THE EFFECT OF LOCOMOTOR ASSISTED THERAPY ON LOWER EXTREMITY MOTOR PERFORMANCE IN TYPICALLY DEVELOPING CHILDREN AND CHILDREN WITH CEREBRAL PALSY

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The Effect of Locomotor Assisted Therapy on Lower Extremity Motor Performance in Typically Developing Children and Children with Cerebral Palsy

Background: Ambulation is critical to a child's participation, development of self-concept, and quality of life. Children with cerebral palsy (CP) frequently exhibit limitation in walking proficiency which has been identified as the primary physical disability. Traditional rehabilitative treatment techniques to improve ambulation for children with CP reveal inconsistent results. Driven gait orthosis (DGO) training is a novel approach focusing on motor learning principles that foster cortical neural plasticity.

Objective: The objectives are to determine if: (i) the lower extremity muscle activation patterns of children with CP are similar to age-matched TD children in overground (OG) walking, (ii) DGO training replicates muscle activation patterns in OG ambulation in TD children, (iii) the lower extremity muscle activation patterns in OG walking of children with CP are similar to their muscle activation patterns with DGO assistance, and (iv) DGO training promotes unimpaired muscle activation patterns in children with CP.

Methods: Muscle activity patterns of the rectus femoris, semitendinosus, gluteus maximus and gluteus medius were recorded in the OG and DGO walking conditions of children with CP and age-matched TD. The gait cycles were identified and the data was averaged to produce final average gait cycle time normalized values.

Results: In comparing the variability of the muscle activation patterns within the subject groups, CP DGO walking was considerably lower than CP OG. In comparing the muscle activation patterns in each condition, consistent differences ($p < .05$) were noted in terminal stance, pre-swing and initial swing phases of gait with the DGO condition consistently revealing greater muscle unit recruitment.

Conclusion: The results indicate that training in the DGO provided the ability to practice with measurably repetitive movement as evidenced by decreased variability. Consistent differences were noted in muscle activation patterns in the terminal stance, pre-swing and initial swing phases of gait when most of these muscles are primarily inactive. The alteration in ground reaction force within the DGO environment may play a role in this variance. With the goal of normalizing gait, it is important that the effect of these parameters on ground reaction forces be considered in the use of DGO rehabilitation.

Peter Altenburger, PhD, Chair

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Chapter 1 : Background

Introduction

Ambulation ability is a critical component of participation in peer related activities across the life span.[1-3] Participation, defined as involvement in school activities or play, serves as a major factor in childhood development of self-concept and improved quality of life[4,5] and is part of the International Classification of Functioning, Disability and Health model standardizing the approach to rehabilitation care.[6]

Limitation in walking proficiency has been identified as the primary physical disability in children with cerebral palsy (CP)[7] and therefore inhibits participation in peer activities, threatening the development of independent mobility. Correlation has been found between walking ability and peer participation in children with CP indicating gait impairment is a significant predictor of lower scores in activity and participation.[1-3] Accordingly, studies have shown that limited peer related participation, dependent lifestyles (67%) and low rates of employment (53%) are dominant in the lives of adults with CP[8-11] contributing to an estimated lifetime health cost, for children born in the United States in 2000, of 11.5 billion dollars.[12]

Background of Problem

Impaired walking ability in children with CP is due to alterations in gait characteristics such as agonist-antagonist co-activation, crouched posture, and impaired kinetic motion. These limitations cause a child's walking ability to be inefficient resulting in high-energy expenditure during gait.[7,13-15] Current therapeutic strategies in overground gait training demonstrate inconsistent effects on correcting abnormal kinematics.[16,17] Newer approaches such as driven gait orthosis (DGO) training for children with CP have been found to provide consistent, measurably repetitive, task specific training which is necessary for neuroplastic change that could foster volitional muscle activation and normalized kinematics.[15,18] No other form of current therapy provides a training environment with the consistent, repetitive approach found with the DGO.[15]

Theoretical Framework

Motor learning and motor control principles based on the ability to make permanent changes in the neural pathways (neural plasticity) are the cornerstone of rehabilitation techniques in adults and children with neurological insult. These principles and techniques are based on extensive research and form the basis of current neurological treatment by physical therapists.[19] Neural plasticity principles are based on practice, specificity, repetition, intensity, salience, age, and transference.[20]

