EXAMINING SPASTICITY AFTER SPINAL CORD INJURY USING A NOVEL ROBOTIC ASSESSMENT

by

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DOCTOR OF SCIENCE IN PHYSICAL THERAPY

ABSTRACT

This study investigated a novel robotic assessment of spasticity resulting from a spinal cord injury (SCI). Torque data was analyzed to provide a single measure spasticity score. Three participants with motor incomplete SCI and resultant spasticity were compared to three non-injured participants (NI) using three different angular velocities of passive lower extremity movement in the Lokomat gait orthosis. The mean spasticity scores (NI vs. SCI) at 120°/s, 180°/s, and 240°/s were: 0.41 ± 0.30 vs. 3.70 ± 2.07; 0.65 ± 0.49 vs. 4.33 ± 3.57; and 1.55 ± 1.16 vs. 5.26 ± 3.99, respectively. Mean surface electrode electromyography measures (NI vs. SCI) during the passive movement at each velocity were the following: 0.73 ± 0.11 mv/s vs. 5.13 ± 3.12 mv/s; 0.69 ± 0.10 mv/s vs. 4.01 ± 3.18 mv/s; and 0.75 ± 0.13 mv/s vs. 5.08 ± 2.90 mv/s, respectively. A general trend was found of increasing spasticity score with increasing joint angular velocity. These preliminary results show that the torque-derived spasticity score used here may offer an objective, quantitative method for characterizing and tracking spasticity.

Key Words: electromyography, robotic assessment, spasticity, spasticity score, spinal cord injury
DEDICATION

This dissertation is dedicated to my husband, parents, extended family, and friends who have all shown their love and support during this journey. I also dedicate this work to the Director and faculty of the UAB DScPT program for their guidance and patience throughout this experience. I hope to make you all proud!
ACKNOWLEDGEMENTS

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LIST OF ABBREVIATIONS

ADL activities of daily living
AIS ASIA Impairment Scale
BWSLT body-weight supported locomotor training
EMG electromyography
MAS Modified Ashworth Scale
MSE mean squared error
NI non-injured
RMS root mean squared
SCATS Spinal Cord Assessment Tool of Spastic Reflexes
SCI spinal cord injury
INTRODUCTION

Spasticity is a common sequela of spinal cord injury (SCI) with 78-93% of those with tetraplegia and 72-73% of those with paraplegia reporting symptoms of spasticity more than one year post-injury.\textsuperscript{1} The European SPASM network\textsuperscript{2} has defined spasticity as “disordered sensori-motor control, resulting from an upper motor neuron lesion, presenting as intermittent or sustained involuntary activation of muscles.” Measurement of this “involuntary activation of muscles” has been an elusive endeavor for clinicians and researchers. Spasticity has been measured with clinical, biomechanical, and electrophysiological assessments - typically in supine, prone, or sitting – with each type of assessment having its own limitations. Many of these measures use passive joint movements during testing. The resistance detected during this passive movement includes both neural and musculoskeletal components. Currently, a single clinical or research measure cannot distinguish the contribution of each of these components to the presentation of the spasticity. The ability to accurately quantify muscle spasms would provide a more complete assessment of impairments and functional limitations, leading to appropriate treatment selections.

The Ashworth Scale and Modified Ashworth Scale are commonly used in the clinic and even in clinical research as a subjective, ordinal measure of spasticity, despite their poor intra- and inter-rater reliability, construct validity, and sensitivity to change.\textsuperscript{2-5} Sköld et al.\textsuperscript{1} found that the Modified Ashworth Scale elicited spasticity in only 60% of the participants,
demonstrating the importance of finding other measures to capture spasticity. A more recent clinical assessment of spasticity called the Spinal Cord Assessment Tool of Spastic Reflexes (SCATS) has been tested and found to have good reliability. However, Wirz et al. found there were no significant reductions in Ashworth Scale scores or those of the flexor spasm or clonus tests of the SCATS following body weight supported locomotor training in a group of people with chronic, motor incomplete SCI, suggesting it too may not be sensitive to change.

Biomechanical tests for spasticity include isokinetic and hand-held dynamometry (also known as myometry). Studies using isokinetic dynamometry comparing torque resistance to passive movement between people with and without SCI have demonstrated mixed results with some even showing the non-injured group having greater spasticity than those with SCI. The protocols of these studies include movements at differing velocities and differing numbers of testing repetitions, so results are difficult to compare. Lamontagne et al. reported that hand-held dynamometry has been shown to have high intra-rater reliability, but moderate inter-rater reliability due to different directions of stretch between raters. In a small group of people with chronic SCI, it has been shown that hand-held dynamometry had greater variability, was less repeatable, and underestimated the neurological aspects of torque at both low (5°/s) and high (180°/s) velocities compared to isokinetic dynamometry at the ankle. Electrophysiological tests include the H-reflex and/or electromyography (EMG). The H-reflex is the gold standard in research for neural excitability, but is difficult to use clinically. EMG has been recommended during passive movement testing to distinguish neurological aspects of
resistive torque from musculo-tendinous stiffness.\textsuperscript{13,14} Biomechanical and
electrophysiological tests are often expensive and difficult to implement in the clinic.

