ROBOT-ASSISTED GAIT TRAINING FOR CHILDREN WITH CEREBRAL PALSY: A LITERATURE REVIEW

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ABSTRACT Cerebral palsy (CP) is a motor dysfunction due to nonprogressive neurological brain disorder in early development that leads to motor deficits, particularly involving gait and posture. CP is the most common child onset neuromotor disability, affecting over 17 million people worldwide. Most children with CP walk with abnormal gait patterns such as equinus or crouch gait, leading to secondary impairments and low quality of life. The most common treatments for crouch gait include surgery, botulinum toxin injections, physical therapy/strengthening, and orthotic interventions. Orthopaedic surgeries such as hamstring lengthening are advocated when hamstring muscles become excessively short; however, repeat lengthening is contraindicated. Recently, robot-assisted gait training (RAGT) has been used as a repetitive and task-specific therapy for children with CP. Exoskeleton intended to treat crouch gait by providing extension torque at the knee joint and on its ability to increase knee extension during over-ground walking in children with CP. Providing a more upright posture and the accompanying favourable reduction in the knee extensor moment over extended periods of time could be critical for stopping or slowing the progression of crouch through adolescence and early adulthood. The powered exoskeleton significantly altered lower extremity kinematics and reduced the crouch gait. In addition, the overall knee range of motion for the entire gait cycle was significantly increased during walking with the powered exoskeleton, resulting in a closer trajectory to that of normal waking. With technology playing an increasing role in health care, there is potential for robot-assisted gait training to play a role in the rehabilitation of people impacted by CP and other neurological conditions. Most studies have identified an emerging body of evidence suggesting that robot-assisted gait training could improve gait in individuals with CP with minimal adverse effects and over long-term use.

KEYWORDS Robot-Assisted Gait Training, Cerebral Palsy, driven gait orthoses, partial body-weight supported treadmill training

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Introduction

Cerebral palsy

Cerebral palsy (CP) is a motor dysfunction due to nonprogressive neurological brain disorder in early development that leads to motor deficits, particularly involving gait and posture[1-2]. CP is the most common child onset neuromotor disability, affecting over 17 million people worldwide[2]. Most children with CP walk with abnormal gait patterns such as equinus or crouch gait.
gait, leading to secondary impairments and low quality of life. Crouch gait is characterized by excessive knee flexion in early and/or mid stance and may be accompanied by other deficits at the hip and/or ankle. Muscle weakness, spasticity, contractures, and impaired selective motor control have all been shown to contribute to crouch gait in CP to varying degrees across individuals. Crouch gait can lead to joint pain, degenerative arthritis due to elevated joint contact forces, bony deformities, increased risk of falls from inadequate foot clearance, and increased walking energy demands. The most common treatments for crouch gait include surgery, botulinum toxin injections, physical therapy/strengthening, and orthotic interventions. Orthopaedic surgeries such as hamstring lengthening are advocated when hamstring muscles become excessively short; however, repeat lengthening is contraindicated[1-3].

**Robot-Assisted Gait Training**

The number of technological devices that therapists can utilize to treat people with neurological impairments has grown substantially during the last decade, both in adulthood and childhood, in several motor diseases. Robot-based therapies have been developed and improved beyond reducing the clinician’s effort. Alongside this growth in clinical use, research involving robotic therapy has grown rapidly. Despite this increase in research activity and clinical use, the effectiveness of robot-assisted interventions in neurorehabilitation is still in debate[4-6]. Recently, robot-assisted gait training (RAGT) has been used as a repetitive and task-specific therapy for children with CP. Exoskeleton intended to treat crouch gait by providing extension torque at the knee joint and on its ability to increase knee extension during over-ground walking in children with CP. Providing a more upright posture and the accompanying favourable reduction in the knee extensor moment over extended periods of time could be critical for stopping or slowing the progression of crouch through adolescence and early adulthood. During early stance, the knee joint exhibited a normal loading response despite the extension assistance from the exoskeleton. Biological knee joint power remained similar between walking with exoskeleton assist-on and without the exoskeleton. The increased knee extension resulting from extension assistance was met with a concomitant reduction in the knee extensor moment[7]. RAGT also involves the practice of complex repetitive gait cycles using body-weight support to meet the gait requirements in weak lower limbs, and it exerts less cardiorespiratory stress than over-ground gait training or gait training without robot assistance. The robotic device is composed of an exoskeleton that contains a motor with a planetary gear head connected to a custom chain-and-sprocket transmission assembly mounted at the knee to custom-moulded thermoplastic braces to provide support and balance to the child during over-ground training. Orthotic bracing aimed to increase the mobility of individuals with a crouch gait may block or restrict motion at the ankle and/or the knee joint to provide passive weight support or suppress unwanted motions. The exoskeleton’s ankle joint is a simple hinge set for free rotation. A finite state machine differentiates between the stance, early swing (knee flexion), and late swing (knee extension) phases of gait using data from an embedded force-sensitive resistor and knee angle encoder[5-8].