Basic concepts in motor learning including variability in practice, practicing components of movement, task attention, feedback and environmental progression, give further clinical guidance for optimal neural plastic change.[21] It must be noted that research has discovered that children and adults vary in their response to the specifics of motor learning concepts and this must be taken into account when working with children.[22-24]

DGO addresses most neural plasticity principles with training that drives brain function associated with walking in a specific manner (“use it and improve it” and specificity), measurably repetitive movement to induce plasticity (repetition), intensity of movement to induce plasticity (intensity), saliency, use in children where training induced plasticity occurs more readily, and transference in training of walking in a straight line which can enhance acquisition of similar movements in walking.

Motor learning concepts for children are targeted with DGO training including block practice of a complex movement, practice of the complete task, the ability to progress through the cognitive stages of task attention at the child's rate, various forms of extrinsic feedback that enhance a child's motor learning and environmental progression within the software options. Theoretically, DGO training follows many of the motor learning and neural plasticity principles specific to children and thus should be an excellent option for ambulation training in those with neuro-motor impairment.

Statement of the Problem

Much of the initial research involving DGO training has been performed on adults. As a consequence, there is little known regarding the potential impact this type of training could have on children with CP.[15,25] The literature supports the finding that DGO training offers consistent, measurably repetitive, task specific training; however, the effects of DGO application on the volitional muscle activation patterns of children with gait impairments from CP is not fully known. The findings from this research will enhance the evidence and thus the clinical decision making for therapists seeking to augment functional independent ambulation which will consequently maximize functional independence and quality of life for children with CP.

Purpose of Study

This study is intended 1) to determine if the muscle activation patterns of children with CP differ from age-matched TD children in overground walking, 2) to determine if DGO training replicates unimpaired muscle activation patterns in overground ambulation in TD children, 3) to determine if DGO training replicates muscle activation patterns in overground walking in children with CP and 4) to determine if DGO training promotes unimpaired muscle activation patterns in children with CP.

Significance of Study

No known research has determined whether DGO training in TD children replicates unimpaired volitional muscle activation patterns of the lower extremity in overground ambulation of those same children. One study has evaluated the influence of DGO training on muscle activation patterns of TD children and children with CP comparing them to overground muscle activation reference data of unimpaired children grouped by age range.[26] This study by Schuler et al. looked at the muscle activation patterns of four muscles (tibialis anterior, gastrocnemius lateralis, vastus medialis, and biceps femoris) during three walking conditions (DGO walking, DGO walking with therapist motivation and walking unassisted on a standard treadmill) with 8 healthy children and 9 children with motor impairments. Although they concluded that walking in the DGO resulted in physiological activation of most of the muscles recorded, they also documented agonist-antagonist co-contraction in the children with motor impairment and decreased overall surface EMG amplitude differences when compared with overground walking reference data. However, this study has limitations. The sample sizes were small, the subjects were not age-matched and they did not include overground walking in their data collection for comparison.[27]

DGO training provides a unique opportunity to enhance motor learning in children, who are often difficult to motivate in focused activity, and provides limitless possibilities to alter impaired motor development. However, if the volitional muscle activation patterns promoted by this tool are inaccurate, potential for further impairment exists. This aspect of DGO treatment is basic to its appropriate use by the physical therapist. The results of this study will maximize the effectiveness of the clinical application and use of DGO treatment. The importance of promoting independent ambulation and functional daily activities that lead to maximal functional independence is reflected in the documented decreased participation, decreased quality of life, and significant lifetime health care costs of the child with CP. DGO training is an excellent option in treatment of children with CP due to its task specific, intense, and measurably repetitive characteristics, however the effect of DGO training must be precisely explored to maximize its use as an effective gait training treatment.

Research Hypotheses

Hypothesis 1: The lower extremity muscle activation patterns of children with CP are dissimilar to age-matched TD children in overground walking.

Hypothesis 2: For children with CP, DGO assistance will replicate age-matched TD lower extremity muscle activation patterns in overground ambulation.

Hypothesis 3: For TD children, DGO assistance will replicate their muscle activation patterns recorded during overground ambulation.

