Robotic-Assisted Gait Training Therapies for Pediatric Cerebral Palsy: A Review

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Abstract: *Background*: Children and adolescents with CP experience many types of disability and functional impairment that effect the gait cycle. New robotic gait therapies adapted to pediatric patients provide a safe, highly repetitive, and task-specific therapeutic venue for the rehabilitation and elicitation of a more natural walking gait. While the use of robotic-assisted gait training (RAGT) is a relatively novel therapeutic approach to gait therapy, several studies have examined the efficacy of this therapeutic modality in pediatric patients with CP.

Purpose: The purpose of this review is to examine the trends in the therapeutic efficacy of utilizing RAGT therapy as a gait restorative modality for children with CP.

Results: The present studies show that RAGT therapy may provide multiple therapeutic benefits to children with CP, including statistically significant improvements in gross motor function and multiple gait characteristics. Also, RAGT therapy may be a safe and favorable complement to current physiotherapy regimens.

Conclusion: As various degrees of functional improvement are a noticeable trend among all presented studies, further study in this therapeutic technique is warranted, and implementation of similar therapeutic protocol may be valuable to a rehabilitation care plan. The highly repetitive and task-specific nature of RAGT may provide a valuable paradigm for children with CP whom have never learned a normal gait pattern.

Keywords: Cerebral palsy, pediatric, gross motor function, robotic-assisted gait training, robotics.

Cerebral palsy (CP) is a broad term used to describe a small group of nonprogressive syndromes concomitant with brain lesions that occur during early development and produce variable degrees of motor impairment [1-4]. Individuals with CP may display slowed balance reaction, high levels of spasticity, special behavioral needs, significant muscle weakness, sensory deficiencies and distorted joint kinetics [5,6]. Almost all patients with CP exhibit some form of abnormal gait. Common gait abnormalities associated with CP are a widened lower-extremity support base, reduced stride and step length, decrease walking speed, and generalized upper and lower limb disability [7,8]. Patients with CP often undergo multiple surgical interventions in the effort to minimize these disabling comorbidities, thus making a regular therapeutic gait improvement program difficult to maintain [9,10].

Children with CP have shown to score lower on neuropsychological assessments testing motor and cognitive task persistence, while scoring highly in social task persistence [11]. These findings are similar to previous studies that found that children possessing developmental delays and disorders often display pleasure and curiosity while playing, yet exhibit high levels of passivity and low levels of motivation [12,13]. This difficulty maintaining motivation is also an obstacle for CP rehabilitation, which often necessitates prolonged motor involvement due to predominant emphasis on functional gait recovery [14,15]. To this effect, modern rehabilitation therapies for individuals with motor disabilities have shown positive outcomes when emphasis is placed on repetitive, high-intensity activities that are goal oriented and task specific in nature [16,17]. New research is showing promising results in children with sensorimotor impairment using new robotic technologies that emphasize patient, therapist, and robotic interactivity [18-20]. These interactive new therapies, namely robotic-assisted gait training (RAGT), emphasize the active participation of the patient, thus helping prolong attention, motivation, and participation.

BACKGROUND: ROBOTICS-ASSISTED GAIT THERAPIES

Traditional gait therapies for children and adults with motor disabilities have emphasized utilizing body-weight support and the use of a treadmill to establish a rhythmic gait pattern. Studies testing the use of body-weight supported treadmill training (BWSTT) as a gait restorative therapy have yielded positive metabolic and

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function results for patients with both neurological injury, and disease [21-27]. Additionally, several studies have tested the effects of BWSTT in children with CP, yielding highly varying results [28-32]. Due to the relatively high level of manual resources required in traditional BWSTT programs, recent technologies utilizing robotics are now becoming more commonly used in adults with stroke and spinal cord injury (SCI). However, these studies are showing equally inconsistent results [33-36].

