Full Title: Walking In A Robotic Exoskeleton Does Not Mimic Natural Gait

Short Title: Walking in a Robotic Exoskeleton

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ABSTRACT

BACKGROUND: Robotic exoskeleton devices enable individuals with lower extremity weakness to stand up and walk over ground with a full-weight bearing and reciprocal gait. Limited information is available on how an exoskeleton robotic affects gait characteristics. The purpose of this study was to examine whether wearing a robotic exoskeleton affects temporospatial parameters, kinematics, and muscle activity during gait.

METHODS: Fifteen healthy adults (age: 26.2±8.3 years, 6 men, 9 women) completed the study. Each participant performed walking under two conditions, with and without wearing a robotic exoskeleton (EKSO). A 10-camera motion analysis system synchronized with 6 force plates and a surface electromyographic (EMG) system captured temporospatial and kinematic gait parameters and lower extremity muscle activity. Five walking trials were collected for each condition and included for data analysis.

RESULTS: Differences were observed between the two conditions in temporospatial gait parameters of speed, stride length, and double limb support time. When wearing EKSO, hip and ankle range of motion were reduced and knee range of motion increased during the stance phase. However, during swing phase, knee and ankle range of motion were reduced when wearing exoskeleton bionic suit. EMG activity decreased bilaterally in the stance phase for all muscle groups of the lower extremities, and in the swing phase for the distal muscle groups (tibialis anterior and soleus) as well as left medial hamstrings when participants were wearing EKSO.

CONCLUSION: Wearing EKSO altered temporospatial gait parameters, lower extremity kinematics and muscle activity during gait in healthy adults. EKSO appears to promote a type of gait that is disparate from normal gait in first time users. More research is needed to determine the impact on gait training with EKSO in people with gait impairments.
KEY WORDS: Lower Extremity, Muscle Activation, Electromyography, Kinematics, Biomechanics, Range of Motion
BACKGROUND

Walking is a complicated process requiring optimal muscle activation and joint mobility to control dynamic balance and posture for different environments. Typified by characteristic muscle activity and kinematic patterns governed by pre-designed central nervous system motor programs [1], walking consists of identifiable sequential patterns within a relative timing mechanism [2]. However, an injury to the neuromuscular system is likely to result in atypical walking patterns of both kinematics and muscle activity performance.

Recovery of walking continues to be a primary goal for persons with neurological deficits and a contributing factor to quality of life [3,4]. Therefore, learning to walk is a major goal during rehabilitation [5,6]. Although the optimal therapeutic intervention to achieve full recovery of gait remains unknown for many patients with neurologic injuries, any rehabilitation effort intended to drive neuroplastic changes towards motor recovery should incorporate principles of neuroplasticity. Specifically, inclusion of factors (i.e. loading the sole of the foot, attaining adequate hip extension movement) to facilitate appropriate electromyographic (EMG) patterns are thought to be crucial [7]. Locomotor training seeks to capitalize on these established principles [8-10].

Recently, robotic exoskeletons have been developed and offer a relatively new form of locomotor training. Robotic exoskeleton devices enable individuals with lower extremity weakness (i.e. people with stroke or spinal cord injury) to stand up and walk over ground with a full-weight bearing and reciprocal gait. By adding actuators at the orthotic joint, robotic exoskeletons provide an external source of controlled joint power. Several exoskeletons have been developed for gait restoration, with much variation in the actuator and sensing technologies. Although there are some commercially available devices, like the ReWalk or EKSO, the technology is not yet mature enough to produce unlimited community ambulation [11-13].
Though gait training with exoskeletons has been shown to be safe, well tolerated, with no significant complications [14] over distances of 40 meters to 100 meters [15], it is unclear how closely the gait of a person wearing a robotic exoskeleton approximates normal gait. Two recent case studies highlight the impact of a robotic exoskeleton on gait characteristics. In the first case study, lower extremity range of motion was generally smaller with greater hip and knee power generation for the exoskeleton gait [16]. However, the second case study indicated improved symmetry on temporospatial variables and increased gait speed after robotic exoskeleton gait training in a person with stroke [17].

A common goal of gait retraining is to promote locomotor features typical of normal gait. However, the current robotic exoskeleton may promote different walking characteristics. These differences in gait parameters may be accompanied by dissimilarities in kinematics and muscle activity typically observed in normal walking. It is crucial to identify the differences between exoskeleton walking and normal walking prior to using a robotic exoskeleton system for gait training. Therefore, the purpose of this study was to examine whether wearing a robotic exoskeleton suit affects kinematic and muscle activity of lower extremities during walking. We compared healthy individuals’ gait parameters under two conditions: normal walking and walking in the robotic exoskeleton suit.