Hypothesis 4: For children with CP, the lower extremity muscle activation patterns in overground walking are dissimilar to their muscle activation patterns with DGO assistance.

Primary Research Questions

Research Question 1: Are the muscle activation patterns of the rectus femoris, semitendinosus, gluteus maximus, and gluteus medius of children with CP dissimilar to age-matched TD children in overground walking?

Research Question 2: For children with CP, does DGO assistance at 100% guidance force replicate age-matched TD overground muscle activation patterns of the rectus femoris, semitendinosus, gluteus maximus and gluteus medius?

Research Question 3: For TD children, does ambulatory training with DGO assistance at 100% guidance force replicate their muscle activation patterns of the rectus femoris, semitendinosus, gluteus maximus, and gluteus medius in overground ambulation?

Research Question 4: For children with CP, are the muscle activation patterns of the rectus femoris, semitendinosus, gluteus maximus, and gluteus medius in overground walking dissimilar to their muscle activation patterns with DGO assistance at 100% guidance force?

Research Design

Volitional muscle activity patterns of the lower limb during several walking conditions were recorded utilizing surface EMG protocol. The data was analyzed and compared for both TD children and children diagnosed with CP. Training paradigms included overground ambulation and DGO ambulation with 100% guidance force.

Delimitations

Delimitations imposed in this study for the group of children with CP include diagnosis of cerebral palsy, ages 4-12 years, minimum femur length of 21 cm, ability to ambulate barefoot with or without an assistive device for at least 20 feet, absence of a severe deficit in visual acuity and/or visual field, and ability to follow one-step verbal directions. The children with CP were limited to those who have not had Botox injections in the past 3 months and did not have a history of muscle tendon transfers. For typically developing (TD) children, ages were limited to 4 - 12 years with a minimum femur length of 21 cm and absence of a severe deficit in visual acuity and/or visual field.

Assumptions

Assumptions will be made in the following areas: 1) subjects will be not fatigued before starting walking conditions, thus presenting their normal strength and endurance and 2) the CP subjects will be accurately diagnosed by their physicians with CP.

Limitations

Potential limitations include difficulty in identification of the muscles in the child with CP. Some muscles can be very small or difficult to locate due to imbalance and abnormal use/disuse. Two trained investigators were present for each trial to assure the ability to accurately locate each muscle and appropriate muscle activity was verified. Since the testing sessions were in the late afternoon on most occasions, if mild fatigue was identified during the session, a short break was instituted. Due to the EMG sensor placements, orthotics were not used in any walking condition. In unsupported walking conditions such as overground walking, the subjects' gait may have been compromised due to the lack of orthotic support. This was taken into consideration when interpreting the results. Finally, in comparing the volitional muscle activation patterns of the children with CP to their age-matched TD counterpart, it must be remembered that this is a general comparison and not as exact as the ability to compare the TD children with themselves. Overall, this is more accurate than comparing to a referenced age group muscle activation pattern which introduces a span of age ranges and numbers of children in the average.

Study Significance

Children with CP face a lifetime of neuromuscular challenges that compromise their ambulation and negatively affect their ability to function and participate in life activities leading to dependency and elevated health care costs as adults. This scenario can be altered with improved ambulation ability early in the lifespan as the child with CP develops self-concept and expectations of participation. Alongside traditional therapy, DGO training is a novel treatment tool that provides the intense, measurably repetitive, and task-specific training necessary to augment neuroplasticty and affect lifelong change in neuromotor patterns of movement. It is essential that these patterns be altered appropriately as early as possible to foster improved ambulation and enhanced participation. Consequently, the child with CP will become an adult with maximized independence, decreased health care costs and most importantly, improved quality of life.

Definition of Terms

1. *Cerebral palsy* (CP), according to Bax et al., “describes a group of disorders of the development of movement and posture, causing activity limitation, that are attributed to non-progressive disturbances that occurred in the developing fetal or infant brain. The motor disorders of cerebral palsy are often accompanied by disturbances of sensation, cognition, communication, perception, and/or behavior, and/or by a seizure disorder.” [28]

2. *Typically Developing* (TD) refers to children who are developing normally with no diagnosed impairment.

