Locomotor training through a 3D cable-driven robotic system for walking function in children with cerebral palsy: a pilot study

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Abstract— **Locomotor training using treadmill has been shown to elicit significant improvements in locomotor ability for some children with cerebral palsy (CP), the functional gains are relatively small and it requires greater involvement from a physical therapist. Current robotic gait training systems are effective in reducing the strenuous work of a physical therapist during locomotor training, but are less effective in improving locomotor function in some children with CP due to the limitations of the systems. Thus, a 3D cable-driven robotic gait training system was developed and tested in five children with CP through a 6 week of long-term gait training. Results indicated that both overground walking speed and 6 minute walking distance improved after robot assisted treadmill training through the cable-driven robotic system, and partially retained at 8 weeks after the end of training. Results from this pilot study indicated that it seems feasible to conduct locomotor training in children with CP through the 3D cable-driven robotic system.**

I. INTRODUCTION

Cerebral palsy (CP) is the most prevalent physical disability originating in childhood with an incidence of 2-3 per 1,000 live births [1]. Most of children with CP have difficulty in walking [2, 3]. Reduced waking speed and endurance are two of the main functional limitations [4]. Attaining functional walking ability is often an important functional goal for children with CP. Ambulation plays a central role in healthy bone development [5] and children who are able to ambulate are more accomplished in activities of daily living and social roles, such as participation in the community, than children who use a wheelchair [6]. The development of independent walking capacity and endurance are often the focus of therapeutic interventions for children with CP.

Body weight supported treadmill training (BWSTT) has been used to improve the locomotor function in children with CP [7]. While statistically significant improvements in walking capacity with BWSTT have been shown, the function gains are relative small [8]. In addition, BWSTT requires greater involvement from a physical therapist [9].

Recently, the pediatric Lokomat (Hocoma AG, Volketswil, Switzerland) has been developed to provide robotic assistance in children with CP [10]. While current robotic system is effective in reducing therapist labor during locomotor training and increasing the total duration of training, it shows relatively limited functional gains for some children with CP. For instance, a recent randomized study indicated that only 0.02 ± 0.12 m/s (0.04 ± 0.11 m/s for the control group and with no significant difference between two groups) gait speed improvement was obtained following prolonged (20 sessions) robotic BWSTT using the pediatric Lokomat [24].

The less effectiveness of current robotic system may be due the following limitations: For instance, the limited degrees of freedom of the pediatric Lokomat only allows movement in the sagittal plane, which may severely affect gait dynamics [11]. In addition, a fixed trajectory control strategy and low backdrivable ball screw actuators used in the current robotic system may encourage a passive instead of active training. Thus, there is a need to develop new robotic systems to improve locomotor function in children with CP.

Results from animal and human studies suggested that the neural reorganization achieved during rehabilitation is highly dependent on the magnitude and specificity of neural activity. Thus, increasing intensity of neural activity during locomotor training should improve the training effect, consistent with use-dependent synaptic plasticity, as expressed in “Hebb’s Rule” [12]. As a result, motor training paradigms that emphasize active movements are more effective in producing plasticity in spinal circuits and should increase volitional locomotor performance when compared to passive movement training [13, 14]. In addition, practice is more effective when it is task-specific [15, 16].

A natural gait pattern includes movements of the hip joint in the coronal plane (ab-/adduction) and lateral movements of the pelvis to displace the body's center of

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mass over the weight-bearing leg [17]. In addition, motor learning studies indicate that the more similarities between tasks of learning and application, the more transfer will take place [18]. Thus, we postulate that the carryover from treadmill training to overground walking will be improved if subjects walk on a treadmill with more natural gait patterns, while applying forces to both the pelvis and legs. Further, we postulate that repeated exposure of pelvis and leg assistance force during treadmill training may induce functional improvements in walking speed and endurance in children with CP.