These robotic systems often consist of an electronic exoskeleton driven by centralized computer software, which provides the patient with needed body-weight support, and a synchronized stepping pattern conducive to normal gait stance, rhythm, and motion [37-39]. This motorized exoskeleton works in conjunction with an underlying treadmill. Of additional benefit is the positioning of the therapist during RAGT sessions. With pediatric rehabilitation having a considerable implication on both patient function and emotion, the therapist's encouraging and motivational role is of paramount importance during the therapeutic process [40,41]. During RAGT sessions, therapists are free to move around the patient, provide verbal feedback, motivation, and encouragement. Additionally, the therapist is free to examine patient posture and movement, as well as give valuable feedback about their performance [42]. Several RAGT systems also provide both the patient and therapist with biofeedback that can be programmed to make the therapy both challenging and interactive for the patient. However, studies testing the effectiveness of the interactivity of RAGT biofeedback technologies are showing considerable limitations in the accuracy and reliability of the biofeedback [43,44].

ROBOTIC-ASSISTED GAIT TRAINING FOR PEDIATRIC CEREBRAL PALSY

With more robotic gait restoration systems becoming available to the pediatric population, a small but growing number of studies have been performed testing their efficacy [45-54]. For the purposes of this review, only studies utilizing Lokomat and Gait Trainer I (GT 1) will be examined due to their widespread use and utility for the entire gait cycle. Robotic orthoses used for the rehabilitation of localized ankle and joint rehabilitation will also be excluded.

A preliminary study performed by *Meyer-Heim et al.* examined the functional gait recovery capabilities of a RAGT protocol in children with central gait disabilities [45]. The exercise protocol consisted of 26 inpatient and outpatient children, most of whom had a diagnosis of CP and Gross Motor Function Classification System (GMFCS) levels of I-IV. Participants completed 12-19 RAGT sessions at 2-5 times per week. Post-study results showed statistically significant increases in both 6-minute walk tests and walking speed as well as significant improvements in Gait Motor Function Measure (GMFM) dimensions D (standing) and E (walking), and Functional Ambulation Categories (FAC) compared to pre-test values. Further study performed by *Meyer-Heim et al.* tested at 3-5 week RAGT exercise program performed for 45 minutes, 3-5 times per week in 22 children with CP and GMFCS levels II–IV [46]. Similar to the previous study, results showed statistically significant increases in both maximum gait speed and mean standing characteristics as tested by GMFM-66. Additionally, improvements were found in average 6-minute walk test, FAC, and GMFM-E, however these increases were not statistically significant. It should also be noted that these studies [45,46]. contained participants that also received additional impatient therapies during the study.

A study performed by *Borggraefe et al.* using RAGT as the only gait rehabilitation modality was later completed and found comparable improvements in gait characteristics [47]. In this study 20 children and adolescents (average age 11 $\pm$ 5.1) with GMFCS I-IV CP completed 12 RAGT sessions performed 4 times per week. These RAGT sessions averaged 38 minutes in length and were performed until the participant verbalized his or her exhaustion or stopped at a maximum time of 50 minutes. Compared to pre-test values, results showed a statistically significant increases in GMFM-D and GMFM-E scores of 5.9% and 5.3% respectively. Additionally, GMFM-E score improvements appeared to be correlated with both total walking distance and total walking time. The researchers of this study also note that significantly greater improvements were found in patients with GMFCS levels I and II than in levels III and IV. A later study performed by *Borggraefe et al.* explored the long-term sustainability of these favorable gait performance outcomes using the same 12-session, 4 times per week, RAGT exercise protocol, and taking gait parameter measurements immediately before, immediately after, and 6-months after the trial [48]. Results showed similar improvements in both GMFM-D and GMFM-E scores as well as gait speed and walking endurance as measured by 6-minute walk test immediately after the 12 sessions. These gait characteristics appeared to persist and even improve when measured 6 months later. However it should be noted that during the 6 months following this RAGT exercise protocol, patients continued a less intensive rehabilitation program consisting of 1-2 conventional physiotherapy sessions per week, and 7 of the 12 participants also receiving additional RAGT 2-3 times per month. This lessened rehabilitation intensity may be important, as it could provide indication as to a sufficient gait maintenance protocol. The results of both of these studies are in congruence with an additional preliminary case report performed on a 6-year-old boy with GMFCS level III CP who complete the same 3 week RAGT protocol [49]. Similar to the above studies, results showed statistically significant improvements in both GMFM-D and GMFM-E scores, as well as a slight but notable decrease in spasticity.