3. *Driven Gait Orthosis* (DGO) is a robotic assisted treadmill ambulation training device developed for adults in 2000[25] and adapted for children in 2006.[15]

4. *Lokomat* is a driven gait orthosis (DGO) developed by Hocoma in Volderswil, Switzerland in 2000.[15,29]

5. *Guidance force* determines how much guidance the Lokomat is giving to the user’s movement. A value of 100% corresponds to strict guidance whereas a value of 0% gives no guidance.[29]

6. *Body weight support* is unweighting of the body weight provided by a harness and a counter weight system that permits individualized, adjustable body weight support within a range of 5 to 80 kg in 5 kg increments.[29]

7. *Feedback* is a visual biofeedback system in the Lokomat which displays the user’s activity in real time on a separate monitor while the user is walking, allowing them to modify their performance as they are walking.[29]

8. *Neural plasticity*, according to Shumway and Woollacott, 4th ed. "a continuum from short-term changes in the efficiency or strength of synaptic connections, to long-term structural changes in the organization and numbers of connections among neurons".[19]

9. *Motor learning*, according to Shumway-Cook and Woollacott, 4th ed. is “the acquisition or modification of a movement”.[19]

10. *International Classification of Functioning, Disability and Health* (ICF) is an international classification system developed by the World Health

Organization that provides “standard language and framework for the description of health and health-related states”.[6]

11. *Gross Motor Function Measure* (GMFM) is a criterion-referenced observational measure that was developed and validated to assess the gross motor skills of children with CP. The GMFM-88 contains 88 items divided into 5 gross motor dimensions including lying and rolling (dimension A), sitting (dimension B), crawling and kneeling (dimension C), standing (dimension E) and walking, running, jumping (dimension F).[30]

Chapter 2 : Review of Literature

Cerebral Palsy and Quality of Life

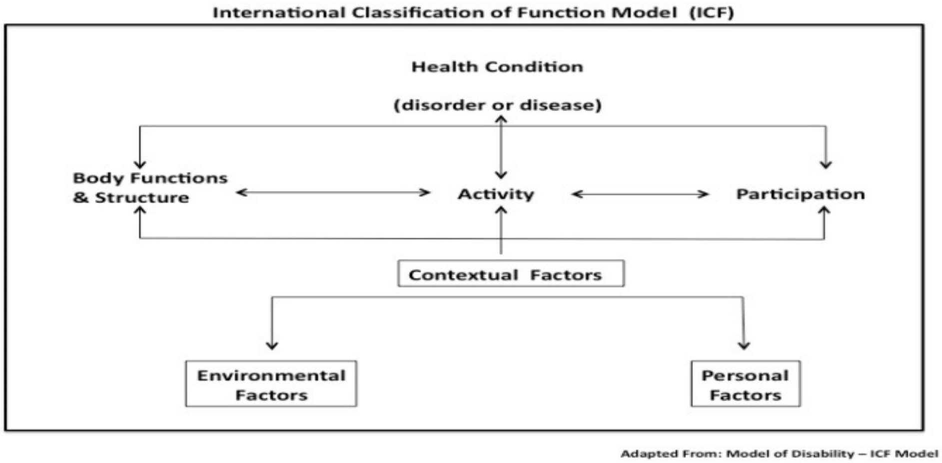
Affecting over 1 in 500 children,[31] cerebral palsy (CP) is the most common childhood neuromuscular disease, creating lifelong consequences of neurologic and orthopedic impairment.[8,28] Cerebral palsy is the most common etiology for interference with normal motor development.[8] Cerebral palsy is defined by Bax et al. as:

> Cerebral palsy (CP) describes a group of disorders of the development of movement and posture, causing activity limitation, that are attributed to non-progressive disturbances that occurred in the developing fetal or infant brain. The motor disorders of cerebral palsy are often accompanied by disturbances of sensation, cognition, communication, perception, and/or behavior, and/or by a seizure disorder.[28]

Children with CP report the lowest quality of life of any chronic childhood condition.[32] Within the CP group, Varni et al. found that children with CP (ages 5 - 18 years) self-reported their health-related quality of life in correlation with the severity of their physical disability with hemiplegic children reporting a higher quality of life than diplegic and both higher than quadriplegic children.[33] In regard to the least severe CP group, Russo et al. concluded that children with hemiplegic CP experience reduced quality of life and self-concept when compared to normally developing peers in self-reported studies particularly in the areas of physical competence and athletic competence.[34] The neurological and orthopedic impairments associated with CP create physical disability which negatively affects quality of life and development of self-concept in children with CP and correlates to the severity of their physical disability.