Currently, L-STIFF is a biomechanical, commercially available assessment tool used
with the Lokomat to evaluate proximal lower extremity resistance to passive movement
in the clinic.\textsuperscript{15,16} This resistance measure includes both neuropathological and tissue
mechanical sources. During hip and knee flexion and extension movement patterns,
sensors within these Lokomat joints record the resistance of the limb to the passive
angular range of motion at three specified angular velocities (30\degree/s, 60\degree/s, and 120\degree/s).
The current L-STIFF assessment has been used to show reduced resistance in lower
extremities following gait training in the Lokomat for adults with chronic SCI\textsuperscript{15,17} and
children with cerebral palsy,\textsuperscript{16} particularly at the higher velocities. However, Mosby et
al.\textsuperscript{18} found no significant difference at any of the velocities before and after a single 30-
minute bout of either standing or walking in the Lokomat. These authors suspected that
the L-STIFF values likely represented the mechanical properties of the muscle and
connective tissues of the knee joint. They postulated that the neurological aspects of any
spasticity remained undetected due to the slow velocities of testing, and suggested that
faster velocities may be needed to truly assess spasticity. Using an experimental velocity
of 240\degree/s on one participant with mild spasticity, they found a new peak on the L-STIFF
curve that was not seen at 120\degree/s, suggesting that it may be represent neurological
‘catch’.\textsuperscript{18} The currently available velocities may be too slow, possibly limiting L-STIFF’s
ability to capture any neural component of resistance, such as velocity-dependent
‘catches’ or spasms, especially in mild cases of spasticity.\textsuperscript{15,16,18}
We utilized a version of the L-STIFF software that provides parametric data of limb resistance at the hip and knee joints during a movement sequence in the more functional upright position and at faster angular velocities representing more normal lower extremity movement. A new pattern of sequenced movements was created and programmed for the new L-STIFF software that closely approximates the movements of the clinical Ashworth test. The ability to mimic the Ashworth test in a more functional upright position allows the inclusion of potential neurological effects from upright-activated brainstem-spinal pathways. The new software was designed to move the joints quickly enough to characterize the neural component of joint resistance at any level of spasticity. A new data analysis method was also developed in an attempt to separate out the mechanical properties of the L-STIFF resistance data and better isolate the neurological component.

The first aim of this proof of concept pilot study was to determine if the new L-STIFF assessment and a new resultant spasticity score could capture and quantify pathology related to the neurological aspects of resistance to imposed movement at the knee. We hypothesized that the spasticity scores and electromyographic measurements of involved muscles in people with motor incomplete spinal cord injury being passively moved through an L-STIFF upright Ashworth pattern would be larger than those without injury. The second aim of this study was to determine a relationship between the spasticity scores of the new L-STIFF upright Ashworth pattern and supine Modified Ashworth Scale scores. We hypothesized that there would be a positive relationship between the objective Lokomat-based spasticity scores and the subjective scores of the supine Ashworth Scale.
METHODS

Participants

This study included three participants with motor incomplete, upper motor neuron SCI with some degree of spasticity (scores of 1 to 3 out of 4 on the MAS). It also included three non-injured (NI) participants for comparison. Because this was a “proof of concept” pilot project a small sample was appropriate. Participants with both mild and severe, flexor and extensor spasticity were recruited. A convenience sample of patients with SCI at Shepherd Center in Atlanta, GA was used for this study. Participants provided written, informed consent and the study was approved by the Institutional Review Boards of both the Shepherd Center and the University of Alabama at Birmingham. All demographic data are presented in Table 1.
Table 1

Demographic Data of Study Participants

<table>
<thead>
<tr>
<th>Gender</th>
<th>Age (yrs)</th>
<th>Height (in/cm)</th>
<th>Weight (lb/kg)</th>
<th>Time Since Injury</th>
<th>LOI</th>
<th>AIS</th>
<th>Anti-spasticity Medications</th>
<th>Mobility</th>
</tr>
</thead>
<tbody>
<tr>
<td>NI 1 M</td>
<td>30</td>
<td>67.0 / 170</td>
<td>161 / 73</td>
<td></td>
<td></td>
<td></td>
<td>Baclofen (40 mg, tid),</td>
<td>Slow limited community walker with RW</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Flexeril (10 mg at pm)</td>
<td>Can walk with bilateral crutches, but chooses WC</td>
</tr>
<tr>
<td>NI 2 F</td>
<td>29</td>
<td>62.0 / 158</td>
<td>130 / 59</td>
<td></td>
<td></td>
<td></td>
<td>Valium (10mg, qd or bid)</td>
<td>Community walker w/left cane</td>
</tr>
<tr>
<td>NI 3 M</td>
<td>23</td>
<td>75.5 / 192</td>
<td>185 / 84</td>
<td></td>
<td></td>
<td></td>
<td>(Used Baclofen in past)</td>
<td></td>
</tr>
<tr>
<td>SCI 1 F</td>
<td>28</td>
<td>69.0 / 176</td>
<td>152 / 69</td>
<td>5 years</td>
<td>C6</td>
<td>D</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>SCI 2 M</td>
<td>28</td>
<td>74.5 / 189</td>
<td>154 / 70</td>
<td>8 years</td>
<td>C7</td>
<td>D</td>
<td>Baclofen (40 mg, tid),</td>
<td></td>
</tr>
<tr>
<td>SCI 3 M</td>
<td>30</td>
<td>69.0 / 175</td>
<td>158 / 72</td>
<td>11 years</td>
<td>C5</td>
<td>D</td>
<td>Flexeril (10 mg at pm)</td>
<td></td>
</tr>
</tbody>
</table>

Procedures

A licensed physical therapist, experienced with the SCI population, screened the participant by performing the Thomas Test and Straight Leg Raise supine on a mat. The knee must flex to 80° and the hip must flex to at least 80° to pass each of these tests, respectively. These tests ensured that the biceps femori and rectus femori were of sufficient length to reduce the risk injury in the study. These exclusion criteria also ensured that the participants did not have excessive muscle shortening, which could confound any resistance results found during the L-STIFF assessment. The tests were performed relatively quickly to minimize any effects from brief stretching. Next, a Modified Ashworth exam was performed on the bilateral hip and knee flexors and extensors with the participant in supine on a mat based on the description as it is
performed in a multi-center, activity-based therapy program for the SCI population. (NeuroRecovery Network Outcome Measures Manual, version 4.2, June 2011.)