II. METHOD

A. Subjects

Five children (two girls) with spastic CP were recruited to participate in this study. Mean age was 12.8 ± 2.8 years old. According to the Gross Motor Function Classification System (GMFCS) [19], 2 of them were classified as level II, 2 of them were classified as level III, and 1 of them were classified as level IV. Three of them were quadriplegia and two of them were diplegia. Inclusion criteria: a) age 4 - 16 years old; b) spastic CP; c) without Botulinum toxin treatment or surgery within 3 months before the onset of the study; d) GMFCS levels was I to IV; e) able to signal pain, fear or discomfort reliably.

Exclusion criteria: a) severe lower extremity contractures, fractures, osseous instabilities, and osteoporosis; b) severe disproportional bone growth and unhealed skin lesions in the lower extremities; c) thromboembolic diseases, cardiovascular instability, and aggressive or self-harming behaviors. All subjects required medical clearance for participation. All procedures were approved by the Institutional Review Board of Northwestern University Medical School. Written informed consent was obtained from all subjects.

B. Apparatus:

A custom designed 3D cable-driven gait training system 3DCaLT was used to apply controlled forces to the pelvis and legs during treadmill walking, see Figure 1. The cable-driven robotic gait training system for leg assistance has been reported before [20]. In this study, additional two motors (AKM33H, Kollmorgen, Drive amplifier, Servostar 30661) were attached at the side of treadmill to provide controlled forces at the pelvis. Four cables, consists of nylon-coated stainless-steel cables (1.6mm), driven by four motors, are affixed to custom braces that are strapped to the pelvis and legs to provide controlled forces to the pelvis and legs. The cable-driven system is compliant and highly backdrivable [20], which allows freedom for the patients to voluntarily move their limbs with a naturalistic gait pattern. Two custom designed 3D position sensors were attached at the pelvis and leg above ankle and were used to record pelvis and ankle position during treadmill walking. The ankle position signals were used to trigger pelvis and ankle loading at targeted phase of gait. Tension/compression loadcells (MLP-25, Transducer Techniques, CA) were integrated into the ankle straps and waist brace in series with cables through which the ankle and the pelvis assistance forces were delivered.

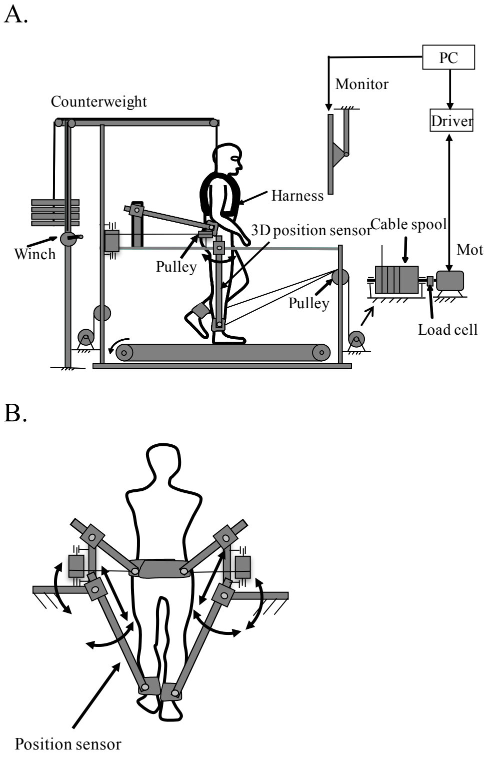

Figure 1. The illustration of the 3D cable-driven robotic gait training system. **A**. Side view of the cable-driven robotic system. Two cables were attached to the ankle of the leg for leg swing assistance. **B**. Back view of the 3D cable-driven robotic system. Two cables were attached to the pelvis for providing controlled mediolateral force for weight shift.