The proposed robotic rehabilitation therapy works around a key factor: implementing strength and power exercises simultaneously than over-ground walking guidance, performing in parallel an active head-trunk control therapy. As a result, the robot-based program recreates a situation as similar as possible to a real gait scenario. It encourages the patients to control different movements associated with gait: individual movements of lower limb joints and the synergy between them while maintaining a proper posture of the upper body[5]. Robot-assisted gait training (RAGT) provides conditions that support motor learning principles (such as intensity, repetition, task specificity, and participation) to promote both neuroplastic changes and nonmotor recovery in patients with central nervous system-related gait disorders which use partial body-weight supported treadmill training (PBWSTT) as a treatment approach. Although two or even three therapists may be needed in severely affected patients to support the movement of the legs and stabilize the pelvis and the trunk, PBWSTT takes an important role in gait rehabilitation of adult patients with a diagnosis of stroke, incomplete spinal cord injury (SCI), Parkinson’s disease (PD) or multiple sclerosis (MS). There is also an increasing body of evidence that PBWSTT improves walking ability, speed and endurance in children, with most evidence available for children with mild to moderate cerebral palsy[4,9,11]. Furthermore, the use of treadmill training has demonstrated improvement in walking capacity in some children with CP. For instance, results have demonstrated improvements in gait velocity, endurance, and the Gross Motor Function Classification System (GMFCS) measures[12].

One domain of rehabilitation robots involves driven gait orthoses (DGO) for robot-assisted gait training (RAGT), which have been initially developed for adults and subsequently adapted for children. One of these DGOs is the Lokomat which allows children to start at the age of approximately four years[11]. The Lokomat exoskeleton system comprises a treadmill belt, a weight support system and a driven gait orthosis for both legs. Traditional and floor reaction ankle-foot orthoses (AFO and FRAFO, respectively) have been shown to improve knee extension and spatiotemporal gait parameters while worn temporarily. There are pediatric leg orthoses for children and adult leg orthoses, depending on the patient’s size. The patient is secured with three cuffs per leg to the orthosis. The hip and knee joints of the device are actuated. The robotic control uses an adjustable (impedance) controller with predefined adjustable trajectories for hip and knee joints. Elastic straps provide dorsiflexion assistance to the feet. The Lokomat system can be adjusted to fit each patient’s best possible fit. Therapists can use games for increasing patients’ motivation. Recent developments include a FreeD mode (moveable pelvis and leg cuffs), new control mechanisms (i.e. path control rather than position control) and innovative virtual scenarios. Protocols for PBWSTT as well as RAGT in children are very heterogeneous. Session frequencies range from 2 to 5 times per week, session durations vary, with most studies reporting 20 to 30 min of treadmill walking per session, and length of treatment varies from 2 weeks to 5 months. This holds for all contraindications outlined in the Lokomat manufacturer’s manual, for example, severe lower extremity contractures (i.e. > 20° knee extension deficit, >40° hip extension deficit), bone fractures, osseous instability, osteoporosis, severe leg length discrepancy, severe cognitive deficits, open skin lesions or circulatory problems[4,11].

Honda Walking Assist (HWA) is a mobile exoskeleton robot that assists hip flexion and extension of both limbs during gait. The HWA assists only a single joint and does not limit the degree of freedom on other joints, effective for sufficient locomotor learning. A previous study reported that the HWA effectively reduced energy expenditure in healthy young adults. Most chil-
children with CP have neurological problems on both legs, and assisting both hip movements with the HWA would be an effective way to learn the symmetrical gait pattern. The HWA consists of a lumbar part with batteries, two actuators, and two thigh frames. The actuators are on the lateral side of each hip joint and produce hip flexion and extension assistive torques. The HWA detects the gait cycle by the potentiometers (set beside the actuators) and produces flexion and extension torques on the swing and stance phases, respectively[1].