A similar follow-up study performed by *Smania et al.* examined 18 children with CP and GMFCS levels II-IV [50]. During this study, participants were matched and divided evenly into an experimental group and a control group, which received 30 minutes of RAGT plus 10 minutes of stretching, and 45 minutes of conventional physiotherapy, respectively. Each group completed 10 sessions, held over 2 weeks. While no significant changes were found in the control group, the experimental group showed statistically significant improvements in 10-meter walk test, 6-minute walk test, step length, hip kinematics, and gait speed compared to pre-test values. However, no resulting changes in functional independence were found in WeeFIM scores. All post-test improvements persisted or even improved when measured during a 1-month follow-up assessment. The authors of this study noted that this may be due to a desire of the children to practice their new gait abilities in their daily lives. However, not all studies testing the efficacy of RAGT in the pediatric CP population are showing substantial improvements. A study performed by *Druzbicki et al.* tested a similar protocol including 20 sessions of either 45 minutes of RAGT or 45 minutes of motor control exercises with a physiotherapist [51]. While results showed both inconsistent and insignificant findings in almost all tested parameters, the authors noted many limitations, and no conclusive findings were reported. Due to the inconclusiveness of these results, this study will not be included in Table **1** or later discussion.

While deficits in balance and high levels of muscle hypertonia are common in CP patients, few studies have examined the effects of RAGT on these symptoms. Additional study by *Druzbicki et al.* assessed the impact of RAGT on patient balance [52]. During this study, 13 children with CP, GMFCS levels II or III, completed either RAGT (n=9) or conventional physiotherapy (n=5), 5 times per week for 4 weeks. Balance was assessed and measured using a stabilometric platform. Results from this study showed that the children that participated in the RAGT protocol scored significantly higher in post-test balance assessments compared to pre-test values. Further study by *Schmartz et al.* tested the effects of a single RAGT session on muscle stiffness in 10 children with spastic CP [53]. Results showed that after the RAGT session, participants exhibited a statistically significant decrease in lower-limb muscle stiffness. Additionally, the authors found that decreases in muscle stiffness were greater in children originally presenting with more severe muscle hypertonia.

Additional consideration however, should be given to how RAGT therapy is perceived by the patients and the parents of the patients, as well as the safety of the therapy in general. To date, only one study has been performed examining the safety of RAGT therapy [54]. This study surveyed 89 children (58 with CP) with gait disorders that participated in an average of 15 RAGT sessions at two separate rehabilitation centers. Of these participants, 42.7% reported adverse reactions to the therapy. The majority of these adverse reactions were skin erythema and localized muscle pain. The authors of the study concluded that RAGT was a safe gait restoration modality due to only 5.6% of the surveyed participants lessening or discontinuing their participation in the therapy, and that no severe side-effects had been reported.

Two recent studies have been conducted assessing the perceptions of both the children with CP, and the parents of children with CP, involved in RAGT therapies [55,56]. These studies showed two important findings of the child's perspective of RAGT involvement. The first was that less interest was placed on interacting with the robot during therapy than with the people the child interacted with during therapy. And second, these children considered the way they walked outside of therapy as "normal" and expressed little to no desire to walk like other non-disabled children. This disinterest to walk like other children was in sharp contrast to the perspectives held by the parents of children with CP. Results showed that parents valued their child walking "correctly" very highly, and considered it a predictor of the current and future welfare of their child. These findings should help emphasize the importance of the role of the therapist