- Allow 2 minutes of relaxation supine on a mat.
- To score hip extensors, flex hip to approximately 90° and knee to approximately 120°.
- To score knee flexors, extend knee to 0° while extending hip to approximately 45° to prevent tight hamstrings from providing resistance.
- To score knee extensors, flex knee to 120° while flexing hip to approximately 90°.
- To score hip flexors, extend hip and knee to 0°.
- Allow participant to relax supine and repeat with other leg.

Each movement occurred during a one-second timeframe and was performed no more than twice. An rest between each movement allowed any spasticity elicited from the movement to dissipate before the next muscle group is tested. Each of the muscle groups was scored 0-4 according to the Modified Ashworth Scale.

After completion of the Modified Ashworth Scale, EMG recording electrodes were applied to the knee flexors and knee extensors of the NI participants’ left lower extremity and to the SCI participants’ lower extremity scored as having greater spasticity. The skin was cleaned with alcohol wipes and slightly abraded with a skin preparation gel. Sensor electrodes were placed over the rectus femoris and lateral biceps femoris, with a ground electrode placed on the fibular head of the same leg being studied. Electrical activity of the muscles was recorded using pairs of silver-silver chloride surface electrodes placed three cm apart on the skin to provide inter-pair impedance of less than 500 KΩ. Data was
digitally sampled by an on-line digital-to-analog conversion system (Phoenix, EMS-Handels GmbH, Korneuburg, Austria) at 1000 Hz. The signals were amplified using the Phoenix amplifiers over a bandwidth of 10-1000 Hz and digitized at 2048 Hz per channel. Signals are then processed and viewed by a customized BIOPAC MP150 Data Acquisition System for Windows (BIOPAC Systems, Inc., Goleta, CA) acquisition software.

The participant was fitted in a harness and placed in the Lokomat system. Fitting for the Lokomat device was conducted using the standard protocol as defined by the manufacturer (Hocoma Lokomat User Manual, 2009). The participant’s skin was protected from shearing and pressure from the Lokomat with gel pads, foam pads, and elastic wraps. Once participants were placed into the Lokomat, they were suspended approximately six inches over the treadmill. Participants were asked to relax in this upright position for 1-2 minutes.

Knee joint resistance was then assessed with a series of lower extremity movements in the Lokomat while the participant was instructed to remain relaxed. The upright Ashworth pattern was created to mimic the supine Modified Ashworth test as described above, but in the more functional upright position. The pattern utilizes the same four movements in the same order: 1) both hip and knee flex to maximum end ranges, 2) the knee extends to approximately 0\(^\circ\) while the hip remains flexed, 3) the knee flexes to end range while hip remains flexed, and 4) the hip and knee extend to approximately 0\(^\circ\) to return to the start position. The hip is limited to 42\(^\circ\) of flexion and the knee is limited to 80\(^\circ\) of flexion due to hardware constraints of the robot. Five seconds elapsed between each of these four movements. Raw angle and torque data were collected for analysis for each of the four
movements at each the knee joints. However, only movement 2 of knee extension from 80° to 0° with the hip flexed at 42° was analyzed for this study.

This assessment pattern was programmed to deliver a sequence of changing angular velocities for each participant: slow → medium → fast. For each joint, the slow speed was 120°/s; the medium speed was 180°/s, and the fast speed was 240°/s. The slowest speed of 120°/s is the maximum speed allowed commercially, while the fastest speed of 240°/s is the angular velocity seen at the knee during normal walking speeds. The medium speed of 180°/s allows insight as to whether any changes seen in the neurological aspects of the curves are gradual or an “all-or-none” phenomena. While the greatest chance of capturing the neurological aspect of knee stiffness was thought to be at the fastest speed, this protocol used the slow-to-fast sequence to ensure the safety of each participant’s muscles and connective tissues. This was also recommended by the manufacturer. The program delivered the pattern at the slow angular velocity for the hip and knee of the left leg and then repeated the pattern for the right leg, before moving on to the next faster speed. Approximately one minute of rest between each speed of each assessment pattern allowed the participant’s muscles to relax before data collection. This was verified by the real-time EMG data. Due to constraints of the software and hardware, all L-STIFF testing was performed at 100% body weight support, or no weight bearing at all. Total testing time in the Lokomat was approximately 15 minutes. The participant returned to the mat in the supine position and was allowed to relax for at least two minutes or until all muscles relaxed. To determine if the L-STIFF assessment affected the MAS scores, a second supine Modified Ashworth exam was performed.
Data Analysis

Data from the single-joint second movement in the upright Ashworth pattern was analyzed. First, the angle, angular velocity, and angular acceleration were plotted over time to understand how the robot was moving the participants’ legs and to ensure its consistency between participants. Next, the data from both healthy left and right knees were analyzed for all non-injured (NI) participants. For the participants with SCI, the data for the knee of the lower extremity with the greater spasticity were analyzed. All the knee data were analyzed during this knee extension movement at the three angular velocities (120°/s, 180°/s, and 240°/s). Time, angle, and torque data were exported from the Lokomat and the electromyography (EMG) data of the knee flexors and extensors were extracted from the Pegasus EMG system. All of these files were imported into MATLAB, version 7, R2010a (The MathWorks, Inc.) for analysis.