METHODS

Participants

Healthy adults 18 to 70 years old without any neurological disorder were recruited from the local community. Exclusion criteria was based in part on the limitations of the robotic exoskeleton (EKSO) used in this study and included: 1) screen failure of EKSO frame limitations (≤ 100 kg, between 1.58 to 1.88 meters tall, standing hip width ≤ 41.9 cm, near normal range of motion in hips, knees, ankles, and leg length discrepancy ≤ 1.9 cm), 2) severe spinal instability,
3) unresolved deep vein thrombosis, 4) orthostatic hypotension, 5) significant osteoporosis, 6) uncontrolled spasticity (≥ 3 on the Modified Ashworth Scale), 7) uncontrolled autonomic dysreflexia, 8) skin integrity issues on contact surfaces of the device or sitting surfaces, 9) significant cognitive impairments (unable to follow 3 step commands), and 10) pregnancy.

**Instrumentation**

A 10-camera VICON Motion Analysis System (Vicon Motion System, Inc., Centennial, CO) was used to capture the kinematic data. The sampling rate of the 10 cameras was set at 120 Hz and the cameras were time-synchronized with the 6 AMTI force plates, for which the sampling rate was set at 1,200 Hz. The threshold of the force plates was set at 10 Newtons, in order to determine gait events (i.e. heel strikes and toe offs). A VICON Plug-In-Gait model with 15 reflective markers was used to obtain joint motions of lower extremities. Marker placements are shown in Figure 1.

**Figure 1. VICON Plug-In-Gait Model Lower Extremity Marker Placements.**

A Delsys Trigno® EMG system with 10 wireless surface electrodes (Delsys, Inc,, Natick, MA, USA) was used to obtain muscle activities of the right and left gluteus medius, rectus femoris, medial hamstrings, tibialis anterior, and soleus muscles. The bandwidth of the EMG system was set at 20 to 450 Hz with a gain of 1,000. The EMG signal was recorded at a sampling rate of 960 Hz and was timed-synchronized with the VICON Motion Analysis system. The 10 surface electrodes were affixed with self-adhesive tape on the specific location for each muscle following the SENIAM’s (Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles) recommendation. Prior to electrode placement, the patient’s skin in the areas of
electrode placement was cleaned with isopropyl alcohol. If there was excessive hair, a new disposable razor was used to shave the hair to improve the quality of the EMG recording.

**Procedures**

After the participants signed a written consent form approved by the Institutional Review Board of Texas Woman’s University, they completed an intake form for their demographic data (age, sex, leg dominance), past medical history, past surgical history and activity level. The investigator then took anthropometric measurements from each participant. These measurements, including height, weight, standing hip width, range of motion (ROM) in hips, knees, ankles and leg length, were used to ensure that the participants were able to fit the exoskeleton suit, EKSO (Ekso Bionics, Richmond, California). Other anthropometric measurements including leg length, knee width and ankle width as required for the Vicon’s Plug-In-Gait model.

For walking trials, the participants were asked to wear a pair of shorts and a pair of tennis shoes required for the EKSO. Kinematic and EMG data were collected simultaneously. During each walking trial, each participant was asked to look straight ahead if possible and to walk at a self-selected speed on a 7-meter level walkway. For each of the two conditions (with and without wearing the EKSO), five walking trials were collected from each participant. Prior to trials with the EKSO, each participant was given instructions and allowed to practice walking with an EKSO trained therapist for a minimum of 15 minutes and until the therapist was comfortable providing only close supervision to prevent a loss of balance.

**Signal Processing**

First, the collected data was processed using the VICON Nexus software to label markers, fill gaps, determining the gait events, and finally generating c3d files. Each walking
trial was divided into individual gait cycles that began and ended with the heel strike of the same foot, and then the data was normalized in time by percent of the gait cycle. Each complete gait cycle was further divided into a stance phase (%) and a swing phase (%). Next, customized MATLAB (Mathworks Inc., MA, USA) scripts were used to process the c3d files and to generate sagittal joint angles of the hip, knee and ankle as well as temporospatial variables.

Similarly, custom MATLAB scripts were used to process and produce sEMG amplitudes for each walking trial. Root-mean-square (RMS) values of EMG were used to quantify the amount of EMG activity for each walking trial. EMG RMS values were obtained using a window size of 120 samples with 60 samples overlapping. Then, sEMG RMS values were normalized across a complete gait cycle (100%) with 101 data points over the corresponding phase. Finally, sEMG RMS were further normalized with respect to the peak over the gait cycle. The peak EMG value of the corresponding stance or swing phase of each walking trial was used for normalization of EMG values.

