Robotic Exoskeleton Gait Training for Inpatient Rehabilitation in a Young Adult with Traumatic Brain Injury

Karen J. Nolan, Kiran K. Karunakaran, Member, IEEE, Naphtaly Ehrenberg, and Adam G. Kesten

Abstract—Severe and moderate traumatic brain injury (TBI) causes motor deficits leading to impairments in functional ambulation. Motor recovery involves intensive rehabilitation through physical therapy. Current practices in rehabilitation results in variable recovery of motor function and may result in residual gait deviations. Wearable robotic exoskeletons can provide the user with intensive, goal-directed repetition of movement as well as provide the user with stability and balance during gait, compared to conventional physical therapy. During the acute stage of recovery, the brain is healing and relearning and increased intensive motor rehabilitation throughout this stage could result in improved functional ambulation, especially in individuals with severe impairments who are not independent ambulators. This pilot study evaluates the effect of early intervention robotic exoskeleton gait training on lower extremity biomechanics on a 21 year old young adult with TBI.

I. INTRODUCTION

Traumatic brain injury (TBI) is a leading cause of disability in children and adults. There are currently 5.3 million individuals living with the sequelae of TBI and an estimated 2.4 million new injuries reported annually [1]. Individuals with moderate to severe TBI often have deficits in motor function, balance and coordination resulting in inefficient gait and reduced speed during ambulation [2]. Motor recovery post TBI involves rehabilitation through intensive physical therapy which is based on neural adaptation, and progressive task specific repetitive practice based on the principles of neuroplasticity [7, 8]. During conventional gait therapy, individuals with TBI relearn balance and motor skills required for independent ambulation. Conventional therapy has produced improvements in ambulation and motor function but physical therapists may not always be able to provide enough mass practice and repetition for individuals with moderate to severe impairments that require maximum physical assistance during motor practice. Current practices in rehabilitation results in variable recovery of motor function and may result in residual gait deviations. As a result, these residual motor and balance deficits [6], patients develop compensation mechanisms such as hip hiking [5], circumduction [5], steppage [3], and prolonged weight transfer [4] in order to achieve successful ambulation.

During the acute stage of recovery post TBI robotic exoskeleton (RE) based gait training may have the potential to provide early, consistent, and quantitative mobility during motor rehabilitation. REs are electromechanical devices with actuators to provide torque about the human anatomical joint locations of the hip, knee, and/or ankle in the sagittal plane to assist or perform gait [11]. These devices can provide the user with intensive, goal-directed repetition of movement as well as provide the user with stability and balance during gait. Research has shown when during the acute stages of injury, the brain is more susceptible to plasticity or recovery [13]. Therefore, increased intensive rehabilitation during the acute stages of injury could result in improved gait recovery. The purpose of this investigation was to evaluate the effect of early intervention exoskeleton gait training on lower extremity biomechanics for a young adult with TBI.

II. METHODOLOGY

A. Participant

A 21 year old right handed male (height 1.85 m; weight 75.1 kg) currently admitted to an inpatient rehabilitation facility (IRF) post TBI with right-sided hemiplegia, was recruited for participation. The participant was diagnosed with a traumatic subarachnoid hemorrhage and a diffuse axonal injury, (Glasgow Coma Scale of 3T at the time of injury). The participant was admitted to the IRF 30 days post injury and was dependent for all activities of daily living. The motor functional independence measure (FIM) score changed by 35 points from admission (12 points) to discharge (47 points) from IRF, the minimal clinically important difference (MCID) for the motor FIM is 17 points. At the time of enrollment (58 days post injury) the participant was able to: 1) stand upright for 30 minutes with assistance; 2) follow one step instructions and communicate discomfort; and 3) physically fit into the RE - weight (≤220 lbs.), height (≤6’2”), hip width (14-18”). The participant had no additional orthopedic, neuromuscular, or severe neurological pathologies (unrelated to their TBI) that would interfere with their ability to walk. All procedures performed in this investigation were approved by the Human Subjects Review Board and informed consent was obtained prior to study participation.

B. Robotic Exoskeleton Gait Training

Robotic exoskeleton gait training was administered via a commercially available FDA approved robotic exoskeleton (Figure 1, Ekso-GT, Ekso Bionics, Inc., Richmond, CA, USA) for 30 minutes per day, 3 days per week for 4 weeks during inpatient rehabilitation. A licensed physical therapist directed

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K. K. Karunakaran is with Kessler Foundation, West Orange, NJ-07052, Member, IEEE, New Jersey Institute of Technology, Newark, NJ and Children's Specialized Hospital, New Brunswick, NJ (email: kkarunakaran@kesslerfoundation.org)

K. J. Nolan is with Kessler Foundation, West Orange, NJ-07052, and N. Ehrenberg is with Kessler Foundation, West Orange, NJ-07052, and Children's Specialized Hospital, New Brunswick, NJ (email: nehrenberg@kesslerfoundation.org).