Torque Data and the Spasticity Score

The angle and torque information from the joint sensors was analyzed by a new optimization program to graph and quantify the neural component of the resistance of the leg while it was moved passively at increasing angular velocities. This optimization method provided a single numerical number for each movement called the spasticity score. Torque data from the Lokomat were plotted over time and analyzed to determine the spasticity scores. The plot of resistance during the movement at the knee, measured by the Lokomat as torque, includes both the robotic leg and the human leg and their confounding parameters. These parameters include the weight of each due to gravity and the moment of inertia of each due to their mass and its distribution. The commercially-
available version of L-STIFF uses mathematical modeling of the robotic leg and the human leg to account for these parameters and to achieve a measure of “stiffness” or resistance to the passive movement. However, this current measure cannot distinguish between neural and mechanical tissue effects. As an alternative, a program was created for MATLAB that assumed a simple pendulum model of the human lower leg as a rod with a weight at the end, without muscle or other tissues. An iterative optimization method was used in MATLAB to determine the best-fit of the torque vs. time curve while correcting for gravity and rotational inertia. The following general equation was used in this program: 

$$\text{Best-fit curve} = a \cdot \sin(\text{angle} + b) + c \cdot \text{angular velocity} + d \cdot \text{angular acceleration} + e,$$

where the program determined the coefficients $a$, $b$, $c$, $d$, and $e$. The first term $[a \cdot \sin(\text{angle} + b)]$ corresponded to gravity; the second term $[c \cdot \text{angular velocity}]$ corresponded to dampening (resistance); and the third term $[d \cdot \text{angular acceleration}]$ corresponded to inertia. The last term, $[e]$, represented all the constant offsets of the previous terms lumped together. With these terms accounted for, the musculoskeletal component of the spasticity score should be considerably reduced allowing the neural component to be the primary contributor of the spasticity score in this model.

The difference between the original torque curve from the Lokomat and its best-fit curve from the optimization program resulted in a plot of residual torque over time. This graph showed the resistance felt by the Lokomat sensor after accounting for gravity and moments of inertia of the robotic and human legs. While the musculoskeletal components of tissue stiffness could not be completely removed by the model, this graph may be considered a representation of mostly neural components of resistance during the movement. Because the best-fit curve is an estimator of the actual torque output, the
mean squared error (MSE) may be used to quantify the overall difference. Denoting the differences, or residuals, along the curves as “errors”, the MSE takes the average of the squares of the errors. Therefore, the MSE was used to quantify this graphical representation of the essentially neural components of the resistance. This number has been used as the spasticity score.

**EMG Data**

EMG data provided objective neural insight into and verification of the spasticity score. EMG was recorded to detect neural discharges during the passive movement. It would show both phasic and tonic muscle activity generated by spinal circuits controlling these muscles in response to sensory input from muscle stretch and joint movement. EMG data demonstrated the muscle activity during the 4.5 seconds preceding the movement, the activity during the movement itself, and the 4.5 seconds following the movement. The mid-point of the movement was denoted as zero. The MATLAB package was used to filter and rectify the data using a 10 Hz low-pass filter. A non-causal filter was then used to define the presence of muscle activity as 0.1 mV and greater following the beginning of the movement. Given this threshold, the RMS values of the EMG activity during the movements were calculated with MATLAB.

**Clinical Exam Scores**

The Modified Ashworth scores were recorded pre-test and post-test for the SCI group. As mentioned previously, the pre-test scores were used to identify the lower
extremity with the greater spasticity. Changes in the pre-test and post-test scores were then reviewed for general history effects.
RESULTS

The data retrieved from the Lokomat was first analyzed to ensure that it delivered the same movements at the same speeds to all participants. It was verified that the robot behaved with the same angular position, velocity, and acceleration at each of the three speeds for each participant.

Model Results

The model used in this analysis corrected for gravity and moment of inertia of the participant’s and robot’s leg during the movement. Figures 1a and 1b show the gravity-corrected torque curves for representative NI and SCI participants, respectively. The blue line shows the raw data curve, while the red curve shows the best-fit curve for each correction. Subsequently, the differences between the raw and best-fit curves for gravity in Figures 1a and 1b result in the raw data curves seen in Figures 2a and 2b. The best-fit curves in these figures correct for the moment of inertia. While Figures 1 and 2 respectively show the individual contributions of the gravity and moment of inertia corrections, Figures 3a and 3b show the combined effects of both corrections in the best-fit curves on the original raw torque curves. The model’s final best-fit curves for this movement of knee extension accounted for greater than 99% \( R^2 = 0.994-0.999 \) for the NI group and \( R^2 = 0.992-0.997 \) for the SCI group] of the variance for each of the six participants’ data at each angular velocity described in this section. Last, Figures 4a and
4b are the differences between the raw and best-fit data curves from Figures 3a and 3b, respectively. These graphs are therefore the residuals of the raw torque data and the model’s compensation for gravity and moment of inertia. While likely including some musculoskeletal tissue effect, these graphs may be considered well-estimated representations of the effects of neuropathic spasticity as measured by the Lokomat torque sensors.