**Statistical Analysis**

All statistical analyses were performed using SPSS version 24 (IBM Corp., Armonk, NY, USA). Descriptive statistics were performed to describe participants’ demographic data and gait parameters. The average values of all of the complete gait cycles and five walking trials were included in statistical analysis to minimize individual trial variations. Temporospatial parameters of gait were analyzed using paired t-tests. With regard to kinematic data, because there were no differences between the left and right lower extremities, the averages of the right and left maximal sagittal ROM of the hip, knee and ankle joints were used for statistical analysis. Therefore, two separate 2 (condition) x 3 (ROM) repeated measures ANOVAs were used to analyze kinematic variables, one for stance, and swing phase. Due to left and right lower
extremity differences in EMG, each limb was analyzed separately for stance and swing phases. Therefore, four separate 2 (condition) x 5 (muscle) repeated measures ANOVAs were used to analyze the EMG data, two for stance, and two for swing phase, respectively. The α level was set at 0.05 for all statistical analyses.

RESULTS

Fifteen participants completed the study, 6 males and 9 females with an average age of 26.2 ± 8.3 years (range = 19 to 50 years) and an average height and weight of 171.8 ± 7.9 cm (range = 161 to 184.5 cm) and 65.8 ± 11.4 kg (range = 54.5 to 93.5 kg), respectively. Twelve participants reported a right leg dominance. Participants demonstrated significant differences (p < 0.000) between conditions (no EKSO and EKSO) on all temporospatial gait parameters (Table 1). Overall, participants in the EKSO walked slower with shorter steps and greater double limb support time.

Table 1. Temporospatial Gait Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>No EKSO</th>
<th>EKSO</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (m/s)</td>
<td>1.32 ± 0.16</td>
<td>0.31 ± 0.04</td>
<td>&lt; 0.000</td>
</tr>
<tr>
<td>Stride length (m)</td>
<td>1.41 ± 0.12</td>
<td>0.72 ± 0.14</td>
<td>&lt; 0.000</td>
</tr>
<tr>
<td>Double limb support (s)</td>
<td>0.17 ± 0.02</td>
<td>0.45 ± 0.06</td>
<td>&lt; 0.000</td>
</tr>
<tr>
<td>Left step length (m)</td>
<td>0.69 ± 0.06</td>
<td>0.34 ± 0.01</td>
<td>&lt; 0.000</td>
</tr>
<tr>
<td>Right step length (m)</td>
<td>0.72 ± 0.06</td>
<td>0.31 ± 0.16</td>
<td>&lt; 0.000</td>
</tr>
</tbody>
</table>

Note: m = meters, s = seconds, m/s = meters per second; SD = standard deviation.

Table 2 lists the maximal sagittal ROMs at the hip, knee and ankle joints for the stance and the swing phases. The ANOVA resulted in differences between EKSO and no EKSO conditions. In the stance phase, there were significantly less hip and ankle motions, but greater...
knee motions on both lower extremities for the EKSO condition. The ANOVA results also revealed significant differences between the two conditions for the knee and ankle motions in the swing phase, but not at the hip. Specifically, walking with EKSO produced equivalent hip motions, but less knee and ankle motions bilaterally in the swing phases. Figure 2 demonstrates lower extremity joint motion across the gait cycle.

**Table 2: Sagittal Range of Motion (mean ± SD) of Lower Extremity During Gait With and Without Wearing a Robotic Exoskeleton (EKSO).**

<table>
<thead>
<tr>
<th></th>
<th>Stance</th>
<th></th>
<th>Swing</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No EKSO</td>
<td>EKSO</td>
<td>No EKSO</td>
<td>EKSO</td>
</tr>
<tr>
<td>Hip</td>
<td>44.33±5.11</td>
<td>37.90±3.39</td>
<td>0.000*</td>
<td>42.42±4.92</td>
</tr>
<tr>
<td>Knee</td>
<td>23.07±4.52</td>
<td>28.62±5.39</td>
<td>0.006*</td>
<td>56.89±8.24</td>
</tr>
<tr>
<td>Ankle</td>
<td>18.39±2.44</td>
<td>11.74±2.21</td>
<td>0.000*</td>
<td>24.07±7.13</td>
</tr>
</tbody>
</table>

Note: SD = standard deviation; * Significant at p < 0.05.