Table 1: RAGT Studies for Pediatric Patients with Cerebral Palsy

Study	Exercise Protocol	Participants	Improvements (Stat Sign. In Bold)
Meyer-Heim *et al.* [45]	RAGT; 2-5x/wk, 12-19 sessions total.	n=26 children with central gait disability, GMFCS I-IV Mean age= 10 y/o (n=19 with CP)	**Walking Speed (6MWT)** **GMFCS-D&E** **FAC**
Meyer-Heim *et al.* [46]	RAGT; 3-4/wk, 3-5 wks	n=22 CP, GMFCS II-IV Mean age=8.6 y/o	**Max. Walking Speed** **GMFCS-D** 6-minute walk test FAC GMFM-E
Borggraefe *et al.* [47]	RAGT; 4x/wk, 3 wks	n=22 CP, GMFCS I-IV Mean age 11y/o	**GMFM-D (5.9%)**[1] **GMFM-E (5.3%)**[1]
Borggraefe *et al.* [48]	RAGT; 4x/wk, 3 wks	n=14 CP, GMFCS I-IV Mean age 8.2 y/o	**GMFM-D**[2] GMFM-E Walking Speed Walking Endurance
Borggraefe *et al.* [49]	RAGT; 4x/wk, 3 wks	n=1 CP GMFCS III 6 y/o	**GMFM-D** **GMFM-E** Dec. Spasticity
Smania *et al.* [50]	Exp group= 30 min RAGT +10 stretching 10 sessions over 2 wks	n=9 CP GMFCS I-IV Mean age 13 y/o	**10-meter walk test**[3] **6-minute walk test**[3] **Step length**[3] **Hip kinematics**[3] **Gait speed**[3]
	Control group= 45 min conv. physio. 10 sessions over 2 wks	n=9 CP GMFCS I-IV Mean age 12 y/o	No changes in any variables.
Druzbicki *et al.* [52]	Exp. Group= RAGT; 5x/wk, 4 wks	n= 9 CP GMFCS II-III	**Inc. Balance**[4]
	Control Group= Conv. Physio. 5x/wk, 4 wks	n= 5 CP GMFCS II-III	Inc. Balance

[1]Significantly greater improvements GMFCS levels I & II than III & IV.
[2]Results persisted with 6 months with less intensive protocol.
[3]Results persisted to 1-month follow-up
[4]Significantly bigger improvement in experimental group compared to control.

and therapeutic environment in which RAGT takes place, as well as shine light on the necessity of patient engagement during the rehabilitation process.

DISCUSSION

This review presents research performed on the restorative effects of RAGT therapies for children and adolescents with CP. Individuals with CP exhibit diverse levels of mobility impairment, balance and functional deficiencies, and muscle weakness. With more intelligent and interactive technologies becoming available to the field of rehabilitation, RAGT and the use of robotics in gait related therapies are becoming more common, as they can offer a highly repetitive and task-oriented therapeutic treatment [9]. The integration of these therapeutic robotic technologies has been adapted for use by children and adolescents with neuromotor disability and gait impairment. While the use of these robotic and RAGT therapies are a relatively novel approach to pediatric rehabilitation, the studies that have been performed on the efficacy of these treatments have shown that it can help improve many aspects of gait performance and motor function. Additionally, recent technological advancements in virtual reality have shown to work with, and compliment the use of rehabilitation robots and RAGT programs as they help motivate and further challenge children during therapy [57,58].

Although the use of interactive robotics and virtual realities have shown to aid in the gait rehabilitation of children with neuromotor impairment, some studies reported that these robotically aided movements may not be as beneficial or conducive to a natural gait cycle as previously expected. Two recent studies reported that the use of robotic-assisted gait therapies can produce muscle activation patterns unlike that of a natural gait and different than that elicited during non-robotic assisted BWSTT therapies [59,60]. Also, these studies report that the straps and hardware used in RAGT therapies can unnaturally restrict pelvic, truck, and upper-limb movement during exercise sessions. These factors may limit the ability of robotically-aided therapies to produce a natural and efficient gait in treated patients, as well as have implications on safety.

However, a benefit of RAGT therapies is the relatively low amount of manual labor needed from a single therapists compared to other commonly used gait restoration modalities. Recent research on BWSTT reports that a therapist to patient ratio of ≥ 3 to 1 is needed during non-robotic assisted BWSTT, and that this often exceeds the staffing abilities of rehabilitation centers [21]. This is not the case with RAGT, during which only 1 to 2 therapists are needed per patient, and the therapists are free to stand in front of and move around the patient, providing encouragement and guidance when necessary [42]. This may be of specific benefit to the pediatric CP rehabilitation process as studies have shown that these children commonly exhibit highly levels of social task persistence, but also low levels of motivation [11-13].