![Figure 1](image1.png)

**Figure 1.** Gravity-corrected torque curves during knee extension at 180°/s for representative participants from a) the NI group and b) the group with SCI.

![Figure 2](image2.png)

**Figure 2.** Inertia-corrected torque curves during knee extension at 180°/s for representative participants from a) the NI group and b) the group with SCI.
Figure 3. Fully corrected torque curves during knee extension at 180°/s for representative participants from a) the NI group and b) the group with SCI.

Figure 4. Residual torque or “spasticity” curves during knee extension at 180°/s for representative participants from a) the NI group and b) the group with SCI.

The Mean Squared Error (MSE) analyses of these final residual torque graphs for each participant’s bilateral knees for each movement were performed. The resulting number of each MSE analysis became the “spasticity score” for that joint during that particular passive robotic movement. For instance, the spasticity score during knee extension for Figure 2a (NI 1’s left knee) was 0.53; while the spasticity score for Figure 2b (SCI 1’s left knee) was 8.43. The following section will focus on the spasticity scores for the participants’ knee joints during the single-joint knee extension movement.
Spasticity Scores of Non-injured Participants

The averages of the six bilateral knees of the three non-injured participants were used for comparison to the more affected knee of the participants with SCI. Table 2 shows that nearly all spasticity scores for the non-injured participants’ knees were less than 1.0. The spasticity scores ranged from 0.11 at 120°/s to 3.53 at 240°/s. All spasticity scores and their averages at 120°/s were less than 1.0 (0.41 ± 0.30). Five of six knees and the average at 180°/s were less than 1.0 (0.65 ± 0.49). Four of six knees at 240°/s had scores less than 1.0 (1.55 ± 1.16). The knees with spasticity scores greater than 1.0 were those of NI 3 who was very tall with heavy legs. It can also be seen that the spasticity scores generally increase with increasing angular velocity in those without SCI.

Table 2

Spasticity Scores for Both Groups During the Lokomat Movement

<table>
<thead>
<tr>
<th>Angular Velocity</th>
<th>NI 1 Left</th>
<th>NI 1 Right</th>
<th>NI 2 Left</th>
<th>NI 2 Right</th>
<th>NI 3 Left</th>
<th>NI 3 Right</th>
<th>NI Average</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>120°/s</td>
<td>0.30</td>
<td>0.28</td>
<td>0.29</td>
<td>0.11</td>
<td>0.52</td>
<td>0.97</td>
<td>0.41</td>
<td>0.30</td>
</tr>
<tr>
<td>180°/s</td>
<td>0.53</td>
<td>0.44</td>
<td>0.37</td>
<td>0.18</td>
<td>1.53</td>
<td>0.86</td>
<td>0.65</td>
<td>0.49</td>
</tr>
<tr>
<td>240°/s</td>
<td>0.99</td>
<td>0.96</td>
<td>0.82</td>
<td>0.61</td>
<td>3.53</td>
<td>2.39</td>
<td>1.55</td>
<td>1.16</td>
</tr>
<tr>
<td>SCI 1 Left</td>
<td>5.44</td>
<td>4.25</td>
<td></td>
<td></td>
<td>1.41</td>
<td></td>
<td>3.70</td>
<td>2.07</td>
</tr>
<tr>
<td>SCI 2 Left</td>
<td>8.43</td>
<td>2.66</td>
<td>1.89</td>
<td>4.33</td>
<td></td>
<td></td>
<td>5.25</td>
<td>3.57</td>
</tr>
<tr>
<td>SCI 3 Right</td>
<td>9.86</td>
<td>2.71</td>
<td>3.19</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.99</td>
</tr>
</tbody>
</table>
Spasticity Scores of Participants with SCI

To analyze data for the SCI group, the lower extremity with greater spasticity was determined. This was determined based on the pre-test Modified Ashworth scores of the knee flexors during the movement of knee extension. The greater scores were seen in the left knee flexors for SCI 1 and SCI 2. Conversely, the more severe scores were seen in the right knee flexors for SCI 3. Table 2 provides the spasticity scores for each of the participants with SCI at each angular velocity for the lower extremity with greater spasticity. First, all spasticity scores are greater than 1.0. The scores range from 1.41 at 120°/s to 9.86 at 240°/s. At 120°/s, the average was 3.70 ± 2.07. At 180°/s, the average was 4.33 ± 3.57. At 240°/s, the average was 5.26 ± 3.99. Table 2 shows a general trend for the spasticity scores to increase with increasing angular velocity. The one exception was SCI 2, whose left leg was very difficult to initially move during the Ashworth exam, but then became much easier to move.

Electromyographic Results

EMG Data for Non-Injured Participants

Table 3 shows the EMG RMS data from the NI group, revealing essentially no muscle activity from either the left knee flexors or left knee extensors during the knee extension movement. This lack of activity remained independent of angular velocity. Figures 5a and 5b show the EMG activity of the knee extensors and knee flexors, respectively, for a representative NI participant at 180°/s. The gray bar represents the time period in seconds of the robotic movement, with zero as the mid-point of the movement. All EMG activity of each group of muscles of each NI participant at each
angular velocity looks similar, showing no muscle activity. Table 3 provides the RMS values of both muscle groups of the NI group. The average RMS values for the NI group at each velocity were \(0.73 \pm 0.11\) mv/s, \(0.69 \pm 0.10\) mv/s, and \(0.75 \pm 0.13\), respectively.