**Figure 2. Lower Extremity Joint Motion Across the Gait Cycle (Mean with Standard Error).**

Note: % = percentage; Y-axis = range of motion

Table 3 lists the sEMG RMS values (%) of the 10 muscles for the stance and the swing phases. For the stance phase, the ANOVA results showed significant differences between no EKSO and EKSO conditions for all lower extremity muscle groups bilaterally. For the swing phase, the ANOVA results also showed significant differences between no EKSO and EKSO conditions only for distal muscle groups (bilateral soleus and tibialis anterior and left medial hamstrings). Figures 3 and 4 show lower extremity muscle activity across the gait cycle.
<table>
<thead>
<tr>
<th>Muscle</th>
<th>Stance Phase</th>
<th>No EKSO</th>
<th>EKSO</th>
<th>p-value</th>
<th>% difference</th>
<th>Swing Phase</th>
<th>No EKSO</th>
<th>EKSO</th>
<th>p-value</th>
<th>% difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>R GM</td>
<td>0.62±0.07</td>
<td>0.55±0.05</td>
<td>0.003</td>
<td>-11.3</td>
<td></td>
<td>0.59±0.13</td>
<td>0.62±0.10</td>
<td>0.470</td>
<td>6.9</td>
<td></td>
</tr>
<tr>
<td>R RF</td>
<td>0.66±0.08</td>
<td>0.54±0.07</td>
<td>0.001</td>
<td>-18.2</td>
<td>*</td>
<td>0.59±0.08</td>
<td>0.56±0.11</td>
<td>0.425</td>
<td>-5.1</td>
<td></td>
</tr>
<tr>
<td>R MH</td>
<td>0.64±0.07</td>
<td>0.55±0.09</td>
<td>0.010</td>
<td>-15.6</td>
<td>*</td>
<td>0.42±0.06</td>
<td>0.41±0.09</td>
<td>0.620</td>
<td>-2.4</td>
<td></td>
</tr>
<tr>
<td>R TA</td>
<td>0.61±0.04</td>
<td>0.49±0.06</td>
<td>0.000</td>
<td>-19.7</td>
<td>*</td>
<td>0.59±0.11</td>
<td>0.68±0.11</td>
<td>0.018</td>
<td>15.3</td>
<td></td>
</tr>
<tr>
<td>R SOL</td>
<td>0.61±0.06</td>
<td>0.54±0.09</td>
<td>0.003</td>
<td>-11.5</td>
<td>*</td>
<td>0.43±0.15</td>
<td>0.63±0.13</td>
<td>0.004</td>
<td>46.5</td>
<td></td>
</tr>
<tr>
<td>L GM</td>
<td>0.63±0.04</td>
<td>0.56±0.05</td>
<td>0.001</td>
<td>-11.1</td>
<td></td>
<td>0.61±0.08</td>
<td>0.64±0.07</td>
<td>0.222</td>
<td>4.9</td>
<td></td>
</tr>
<tr>
<td>L RF</td>
<td>0.64±0.06</td>
<td>0.54±0.09</td>
<td>0.003</td>
<td>-14.3</td>
<td></td>
<td>0.57±0.10</td>
<td>0.55±0.13</td>
<td>0.723</td>
<td>-1.8</td>
<td></td>
</tr>
<tr>
<td>L MH</td>
<td>0.62±0.09</td>
<td>0.52±0.09</td>
<td>0.007</td>
<td>-16.1</td>
<td></td>
<td>0.59±0.09</td>
<td>0.52±0.10</td>
<td>0.036</td>
<td>-13.6</td>
<td></td>
</tr>
<tr>
<td>L TA</td>
<td>0.62±0.08</td>
<td>0.56±0.10</td>
<td>0.032</td>
<td>-9.7</td>
<td>*</td>
<td>0.60±0.08</td>
<td>0.71±0.06</td>
<td>0.000</td>
<td>18.3</td>
<td></td>
</tr>
<tr>
<td>L SOL</td>
<td>0.60±0.04</td>
<td>0.52±0.07</td>
<td>0.004</td>
<td>-13.3</td>
<td>*</td>
<td>0.42±0.14</td>
<td>0.62±0.13</td>
<td>0.001</td>
<td>47.6</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Amplitude of Lower Extremity Electromyographic Muscle Activity (mean ± SD) During Gait with and without Wearing a Robotic Exoskeleton (EKSO).
Note: SD = standard deviation; R = right; L = left; GM = gluteus medius; RF = rectus femoris; MH = medial hamstring; TA = tibialis anterior; SOL = soleus; % = percentage; * = significant at < 0.05.

Figure 3. Right Lower Extremity Electromyographic Muscle Activity Across the Gait Cycle (Mean with Standard Error).