A. G. Kesten is with Kessler Institute of Rehabilitation, West Orange, NJ-07052 (e-mail: AGKesten@kessler-rehab.com)
all robotic exoskeleton gait training sessions and adjusted the ambulation assistance according to the participant’s progress. The device provides variable motor assistance to participants by assisting the angular joints of the lower extremity through a predefined repetitive trajectory to complete a gait pattern. The RE has two active degrees of freedom bilaterally, at the hip and knee, and a passively sprung ankle joint with adjustable stiffness in the sagittal plane, with an additional two passive degrees of freedom at the hip in the frontal and transverse planes.

Figure 1. Robotic exoskeleton used during 4 weeks of inpatient gait training, Ekso-GT, Ekso Bionics, Inc.[12]

C. Data Collection Procedures

Motion analysis data was collected at 120 Hz (Motion Analysis Corporation, Santa Rosa, CA, USA) at baseline (admission to the study) and follow-up (post 4 weeks of RE training). During each gait analysis session retroreflective markers were placed on anatomical landmarks of the participant based on a modified Helen Hayes marker set in order to quantify kinematic joint angles and temporal spatial parameters during walking. The participant performed ~2-4 walking trials (10 meter distance for each trial) with and without the RE at a self-selected pace and wore shoes for all walking trials. While walking without the RE, the physical therapist provided physical assistance for trunk support, weight transfer and balance. While walking with the RE the participant used a quad cane on the left side. The participant did not utilize any other lower extremity assistive device or dorsiflexion wrap/brace while walking with or without the RE. The participant was allowed to rest or take breaks at any time to minimize the effects of fatigue.

During baseline gait assessments in the RE, an assistive torque was provided bilaterally in the sagittal plane at the hip and knee to complete the preprogrammed gait cycle. All steps were initiated by the participant and in order to trigger a step, the participant performed a lateral weight shift to a predetermined distance from midline to initiate advancement of the back (pre-swing) leg. Auditory cues were delivered as feedback about the extent of lateral and anterior weight shifts performed. Although the anterior weight shift was not a trigger for step advancement, it is important during gait training for normal and efficient weight distribution and anterior progression throughout the gait cycle.

During follow-up gait assessments in the RE, an assistive torque was provided at the hip and knee to the participant’s right leg (affected side) to complete the preprogrammed gait cycle within the specified time duration. For the left side, torque was only provided to the hip and knee in the sagittal plane to offset the weight of the device throughout the gait cycle. Auditory cues were not provided as the subject was able to perform weight shifts and properly orient his body position in both the sagittal and frontal planes in the RE.

D. Data Analysis

Motion Analysis’ Cortex and Mathworks’ MATLAB were used for data analysis. The following characteristics were compared between the two condition and between both sessions: a) The kinematic joint angles of the hip, knee and ankle were computed from joint positions in the sagittal plane. The joint angles were filtered using a 4th order low pass filter, and the filtered data was divided into gait cycles based on the heel strikes of the ipsilateral leg. The average hip, knee and ankle joint angles were then computed; b) The step length was calculated as the difference between the x position of the contralateral heel and the ipsilateral heel; c) The total swing and stance time for the affected side were computed based on the toe off and heel strike of the ipsilateral and contralateral leg for each gait cycle respectively; d) The walking speed was computed from the Cartesian x, y, z position of the ipsilateral heel strikes and time; e) The temporal characteristics were computed as follows: Initial double support (IDS) = Time (Ipsilateral Heel Strike - Contralateral Toe Off) x 100/Total time for the gait cycle. Single Support (SS) = Time (Contralateral Toe Off - Contralateral Heel Strike) x 100/Total time for the gait cycle. Terminal double support (TDS) = Time (Contralateral Heel Strike - Ipsilateral Toe Off) x 100/Total time for the gait cycle. Swing = Time (Ipsilateral Toe off - Ipsilateral Heel Strike) x 100/Total time for gait cycle; and f) Lateral Foot Displacement was calculated as the maximum displacement of the ankle during swing phase. The lateral foot displacement is a quantitative measure of hip circumduction.

III. RESULTS

A. Sagittal Plane Kinematics

Figure 2 shows the sagittal plane kinematics of the hip, knee and ankle with and without the RE on the affected side at both time points. There is reduced variability for the hip, knee, and ankle when walking in the RE as compared to walking without the RE throughout the gait cycle at baseline and 4 weeks post RE. Also, the joint angles on the affected side more closely matched the unaffected side when in RE. There is an observed offset on the unaffected side at 4 weeks post with the RE at the ankle joint (Figure 2c) which may be due to marker placement, though the absolute range of motion is correct. For all three joint angles on the affected side there is also reduced variability at 4 weeks as compared to baseline when walking without the RE. The angle at the ankle shows increased plantar flexion during initial stance followed by increased dorsiflexion compared to baseline without the RE.