### Table 3

**EMG RMS Values for Both Groups During the Lokomat Movement**

<table>
<thead>
<tr>
<th>Angular Velocity</th>
<th>NI 1 Left</th>
<th>NI 1 Right</th>
<th>NI 2 Left</th>
<th>NI 2 Right</th>
<th>NI 3 Left</th>
<th>NI 3 Right</th>
<th>NI Average Left</th>
<th>NI Average Right</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>120°/s</td>
<td>0.88</td>
<td>0.63</td>
<td>0.86</td>
<td>0.70</td>
<td>0.68</td>
<td>0.61</td>
<td>0.73</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>180°/s</td>
<td>0.82</td>
<td>0.59</td>
<td>0.81</td>
<td>0.66</td>
<td>0.66</td>
<td>0.62</td>
<td>0.69</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>240°/s</td>
<td>0.89</td>
<td>0.61</td>
<td>0.92</td>
<td>0.73</td>
<td>0.66</td>
<td>0.70</td>
<td>0.75</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td>SCI 1 Left</td>
<td>1.53</td>
<td>7.05</td>
<td>6.81</td>
<td>5.13</td>
<td>3.12</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SCI 2 Left</td>
<td>2.28</td>
<td>2.07</td>
<td>7.68</td>
<td>4.01</td>
<td>3.18</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SCI 3 Right</td>
<td>2.61</td>
<td>4.37</td>
<td>8.27</td>
<td>5.08</td>
<td>2.90</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 5.** Filtered and rectified EMG activity of (a) knee extensors and (b) knee flexors during knee extension at 180°/s of a representative participant of the NI group.


**EMG Data for Participants with SCI**

The EMG recordings are intended to verify and measure any involuntary (phasic reflex or tonic stretch induced) muscle activity as a component of the torque measured during the passive movements. Figure 6 displays the EMG recordings of the knee extensors and knee flexors of each participant with SCI at each of the angular velocities during the knee extension movement. The vertical gray highlighted area denotes the time period of the movement. Note that the knee flexors, the muscles being lengthened by the imposed movement, were the active muscle group for SCI 1 and SCI 2; however, it was the knee extensors, the muscles being shortened by the imposed movement, that were active for SCI 3. The antagonistic muscle for each of these participants did not show any EMG activity. Table 3 provides the RMS values of the active muscle group in the lower extremity with greater spasticity in the SCI group. The average RMS values for the SCI group at each velocity were $5.13 \pm 3.12 \text{ mv/s}$, $4.01 \pm 3.18 \text{ mv/s}$, and $5.08 \pm 2.90 \text{ mv/s}$, respectively.
Figure 6. Filtered and rectified EMG activity of the active muscle group of each of the SCI participants during passive knee extension at each of the angular velocities.
Clinical Exam Scores

Table 4 shows the Modified Ashworth scores taken pre- and post-test for the left and right knee flexors and extensors of the participants with SCI. Comparing the pre- and post-test scores, most of the scores decreased or remained the same, showing minimal history effects. Recall that the more severe pre-test MAS scores were seen in the left knee flexors for SCI 1 and SCI 2, but in the right knee flexors for SCI 3. However, the active muscle group for SCI 3 during the passive L-STIFF movement was the knee extensors. Thus, the pre-test MAS scores for the knee extensors were used to explore the relationship between MAS scores and spasticity scores. Table 5 provides the spasticity scores found at each MAS score at each angular velocity.

Table 4

*MAS Scores for Participants with SCI*

<table>
<thead>
<tr>
<th></th>
<th>Pre-Test Scores</th>
<th>Post-Test Scores</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Left</td>
<td>Right</td>
</tr>
<tr>
<td>SCI 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee Flexors</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Knee Extensors</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>SCI 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee Flexors</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Knee Extensors</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>SCI 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee Flexors</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Knee Extensors</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>
Table 5

*Spasticity and MAS Scores for Participants with SCI at Each Angular Velocity*

<table>
<thead>
<tr>
<th>MAS Score</th>
<th>Spasticity Score at 120°/s</th>
<th>Spasticity Score at 180°/s</th>
<th>Spasticity Score at 240°/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.41</td>
<td>1.89</td>
<td>3.19</td>
</tr>
<tr>
<td>2</td>
<td>5.44</td>
<td>8.43</td>
<td>9.86</td>
</tr>
<tr>
<td>3</td>
<td>4.25</td>
<td>2.66</td>
<td>2.71</td>
</tr>
</tbody>
</table>
DISCUSSION

Spasticity scores and EMG root mean squared measurements of people with motor incomplete spinal cord injury being passively moved by the Lokomat in an upright Ashworth pattern were larger than those without injury. As shown by Table 2, the individual SCI participant data and large standard deviations in these three participants show the wide variability in spasticity in people with SCI. Comparing the groups in Table 2, the spasticity scores for each individual with SCI were higher than the non-injured individual at 120°/s and 180°/s, but not at 240°/s. At 240°/s, the current model’s best-fit curves may not fit as well due to the overshoot of the Lokomat or for participants with large and heavy lower extremities. The group without spasticity had spasticity score averages that remained well below 1.0 at 120°/s and 180°/s, and was about 1.5 at 240°/s. The scores of the group with spasticity were 9.0 times greater at 120°/s, 6.6 times greater at 180°/s, and 3.4 times greater at 240°/s. Thus, the angular velocity of 120°/s was best able to distinguish spasticity between the groups with these participants. This is contradictory to what was initially thought, as it is the slowest angular velocity used in this study. However, the history effect displayed by SCI 2 appears to be driving the data at 120°/s.