Participation and ICF Framework

Development of self-concept and improved quality of life are also affected by the ability to participate in life situations such as school or play and participation has been found to serve as a major factor in childhood development.[4] For this reason, participation has become part of the International Classification of Functioning, Disability and Health model standardizing the approach to rehabilitation care and treatment (Figure 2.1).[6]



International Classification of Function Model (ICF)

Adapted From: Model of Disability – ICF Model

Figure 2.1: ICF Model of Disability

Beckung & Hagberg studied 176 children with CP aged 5 to 8 years and found that full participation in social relations was possible in only 43%, mild restriction was noted in 18%, moderate restriction in 15%, severe restriction in 14%, and complete restriction in 10%. There was a strong correlation between restriction in mobility and restriction in participation in mobility, education and social relations for children with CP. This supports the relationship seen in the ICF model as activity and participation are strongly linked.[2]

Mitchell et al. studied 122 children with hemiplegic CP who ambulated independently and found significant association between the ability to perform increased physical activity and increased participation in home and community situations. They specifically identified the characteristic of walking endurance as associated with increased physical activity when compared to gross motor functional level, mobility limitations or functional strength. The researchers also identified an association between high inactivity and increasing age and reduced community participation in children with CP.[35]

The impact of reduced participation in life situations is illustrated as the child with CP matures. A strong link has been found between poor social self-efficacy and dependence in adolescents with disabilities which leads to a pattern of isolation and immobility in adulthood.[8] In a study of 101 adults with CP between ages 27 and 74 years in the United States, Murphy et al. found that 34 % of the adults with CP surveyed finished college, 53% were employed and 35% lived independently.[10] O'Grady et al. surveyed 117 adults with CP aged 17 - 51 years finding that 55% were educated beyond high school, less than half were employed and one fifth of those worked 20 hours or less and approximately half were able to live independently of their parents.[11]

Andersson and Mattsson surveyed 221 adults with CP aged 20 to 58 years in Sweden. They found that 14% completed or attended courses in college or university, 61% were living alone, and 25% were employed full-time. Of those employed, the percent employed correlated with the severity of CP, with the hemiplegic CP respondents resulting in the greatest percentage employed. They found that 39% of the total group could walk independently without walking aids both inside and outside the house while 10% could walk only inside. Fifteen percent walked with a walking aid, 27% had never been able to walk, and 9% had stopped walking. [9]

As children with CP grow into adults with CP, decreased activity leads to limited social participation, reduced quality of life and diminished self-concept.[4,35] These factors lead to lower levels of education, dependent lifestyles, and low rates of employment[8-11] contributing to an estimated lifetime health cost, for children born in the United States in 2000, of 11.5 billion dollars.[12]

Ambulation and Participation

The ability to independently ambulate is critical to participation in peer related activities. Impaired walking capacity has been identified as the primary physical disability in children with CP.[7] A study by Oeffinger et al. revealed a correlation between walking ability and participation level in children with CP finding that gait impairment is a significant predictor of lower scores in activity and participation.[1] A relationship has also been found between motor ability and participation level in children with CP finding that the greater the motor disability, the lower the scores in activity and participation.[3] Motor function has been found to be predictive of less participation in mobility, education and social relations for children with CP.[2] Gates et al., in a multi-site project found that children with CP made gains in participation, individual goal performance and satisfaction following an intensive speed treadmill or strengthening program.[36]

Normal Motor Development of Ambulation

In normal motor development, independent ambulation occurs at an average of 12 months of age[17,37] with motor function defined by six milestones identified by the World Health Organization (WHO).[38] These milestones include sitting without support, crawling on hands and knees, standing with assistance, walking with assistance, standing alone, and walking alone. They are achieved by the majority of normally developing children, although the sequence may vary. In progressing through these milestones, the child supports increasing amounts of weight until they reach the ultimate goal of independent ambulation between 8 and 18 months of age, with an average of 12 months of age.[17,37]