The present amount of scientific evidence testament to the efficacy of RAGT therapies for children and adolescents with CP still remains limited, however, there are trends in these study outcomes. All of the studies in this review examining the effects of RAGT therapies on gross motor function and gait characteristics reported one or more statistically significant improvements in gait speed [45,46,50], balance [52], standing [45-49] or walking [45,46,49]. It still remains to be studied however, what frequency, duration, and intensity of RAGT therapies yield the best results. The majority of the studies presented in this review used a RAGT regimen of 2-5 sessions per week, for a total of 3-5 weeks. Additionally, it should be noted that one of the reviewed studies included pediatric subjects diagnosed with diseased or subject of injuries concurrent with central gait disabilities. This study by *Meyer-Heim et al.* [45] examined the effects of RAGT on children with Guillain-Barre syndrome (n=2), stroke (=1), traumatic brain injury (n=1), incomplete paraplegia (n=2), hemorrhagic encephalitis (n=1), and multiple types of CP (n=19). The results from this study showing a statistically significant improvement in gait speed, gross motor function, and functional ambulation category may provide testament to the generalizability of therapeutic benefit of RAGT for children and adolescents with various central gait impairments resultant of congenital or acquired brain or spinal lesions. However, with the lack of additional studies supporting these results, specific conclusions cannot be drawn.

Of the 7 studies reviewed, 4 studies utilized a 4 times per week, session protocol [46-49]. Interestingly, every one of these studies found statistically significant improvements in gross motor function, and 2 of these study found significant improvement in both GMFM-D and GMFM-E [47,49]. Additionally, all three of the studies that utilized a 4 times per week, for 3 week RAGT protocol, found statistically significant improvements in GMFM-D [47-49]. These cross-study similar results may provide testament to the efficacy of a 3-week, 4 sessions per week gait restoration protocol. However little or no follow-up assessment was provided in these studies, thus no long-term benefits can be generally acknowledged.

Two studies included a control group in the study design, with each comparing the results of a more intensive 5 times per week RAGT session frequency to the same frequency of conventional physiotherapy sessions [50, 52]. Perhaps it should be noted that both of these studies reported either no changes, [50] or no significant improvements [52] in any tested gait or motor characteristics in the control groups. Conversely, these studies reported statistically significant improvements in multiple gait and motor characteristics in the group that completed the RAGT protocol, with one study reporting significantly greater improvement in the RAGT group compared to the conventional physiotherapy group.

While the amount of published literature on RAGT therapies for pediatric CP shows consistent pro-therapeutic outcome trends, relatively little is still known about the physiological mechanisms of the elicited healing and rehabilitation on the cellular and chemical level. Perhaps future studies could benefit from the co-application of imaging techniques such as near-infrared spectroscopy or electroencephalogramatic technologies. Results for such studies may help further understand not only which rehabilitation regimen is most effective, but also which patients benefit most from these therapies.

Evidence indicates that there is no statistically significant difference in the daily step activity of children with CP compared to age and sex matched typically developing peers; however, a significant disparity occurs in older children [61]. This suggests that early intervention, may yield the most beneficial results. Intervention during this developmental period is challenging, yet with robotic assistance and virtual environments, these challenges can be ameliorated. Furthermore, parents support these novel interventions given the improvements associated with training and the small risk incurred [55].

In summary, the present literature shows that RAGT therapies may provide multiple therapeutic benefits to children with CP. Also, RAGT therapies may be a safe and favorable complement to current physiotherapy regimens. As various degrees of functional improvement are a noticeable trend among all presented studies in this review, further study in this therapeutic technique is warranted, and implementation of similar therapeutic protocol may be valuable to a rehabilitation care plan. The highly repetitive and task-specific nature of RAGT may provide a valuable paradigm for children with CP whom have never learned a normal gait pattern.

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