Further supporting the first hypothesis, Table 3 shows the EMG RMS values were distinctly higher at each angular velocity during the passive movement for the group with SCI compared to the non-injured group. The EMG results verify that those with SCI did in fact have neurologic aspects to the resistance that the Lokomat was sensing, while showing
that those without SCI did not. The EMG also helped define what the spasticity score measured. The long-duration EMG activity for SCI 1 corresponds to the continuous resistance felt during the MAS exam throughout the knee extension movement. However, while the EMG RMS values were low, the corresponding spasticity scores for SCI 1 were high at each angular velocity.

For SCI 2 the large amount of EMG activity seen during the first movement followed by smaller amounts of activity was also felt during the MAS exam. The initial manual movements on the MAS had large resistance, followed by movements with little resistance. The corresponding initial spasticity score was high, followed by smaller scores. History effects seem to play a large role for this participant. Lamontagne et al., who also saw a high first torque then subsequent decreased torques suggested this effect may be due to muscle thixotropy, or reduced viscosity of tissues with movement. However, it may also be due to different neural reactions to the imposed movement. Studies of isokinetic dynamometry typically include dozens of repetitions of passive movement on the same joint to average the results or simply to reduce the effects of “warming up.” This participant is an example of someone with an SCI who would likely show no spasticity in such a protocol.

For SCI 3 the EMG RMS values started very high and grew with increasing angular velocity. However, the corresponding spasticity scores were low at the lower velocities and only moderate at the fastest velocity. SCI 3 demonstrated strong full-flexion reflexes when supine on a mat. However, the EMG data described above for SCI 3 are the knee extensors during a knee extension movement. This is counterintuitive for this movement, particularly considering his strong supine flexion reflexes. One possible explanation for this unique
finding is that when upright, the vestibulospinal tract becomes active, stimulating anti-
gravity muscles, particularly extensor muscles in the lower extremities.\textsuperscript{20} Perhaps this tract
and the interneurons it activates in the right lower extremity are hypersensitive to the
upright position in this participant. Kakebee et al.\textsuperscript{21} showed that knee extensors after SCI
were more active during passive movement when the hip joint was at 0° compared to 90°;
however, the participants were in supine instead of upright.

The non-injured participant who was the tallest and heaviest, NI 3, had spasticity scores
2-4 times greater at each angular velocity than the other two in that group. Perhaps the
model loses accuracy when used with a person with a longer leg (pendulum arm) with a
heavier foot and shoe (weight at the end). This may be particularly true during the fastest
movements at 240°/s where there is already loss of accuracy due to overshoot at the end of
the movement. Because this larger person’s EMG was silent, another possibility may be
that he had a greater musculoskeletal component than the other two in the NI group.

The trend of increasing spasticity score and increasing RMS values with increasing
velocity generally holds true across each angular velocity for each participant. The
exception comes from SCI 2’s data due to the large initial activity at the slowest speed
followed by small activity at the faster speeds. Many other studies\textsuperscript{5,12,22-24} also showed clear
effects of increasing velocity on spasticity measures. Studies including movements at very
slow angular velocities (~10°/s) showed no muscle activity in their participants,\textsuperscript{12,13}
demonstrating musculoskeletal effects on any torque generated. However, several
authors\textsuperscript{12,16,18} suggest that a velocity of 120°/s will not detect neurological effects on torque
in those with mild spasticity (MAS scores of ~1), but may do so in those with more severe
spasticity. Our data are from the more spastic legs of participants with a range of spasticity.
severity, and the velocity 120°/s was able to distinguish them from those without spasticity. Tuzson et al.²⁵ proposed an individual angular velocity “spasticity threshold” as a measure of spasticity and its effect on walking. Their work with children with cerebral palsy showed a wide range of thresholds, ranging from 60°/s-270°/s. The authors²⁵ determined that those with lower spasticity thresholds had more mild spasticity and less effected walking speeds; while those with higher spasticity thresholds had more severe spasticity and more effected, slower walking speeds.

The second hypothesis of increasing spasticity score with increasing MAS score was not able to be determined. This is due to the small sample size and the small number of categories included in the MAS for those having non-rigid spasticity. While in general there seems to be a trend toward higher spasticity scores with higher MAS scores, it is clear that more data is needed before true trends can be determined. Tsao and Mirbagheri²⁶ found poor correlations between the Modified Ashworth Scale scores and neurophysiologic results, offering three failings of the scale to measure spasticity in a meaningful way. First, the Ashworth tests are performed with the patient in a relaxed state, instead of during active movement. Second, a score is only for one joint and gives no information about the quality of the movement. Third, the score is subjective and ordinal, providing no insight into potential muscular and reflexive components of the spasticity. Additional work with our experimental version of L-STIFF should include a larger and more varied sample, as well as other spasticity measures, such as the functionally-based self-report, the Spinal Cord Injury Spasticity Evaluation Tool (SCI-SET). Measuring spasticity should also be attempted during active, functional movements such as walking. Robotic assessments can help ensure consistency and measure resistance during both passive and active movements.
Hsieh et al.’s conclusion neatly summarizes the use of clinical scales for spasticity:
“Different scales measure different aspects of spasticity and individual tools correlate weakly with each other.” They suggest a battery of tests to capture these different aspects. This also suggests the importance of having EMG with which to interpret mechanical measures, even if this technique is not always easy to apply in the clinical environment by therapists.