The CPWalker rehabilitation platform is a robotic device composed of an exoskeleton linked to a walker that provides support and balance to the child during over-ground training. The device can implement users’ PBWS and adapt exercises to the patient’s capabilities utilizing individual controllers for each joint, which increases the system’s modularity. Each joint of the CPWalker exoskeleton can operate in a wide range of modes (position control mode, impedance control mode, zero-force control mode). The robot imposes a prescribed gait pattern on the user’s lower limbs in position control mode. The aim is that the patient learns the walking motion sequence correctly. Robotic assistance and patient cooperation should achieve implant control modes and the prescribed gait pattern. Three different impedance modes may be executed in CPWalker (high, medium and low), which tolerate variable deviations from the programmed gait trajectories, enhancing the patient’s participation and taking advantage of their residual movements through assist as needed strategies. With Zero-force control mode, the trajectory reference is not given, and the patient entirely moves the legs with a minimum resistance of the exoskeleton. It is used with patients with enough motor control (acquired with the previous modes) but poor balance, so the CPWalker provides stability and PBWS while the patient implements the gait pattern. A clinician may easily control the CPWalker robotic platform through an intuitive interface, which controls and monitors the exercises in real-time. The treatment was conceptualized into two main phases, where the ROM, PBWS and gait velocity were the principal parameters under variation. The first phase improved motor control, teaching the patients the correct motion sequence and increasing strength. The patients were requested to follow the movements established by the exoskeleton with the minimal possible resistance during the swing period, pushing the ground at each step and keeping the maximum flexion-extension values at the end of each gait cycle. Instructions were given to ensure the comprehension of normative gait patterns, and verbal encouragement and direct feedback by graphics in real-time were delivered throughout the sessions. The second phase was to train motor control further and increase power to ensure the transference to the independent gait pattern. Aware of the movement sequence of a normal gait pattern, the patient’s contribution became an important aspect of developing neuroplasticity and preserving the gained motor control. Active participation boosted the patient’s motivation and self-activity[5].

The Walkbot-K system is a robotic-assisted locomotor training device with a built-in ankle actuator to provide an optimal ankle-motion trajectory during ambulation. Adjustable leg length and control of the ankle joint range of motion enabled the Walkbot-K system to approximate human kinematics and kinetics accurately. RAGT with the Walkbot-K system was performed three times/week for six weeks (total, 18 sessions; minimum, 15 sessions), with a duration of 30 min on the Walkbot-K system, excluding the set-up times. Break time was provided when requested by the participant, and the treatment time was maintained for at least 30 min[8].

**Robot-Assisted Gait Training for Cerebral Palsy**

The powered exoskeleton significantly altered lower extremity kinematics and reduced the crouch gait. The overall knee range of motion for the entire gait cycle was significantly increased during walking with the powered exoskeleton, resulting in a closer trajectory to that of normal waking. While there were gains in knee extension during stance, there was also an increase in knee flexion during the swing phase with both the powered exoskeleton. One possible explanation for the increased swing phase knee flexion is the additional mass of the exoskeleton bracing, which may have increased knee flexor activity to assure toe clearance in the walking task. In addition, there were complex interactions between the different joints of the lower limbs during walking. The increased knee ROM during the exoskeleton walking condition may have mitigated the kinematic benefit of extension assistance provided by the motor. A more flexed knee increases the late swing extension requirement during the swing phase as the limb must articulate through a larger ROM. The transition from swing phase flexion to swing phase extension was delayed in the left leg compared to the right, limiting the time available to provide swing phase assistance from the exoskeleton[8].

Several studies have reported that RAGT using robots with a tethered exoskeleton show improvements in gait speed, gait endurance, and gross motor function in individuals with CP. Greater improvements in walking function for children who underwent resistance training than those who underwent assistance training. One possible reason for the differences in functional gains may be that children who underwent resistance training were more actively engaged in the locomotor training session than those who underwent assistance training. In children who underwent assistance training, the central nervous system may adapt to the assistance force applied to the leg(s) during the swing phase of gait by reducing the motor output of the leg muscles. The resistance load applied to both legs during the swing phase may force children to generate additional joint torque to counteract the load and move the leg forward during treadmill training, which may require participants to increase voluntary activation through enhanced supraspinal input to the motoneuron pool and/or increase motoneuron excitability. This is consistent with a study that indicated that only a modest increase in the gait speed of children with CP was observed after robotic training in which a passive guidance force was applied to both legs [9,12].