B. Lateral Foot Displacement

Hip circumduction was quantified using lateral foot displacement. The lateral foot displacement increased (Table I) on the affected side at 4 weeks post indicating increased circumduction compared to baseline without the RE.
TABLE I. LATERAL FOOT DISPLACEMENT

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<tr>
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<th>Affected</th>
<th>Unaffected</th>
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<tbody>
<tr>
<td></td>
<td>Baseline</td>
<td>4 Week Post</td>
</tr>
<tr>
<td>Mean (mm)</td>
<td>89.92</td>
<td>161.45</td>
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<tr>
<td>Std. Error</td>
<td>25.98</td>
<td>14.83</td>
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C. Temporal and Spatial Parameters

Temporal and spatial parameters on the affected side with the RE were consistent at baseline and 4 weeks post intervention (Figure 3a, c, d & e), except for the swing time (Figure 3b) which decreased at 4 weeks post. Percent time spent in the stance phase also increased (Figure 3f) from baseline to 4 weeks post RE. Average walking speed and step length decreased from baseline to 4 weeks post. While walking in the RE at admission and 4 weeks post 79-82% of the gait cycle is spent in stance on the affected side. Without the RE post intervention the participant spent 11% more time in stance throughout the gait cycle (from 59% at baseline to 70% post). On the unaffected side the participant spent 78-86% of the gait cycle in stance regardless of condition. The total time to complete a gait cycle (Figure 3a), and stance time (Figure 3c) on the affected side increased from baseline to 4 weeks post without the RE.

IV. DISCUSSION AND CONCLUSIONS

Individuals with moderate to severe TBI experience motor deficits, and motor recovery may be gradual, taking up to several months, years, or longer. Successful execution of a movement involves co-ordination between various systems (visual, vestibular, proprioception) in the central nervous system. During a TBI, one or more of these systems could experience varying levels of damage and each system may have varying rates of recovery. In this case study we evaluate the effect of early intervention RE gait training for a young adult diagnosed with TBI. According to the motor FIM score this participant significantly improved their motor function from admission to discharge from the IRF.

Without the RE at baseline the participant had decreased dorsiflexion during swing and decreased plantarflexion (Figure 2c) during stance. The decreased dorsiflexion during swing impairs toe/foot clearance during swing leading to pathological compensations to clear the foot such as toe drag, hip circumduction, or a combination of both. Also evident is increased variability in the ankle joint angle throughout the gait cycle which may indicate an inability to control the ankle joint (i.e. dorsiflex/plantar flex their foot) without the RE at baseline. Also, without the RE at baseline on the affected limb, the participant had increased variability at the hip and knee joint angle throughout the gait cycle (Figure 2a and 2b), which may indicate lack of control in these joints as well.

During the post assessment (4 weeks post RE), the participant demonstrated an increased functional range of motion at the ankle with increased plantar flexion during initial stance and increased dorsiflexion (foot clearance) during...
swing (Figure 2c). Decreased variability in the hip, knee and ankle (Figure 2a, 2b, 2c) joints was observed compared to baseline, possibly indicating the emergence of more consistent and controlled joint trajectories in the sagittal plane throughout the gait cycle.

The compensatory mechanism of hip circumduction on the affected side increased (Table I) at 4 weeks post without the RE, despite the RE restricting circumduction during gait training. Circumduction is a pathological compensation for hip and knee weakness and/or lack of control during swing that is typically observed during recovery to improve limb advancement. Although not ideal, participants adopt compensatory mechanisms to successfully walk when unable to ambulate in an efficient pattern due to their injury. The participant was receiving conventional gait therapy in addition to RE therapy to achieve independent ambulation. Therefore, hip circumduction at this stage of recovery may be facilitating mobility and could be helpful in achieving more independent walking [16].

The functional outcome measures of total time, and stance time increased (Figure 3a and 3c) while step length and speed decreased (Figure 3d and 3e) from baseline to 4 weeks post without RE. Based on temporal characteristics (Figure 3f), during walking trials with the RE (at baseline and 4 weeks post) there was a prolonged stance phase, but this was consistent bilaterally indicating a more symmetrical gait cycle when walking with the RE. Thus the participant was trained to perform a temporally symmetrical gait cycle. Before the RE intervention at baseline, the participant was asymmetrical (Figure 3f) during ambulation without RE and spent more time in stance phase on the unaffected limb than the affected limb which is commonly seen in hemiplegic gait. After the RE intervention, there was an increase in stance on the affected side without the RE at 4 weeks post, demonstrating increased symmetry compared to baseline.

Ankle, knee, and hip variability decreased and the total gait cycle (stance to swing) was more symmetrical bilaterally after the RE intervention indicating that the participant is learning to walk in a more consistent and less variable environment. The ideal amount and duration of RE training is still to be determined but this preliminary evidence begins to demonstrate the potential impact of RE gait training on early intervention motor rehabilitation. The results from this single participant are promising, however further validation is needed with a larger sample size.

References

[12] Ekso Bionics Website: http://www.eksobionics.com/ekso

Figure 3. Mean (±/std. error) for the affected side: a) total time to complete a gait cycle; b) swing time; c) stance time; d) step length; and e) speed. Temporal characteristics for the affected and unaffected side with and without RE: f) percentage of initial double support (IDS), single support (SS), terminal double support (TDS), and swing during gait cycle.