Note: Med Hams = medial hamstrings; % = percentage; Y-axis = Volt

Figure 4. Left Lower Extremity Electromyographic Muscle Activity Across the Gait Cycle (Mean with Standard Error).

Note: Med Hams = medial hamstrings; % = percentage; Y-axis = Volt

DISCUSSION

The results showed that walking in an EKSO was dissimilar from typical walking with regard to the lower extremity muscle activity and joint motions, as well as temporospatial gait parameters. Overall, the participants in this study walked in the EKSO at approximately one fourth their average walking speed with nearly half the stride length. These changes likely contributed to an increase in double limb support time. Although the participants were instructed to walk at a self-selected pace during each condition, the participants were unable to match their typical walking performance when walking in the EKSO. One possible explanation for these observed differences is the lack of training by our participants in the EKSO. Even though the participants were instructed in how to initiate a step and given 15 minutes of practice time, this short training may not have been sufficient to allow the participants to reach optimal exoskeleton gait performance. However, a second possible explanation for the differences observed in
temporospatial parameters is the current robotic exoskeleton technological limitations. Specifically, mechanical design and actuators of contemporary exoskeletons are known to limit gait performance and capacity [18]. For instance, actuators are located at the hip and knee joints, but not ankle joints. Contemporary ankle joints are typically either a fixed solid plate or tension spring motion plates.

With changes in temporospatial parameters, it was expected that muscle activity would be impacted as well. It has been shown that walking at slower speeds resulted in decreased muscle activity of the lower extremities during both the stance and swing phases of gait regardless of age [19]. Similarly, we observed an average reduction of nearly 15% muscle activity during stance phase in both lower extremities (see Table 3). This reduction may have been caused by the reduction in speed or by the structural support provided by the EKSO device. However, we did not see a similar reduction in muscle activity in swing phase. On the contrary, an increase of 32% in muscle activity of the distal lower extremity was observed in our study. We speculate that the increase in muscle activity in our study was a result of the EKSO mechanical constraints [18]. In particular, the EKSO footplate limits ankle motion, and this may have required participants to compensate for the reduced ankle mobility.

Beyond limiting ankle ROM, we observed several changes in lower extremity kinematics when walking in the EKSO as compared to when walking without EKSO. During the stance phase, we observed less hip and ankle motion, but greater knee motion when wearing the EKSO. In swing phase, we observed less knee and ankle motions, but no difference in hip motion with EKSO. Overall, it appears that gait in EKSO produced a gait pattern where shorter steps due to limited ankle motion contributed to a shortened trailing limb. Moreover, the limited ankle motion also likely required greater knee flexion during stance. On the EKSO, the footplate and
corresponding upright support does not allow for optimal ankle joint motion. Rather, the mechanical constraints of the EKSO ankle joint appear to influence lower extremity kinematics as well as corresponding muscle activity.

Our participants were without injury and when not in the EKSO, demonstrated walking parameters consistent with typical gait. For individuals with neurologic dysfunction, return to walking is a primary focus of rehabilitation. As previously reported, gait training after neurologic injury should include proper loading the sole of the foot and attain adequate hip extension to facilitate appropriate muscle activation [7]. The findings of this study question whether mechanical constraints in current versions of robotic exoskeletons preclude the possibility of promoting kinematics suitable to induce satisfactory muscle activity. Our participants were novice EKSO users who were tested during their first session wearing EKSO. It is possible that a longer training time with EKSO might have promoted more typical EMG patterns despite the mechanical constraints. Additionally, people with biomechanical limitations from various neurologic and orthopedic injuries are able to walk, albeit with an altered gait cycle and atypical muscle activity [20-22]. Although EKSO does not appear to promote normal gait, it may stimulate an altered functional gait. Although an altered gait is potentially less efficient [23], this functional gait may meet the mobility objectives of a person recovering from neurologic injury.

Limitations

There are several limitations in this study. First, our sample of 15 participants was primarily young, active individuals and this may have limited generalizability of our conclusions. Further, the EKSO requires the use of an assistive device (cane, walker, forearm crutches) while walking. In this study with healthy individuals, we elected not to use an assistive device but provided close supervision to prevent a loss of balance. Use of an assistive device as
recommended by robotic exoskeleton companies may have further altered gait kinematics and muscle activity.

**Conclusion**

EKSO appears to promote a type of gait that is disparate from normal gait in first time users. Specifically, mechanical constraints of the EKSO appeared to alter joint motion and influence muscle activity throughout the gait cycle. More research will be necessary to determine the impact of a robotic exoskeleton on rehabilitation in people with gait impairment.

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**DECLARATION OF INTEREST**

All authors declare no conflict of interest.
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