**Discussion**

A study from Kawasaki et al., 2020, showed that ten spastic CP children with Gross Motor Function Classification Scale level I-III completed robot-assisted gait training (RAGT), and non-assisted gait training (NAGT) were performed on the treadmill with the Honda Walking Assist (HWA) in two different days. Participants also performed 5.5 m overground walks without the HWA before and after treadmill training (pre- and post-trial). During treadmill walking, the peak of both hip and knee angles were measured. Also, we calculated the limb symmetry of the hip range of motion. In addition, gait speed and ground reaction force were measured in overground trials. The result was the maximum hip angle on the limb with fewer hip movements, which was defined as the affected limb, showed a significant
interaction between ASSIST (RAGT and NAGT) and TIME (pre and post-trial) (p < 0.05). In addition, limb symmetry significantly improved after RAGT (p < 0.05), but not in NAGT. Furthermore, the affected limb showed a significant increase in the positive peak of the anterior-posterior ground reaction force during 70–100% of the gait cycle (p < 0.05). However, there was no change in gait speed. The affected limb’s maximum hip flexion and extension angle improved by assisting both hip movements with the HWA. Also, limb symmetry and propulsion force of the affected limb improved. The results suggest that assisting both hip movements with the HWA might effectively improve gait in CP children[1].

A study from Lerner et al., 2017, showed that seven individuals (5–19 years) with mild-moderate crouch gait from cerebral palsy (GMFCS I-II) use powered knee extension assistance for six participants have favourably reduced the excessive stance-phase knee extensor moment present during crouch gait by a mean of 35% in early stance and 76% in late stance. Peak stance-phase knee and hip extension increased by 12° and 8°, respectively. Knee extensor muscle activity decreased slightly during exoskeleton-assisted walking compared to baseline, while some participants’ knee flexor activity was elevated. These findings support the use of wearable exoskeletons to manage crouch gait and provide insights into their future implementation [3]. The following study in 2020 showed that a 6-year-old male participant with spastic diplegia from CP with a powered exoskeleton improved knee extension during stance by 18.1° while total knee range of motion improved by 21.0°. Importantly, they observed no significant decrease in knee extensor muscle activity, indicating the user did not rely solely on the exoskeleton to extend the limb. These results establish the initial feasibility of robotic exoskeletons for the treatment of crouch and provide an impetus for continued investigation of these devices with the aim of deployment for long term gait training in this population [7].

Bayon et al., 2018, showed a clinical evaluation with four pediatric patients with CP using the CPWalker robotic platform. The preliminary evaluation with patients with CP shows improvements in several aspects as strength (74.03 ± 40.20%), mean velocity (21.46 ± 33.79%), step length (17.95 ± 20.45%) or gait performance (e.g. 66 ± 63.54% in Gross Motor Function Measure-88 items, E and D dimensions). The improvements achieved in the short term show the importance of working strength and power functions meanwhile over-ground training with postural control [5].

A single-centre, single-blinded, randomized cross-over trial from Jin et al., 2020 enrolled 20 children with CP with Gross Motor Function Classification System (GMFCS) levels II-IV (13 males; age range, 6.75 ± 2.15 years). The participants were randomized into the RAGT/standard care (SC) (n = 10) and SC/RAGT/SC sequence groups (n = 10). Using a Walkbot-K system, the RAGT program comprised 3 × 30-min sessions/week for six weeks with a continued SC program. The SC program comprised 2–4 conventional physiotherapy sessions/week for six weeks. The result was that RAGT had training benefits for children with CP. Specifically, it improved locomotor function and functional capability for daily activities. These effects were better in ambulatory children with CP. However, as SC interventions continued during the RAGT period, these improvements may also be related to multiple treatment effects [8].

A study from Reiffer et al., 2017, with children aged 6 to 18 years with bilateral spastic cerebral palsy who can walk at least 14 m with or without walking aids, was recruited in two pedi-
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References