C. Protocol:

Treadmill training was performed 3 times per week for 6 weeks with the training time for each visit set at 30-40 minutes, as tolerated, excluding setup time. Treadmill speed was set at maximum comfortable walking speed and gradually increased during the course of training. Body weight support was provided as necessary to prohibit knee buckling or toe drag during treadmill training and gradually decreased during the course of 6 weeks of training. The peak value of the pelvis assistance force was set at ~9% of body weight, and the peak leg assistance force was set at ~4% of body weight, although these peak forces were adjusted based on the tolerance of each subject. The leg assistance load was applied to the ankle starting from late stance to mid-swing, and the pelvis assistance was applied in the mediolateral direction starting heel touch down to mid-stance.

Gait assessment was made at the beginning, post 6 weeks of training, and at 8 weeks after the end of training, using gait speed, endurance (6 minutes walking distance, [21]), and clinical measures of motor function (the dimensions D (standing) and E (walking, running, jumping) of the Gross Motor Function Measure (GMFM-66), [22]) and muscle tone or spasticity (the Modified Ashworth Scale, [23]). Self-selected and fast overground walking speeds were tested using GaitRite (CIR Systems Inc. Sparta, NJ) before and after robot assisted treadmill training, and 8 weeks after the end of training. Three trials were tested for each speed and averaged across three trails.

D. Data analysis

Five children with CP participated in this study and finished all the training and assessment sessions. One subject was sick just before the post training assessment, which may affect the assessment result. Thus, the data from this subject were not included in data analysis. Data were analyzed using scores pre- to post 6 weeks of training, and pre to 8 weeks follow up assessment. Repeated measures ANOVAs were conducted with significance noted at $p < 0.05$.

III. RESULT:

Following 6 weeks of robotic treadmill training through the 3D cable-driven robotic gait training system, both self-selected and fast walking overground gait speed increased for children with CP, although these were no significant due to the small sample size, see Figure 2. Specifically, self-selected and fast walking speeds increased from 0.73 ± 0.27 m/s to 0.78 ± 0.17 m/s (p = 0.5, ANOVA, n = 4), see Figure 2A, and from 1.02 ± 0.34 m/s to 1.08 ± 0.27 m/s (p = 0.3, n = 4) after treadmill training, see Figure 2B. Further, improvements in walking speed were partially retained at follow up (i.e., 0.76 ± 0.25 m/s, p = 0.4 and 1.11 ± 0.37 m/s, p = 0.4, for self-selected and fast walk speeds, respectively). Six minute walking distance increased from 273.4 ± 43.8 m to 304.7 ± 80.6 m after robot assisted treadmill training, although no significant difference was noted (p = 0.26), and was 291.5 ± 99.8 m at follow up (p = 0.6), Figure 3C. In addition, GMFM score also slightly increased from 60.5 ± 8.0 to 61.5 ± 7.2 after robotic treadmill training, and was 61.9 ± 9.0 at the follow up. Spasticity had no change after robotic treadmill training. Specifically, the average of Modified Ashworth Scale score was 0.7 ± 0.2, 0.7 ± 0.7 and 0.6 ± 0.4 before, after robotic treadmill training, and at the follow up, respectively.

Spatialtemporal parameters during overground walking also changed associated with the improved walking speeds after robotic treadmill training. Specifically, the step frequency during walking at a self-selected speed increased from 93.8 ± 25.3 step/min to 103.1 ± 21.9 step/min after robotic treadmill training, and was 99.3 ± 24.6 step/min at the follow up, although no significant difference was noted ($p > 0.05$). In addition, the step frequency during walking at fast speed increased from 126.0 ± 39.0 step/min to 133.1 ± 33.6 step/min after robotic treadmill training, and was 130.7 ± 37.2 step/min at the follow up. In contrast, only modest changes in step length during walking at self-selected and fast speeds were noted after robotic treadmill training through the 3D cable-driven robot. Specifically, step length during walking at a self-selected speed was 0.46 ± 0.07 m, 0.45 ± 0.06 m, and 0.45 ± 0.05 m, before, after treadmill training, and at the follow up, respectively. The step length during walking at fast speed was 0.48 ± 0.04 m, 0.49 ± 0.1 m, and 0.51 ± 0.06 m, before, after treadmill training, and at the follow up, respectively.

