rotational piece of orthosis, (2) Connector piece, (3) Rotary damper, (4) Spring, (5) Damper/spring mount, (6) Lower rotational piece of orthosis, (7) Holsters for calf, thigh, and straps. **(b)** Knee Orthosis fit on a subject

Another intriguing aspect that was investigated via this study 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 [1].

II. BACKGROUND

The coordinated limb control during walking is frequently impaired following central nervous system damage, such as 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 measures (e.g., time spent in double-limb support), spatial measures (e.g., step length), or interlimb coordination [2][3]. Asymmetric gait patterns are common in individuals with stroke and amputations, but are more noticeably evident in transfemoral amputees [4][5]. The asymmetry causes wearers to exert a large amount of effort in order to compensate for unintended motions [6]. In the case of individuals with stroke, 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 [2][7]. Vertical ground reaction forces also are decreased on the paretic limb relative to the nonparetic limb [8]. This is emulated in the decreased weight-bearing of the paretic limb.

Current popular asymmetric gait rehabilitation methods include circular treadmill locomotion [14], split-belt treadmills [15], split-motion training [16], rhythmic cuing [17], balance training [9][3], and others [19]. 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 [20]. Recent work investigating gait rehabilitation has had a principle 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 [21][22][23]. Symmetry, in contrast, measures the quality of the gait pattern [24][25]. Normal gait has been found to be generally symmetric in the kinematics, dynamics, vertical forces, and spatiotemporal parameters between the two legs [26][27].

III. METHODS

A. Experimental Design of the Knee Orthosis

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 device in this particular experiment was estimated 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, $\zeta = 8898\,\text{g-cm-s}/^{\circ}$. 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, $K = 0.457\,\text{kg/mm}$, 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 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.

B. 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 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.

C. Experimental Procedure

Able-bodied subjects were first asked to walk a 10 meter distance so an average baseline walking velocity could be obtained by the researcher. This distance was marked in a hallway and the researcher followed the subject during three trials, maintaining a comfortable distance while keeping time on a stopwatch. Then, the researcher 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 2). 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. The split-belt treadmill system has two separate belts that are able to move at two different velocities. Split-belt treadmills

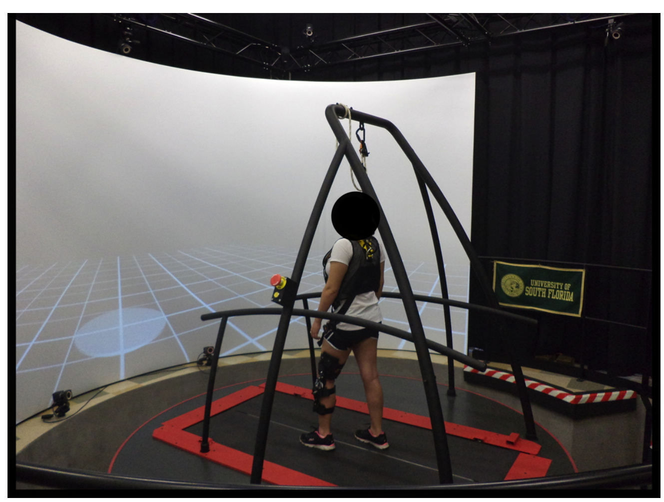

Fig. 2. Subject on the Computer Assisted Rehabilitation Environment

have often been utilized for rehabilitation of stroke patients that have hemiplegia due to their ability to push one foot at a faster rate than the other, thus aiding in the correction of asymmetric gait patterns [3]. Although the split-belts were not used, future tests will use the split-belt treadmill with the stroke simulator to evaluate the combined effects. Spatial and temporal asymmetries in gait occur when the step length of one foot is not equivalent to that of the other [28]. While more exaggerated asymmetries occur in stroke patients and those who possess central nervous system damage, some asymmetries are inherent in able-bodied persons.

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. 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, 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 2. The evaluation 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, the 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 that the researcher would witness an increase in knee flexion of the affected knee and increased force profile that would dissipate within the first minute. Thus, the researcher 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.

IV. RESULTS

The results are summarized in Figure 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 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 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

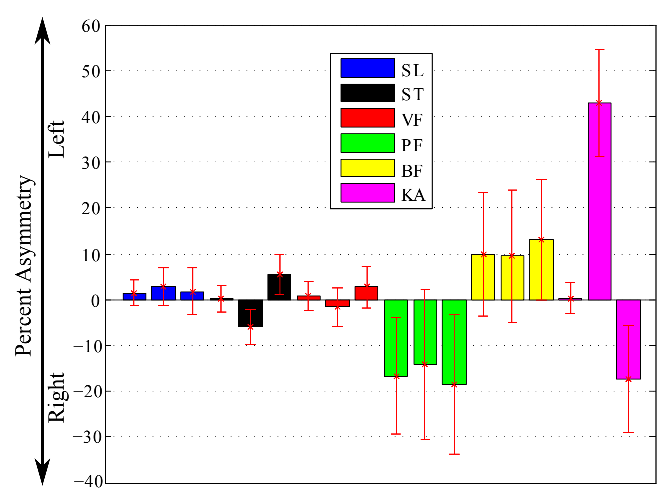

Fig. 3. Bar Graphs Comparing Asymmetries in Gait Parameters Among Baseline (1st bars of each color), Simulator on Left Knee (2nd bars of each color), and Simulator on Right Knee Gait Parameters (3rd bars of each color) vs. Left/Right Asymmetries: Step Length (SL), Step Time (ST), Vertical Forces (VF), Pushoff Forces (PF), Braking Forces (BF), and Knee Angles (KA)

length. This may have been due the subjects adapting their gait to accommodate for the hindrances and acclimating to the velocity of the treadmill.

The side the stroke simulator was worn on made a difference in the affect. After the orthosis had been removed, the non-dominant side returned to the baseline gait pattern slower. The stroke simulator also increased the knee flexion angle immediately after it had been removed on both legs (i.e., an after effect), but was much more pronounced on the non-dominant side. Further study is needed quantify the extent of this observed after-effect.

V. CONCLUSIONS AND FUTURE WORK

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. 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 and how data from such a subject would differ from that of a right leg dominant person.

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