Limitations

The most obvious limitation of this study is the small sample size in each group. Even in this small sample, there is a variety of presentations of spasticity during passive movement in supine and in the upright position. From this initial work, however, there is evidence that the model and spasticity score show promise. Therefore, further research with an expanding sample of participants with SCI and their comparison with non-injured participants is warranted. Also, the Lokomat is limited in its hip flexion to only 42° and in its knee flexion to only 80°, whereas the Ashworth exam tests the hip at 90° flexion and the knee at 120° flexion. Further, the sequence of the angular velocities delivered was consistent to ensure participant safety. When the risk is felt to be sufficiently reduced, additional work with this protocol should randomize the sequences. Only five seconds were programmed between each of the four movements of each leg. The EMG showed that some muscle activity was seen for some the SCI group movements for the full recording duration following the movement. A longer duration between movements is therefore warranted for future studies. This should also increase the accuracy of the spasticity scores.
Another limitation of the spasticity score is that it was not zero for all non-injured participants across all angular velocities. Surprisingly, it is not unusual to discover muscle activity during movement in a non-injured comparison group. Specific to the spasticity score in this report, every model has imperfections, and this one is based on best-fit curves. There will always be some differences between the raw torque data curve from the Lokomat and the best-fit curve. At the fastest velocity, the robot moves so fast that it overshoots the end-range of the movements. So, the best-fit curve typically has the worst fit at the fastest velocities. Additionally, per manufacturer software engineers, the angle and torque data become inaccurate at the hip at a velocity of $240^\circ$/s. Thus, it is good to see that the spasticity score may still be able to distinguish the presence of spasticity at the two slower velocities. Last, the participants in this study were screened to minimize any knee flexor and extensor tightness. It remains unknown how the model would identify spasticity in those with both spasticity and obvious musculoskeletal resistance as is typically seen in people with chronic SCI. Thus, more work will need to be done with the model to continue to improve it with a more varied sample.

The spasticity score at this time requires the Lokomat for its data. Thus, only researchers and clinicians in clinics that have the Lokomat have the immediate potential to quantify spasticity using this method. However, one of the greatest benefits of the spasticity score method is that it can be used with any robot that provides accurate torque and time data. The ability to program a robot to produce functional patterns with a wide range of angular velocities is intriguing. A pattern mimicking stepping has also been created for the Lokomat and is ready for study in our laboratory.
Understanding spasticity, its multifaceted presentations, and its highly variable effects on functional movement is critical to clinical decision-making and long-term planning during rehabilitation; however, assessing spasticity is a constant challenge. Objective measurements may allow therapists to better treat their patients and track their progress for planning and reimbursement. This project explored how to best use a research version of the L-STIFF software and its new movement sequences and higher angular velocities to optimally measure and characterize spasticity in people after SCI.
CONCLUSIONS

The experimental upright Ashworth L-STIFF assessment shows promise in measuring spasticity, especially by allowing more functional upright neurological effects to come into play. Having the ability to alter the velocities and patterns of movements also allows the opportunity to study asymmetries, history effects, speed effects, and single-joint vs. double-joint movement effects. Given the finding of generally larger scores for those with SCI, the MATLAB program and resulting spasticity score show potential in distinguishing those with and without spasticity. However, limitations exist at this point and the program requires further development with a larger and more varied sample. It also seems that the angular velocity of the assessment affects spasticity results. This should be considered relative to the participant’s function in the upright position. Last, the explored relationship between the MAS and spasticity scores is premature at this point. Further work will expand the sample size to include the multifaceted variety of spasticity after SCI, and will optimize the model as a potential clinical measure of the neuropathic component of spasticity with the Lokomat.
LIST OF REFERENCES


APPENDIX

INSTITUTIONAL REVIEW BOARD APPROVAL FORM
UAB's Institutional Review Boards for Human Use (IRBs) have an approved Federalwide Assurance with the Office for Human Research Protections (OHRP). The Assurance number is FWA0005960 and it expires on September 29, 2013. The UAB IRBs are also in compliance with 21 CFR Parts 50 and 56.

Principal Investigator: VANHIEL, LESLIE
Co-Investigator(s):
Protocol Number: F110623003
Protocol Title: Examining Spasticity in Spinal Cord Injury Using a Novel Robotic Assessment

The IRB reviewed and approved the above named project on 8/3/2011. The review was conducted in accordance with UAB's Assurance of Compliance approved by the Department of Health and Human Services. This Project will be subject to Annual continuing review as provided in that Assurance.

This project received FULL COMMITTEE review.

IRB Approval Date: 8/3/2011
Date IRB Approval Issued: 8-17-11
Identification Number: IRB00000726

Albert Oberman, M.D., MPH
Vice Chair of the Institutional Review Board for Human Use (IRB)

Investigators please note:

The IRB approved consent form used in the study must contain the IRB approval date and expiration date.

IRB approval is given for one year unless otherwise noted. For projects subject to annual review research activities may not continue past the one year anniversary of the IRB approval date.

Any modifications in the study methodology, protocol and/or consent form must be submitted for review and approval to the IRB prior to implementation.

Adverse Events and/or unanticipated risks to subjects or others at UAB or other participating institutions must be reported promptly to the IRB.