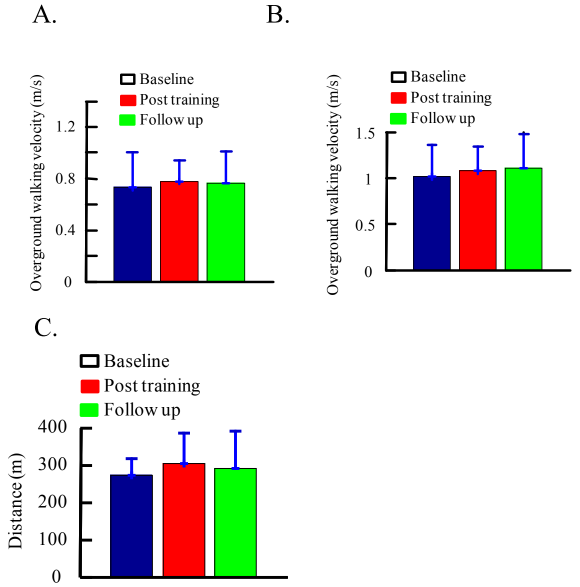

Figure 2. Self-selected, **A**, and fast overground walking speed, **B**, and 6 minute walk distance, **C**, before and after 6 weeks of robotic treadmill training with the 3D cable-driven robotic gait training system, and 8 weeks after the end of training. Data shown in the figure are the mean and standard deviation of gait speed and distance across subjects.

IV. DISCUSSION:

The 3D cable-driven robotic gait training system was used to improve overground walking speed and endurance (assessed using 6 minute walking distance) in children with CP through 6 weeks of treadmill training. Further, the improvements in walking speed and endurance were still partially retained at the follow up, suggesting clinical significance of these robotic training paradigms. Results from this study suggest that robot assisted treadmill training in conjunction with the application of applying controlled forces to both the pelvis and legs, while allowing for a natural stepping pattern seems feasible in improving overground walking speed and endurance in children with CP.

One of the key components of this 3D cable-driven robotic gait training system is that it provides controlled assistance load to both the pelvis, for weight shift, and leg at the ankle, for leg swing, which is distinguished from current pediatric robotic gait training systems. Current pediatric robotic gait system, such as the pediatric Lokomat, only allows for movements in the sagittal plane but provides constraints on the pelvis movement in the mediolateral direction during robot assisted treadmill training. However, a natural gait pattern includes movements of the hip joint in the coronal plane (abduction/adduction) and lateral movements of the pelvis to displace the body's center of mass over the weight-bearing leg [17]. Thus, these constraints may severely affect gait dynamics in children with CP during treadmill training. In contrast, the gait pattern during treadmill training using the 3D cable-driven robot is more close to the natural overground walking pattern. For instance, the 3D cable-driven robotic system provides no constraints on pelvis movement in mediolateral direction but only assistance force for facilitating weight shift. Results from motor learning studies indicate that the more similarities between tasks of learning and application, the more transfer will take place [18]. In addition, cable-driven robotic system is highly backdrivable, which may encourage active involvement of children with CP during locomotor training. Thus, improvements in speed and frequency during overground walking at self-selected and fast speeds after robot assisted treadmill training may be due to the transfer of motor skills obtained during treadmill training to real world overground walking.

Repeated exposure of treadmill training through the 3D cable-driven robotic gait training system may induce functional improvements in walking speed and endurance. In particular, we observed a retention of the functional gains at 8 weeks after the end of treadmill training, suggesting a clinical significant of such training paradigm. This pilot study has several limitations. For instance, the sample size is small and there is no control group with assistance provided by a physical therapist. A randomized controlled long term training study is on going.

V. CONCLUSION

Locomotor training through a treadmill while applying controlled assistance forces at both the pelvis and leg may improve walking speed and endurance in children with CP. Thus, it seems feasible to improve locomotor function in children with CP through the 3D cable-driven robotic gait training system.

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