Maturation of gait is defined by 6 stages including infant stepping, inactive period, supported locomotion, unsupported locomotion, mature similar gait and mature gait. Infant stepping occurs during the first 2 months of life whereas supported locomotion is from 6 -12 months of age and unsupported locomotion or independent locomotion occurs anywhere from 10 - 18 months of age.[39] The inactive period occurs between 4 - 8 months of age, after which the child can initiate locomotion themselves, first seen as crawling and then as supported locomotion. Gait changes rapidly in the first 9 months of walking, initially characterized by a wide base of support and swaying of the trunk.[40] Okamoto et al. performed longitudinal EMG studies of muscles of the leg and found that in the first 3 years of life, walking begins with gross patterns of muscle activation often including co-activation of mutual antagonists. They noted maturation from excessive activation to efficient and economical muscle activation in the leg.[41] As this occurs, the child's base of support decreases with improved stability and gait continues to mature until the adult pattern is established by 7 years of age.[40]

Gait speed is one of the most basic and commonly used parameters in evaluating development of independent ambulation.[37] Muller et al. analyzed the gait speed of 8263 healthy children, aged 1 - 15 years in 6 - 10 trials each. They found that up to the age of 8 years, there was significant increase in gait speed with enhanced gait speed consistency of repeated trials up to the age of 15 years.[37] This maturation of gait allows the child to move with greater speed, consistency and efficiency which promotes participation in peer related activities into adulthood, leading to improved self-concept and enhanced quality of life.

The development of motor function from infant locomotion to adult locomotion must be accompanied by neuromaturation.[39] Although the adult gait pattern is established by 7 years of age,[40] Petersen et al. found developmental changes in corticospinal drive to the ankle dorsiflexors until early adulthood. Studying 44 healthy children, ages 4-15 years, the researchers found a significant age-related increase in motor unit discharge synchronization along with a significant age-related decrease in step to step variability in the foot position in swing phase. These two observations led the authors to deduce that the increased ability to control the ankle joint in swing phase may be related to maturation of corticospinal control.[42] This study reveals that although the adult locomotion pattern is thought to be set by age 7 years, fine tuning continues through the early teenage years which implies refinement in cortical organization and suggests neural plasticity.

Abnormal Motor Development of Ambulation

Impaired walking capacity has been identified as the primary physical disability in children with CP.[7] Deficits, due to damage to the central nervous system, such as spasticity, muscle weakness, impaired coordination and decreased selective motor control interfere with normal development of ambulation.[40,43,44] Slower walking speed, shorter stride length and more time spent in double support are frequent characteristics of CP gait.[45] Johnson et al. conducted a longitudinal study over 32 months on 18 subjects aged 4 to 14 years with spastic diplegia. Temporal and kinematic data obtained from three-dimensional gait analysis across two time intervals were compared. Increases in double support and decreases in single support were significant over time. Also, significant losses of excursion at the hip, knee and ankle were noted. The authors concluded that in contrast to normally developing children, the gait of children with CP worsens over time.[46]

Postural instability and lower extremity agonist-antagonist co-contraction are common factors impeding normal gait development leading to impaired kinetic motion, gait inefficiency, and high energy expenditure.[7,13,14] Prosser et al. studied 16 muscles in the trunk and hips and discovered that children with CP had greater total activation and co-activation for all trunk and hip musculature except the external oblique. They also saw differences in the timing of activation for all muscles studied when compared with the normally developing group.[13]

Tedroff et al. studied muscle activation patterns in children with and without CP when asked to perform maximal voluntary contractions. They specifically studied muscles that are significant in gait, the vastus lateralis, medial hamstring, tibialis anterior, and the lateral gastrocnemius. They found that children with CP, in comparison to those without, more frequently activated muscles other than the prime mover first, especially when the prime mover was a distal muscle.[47] This activation inaccuracy reinforces the impaired kinetic motion, gait inefficiency and high energy expenditure noted earlier making ambulation for children with CP less functional or practical.

In conjunction with ICF constructs, the child with CP reveals postural instability and agonist/antagonist co-contraction (Body Functions and Structure) which lead to impaired ambulation, decreased physical activity and diminished function in daily activities (Activity) which negatively affects participation (Figure 2.2).

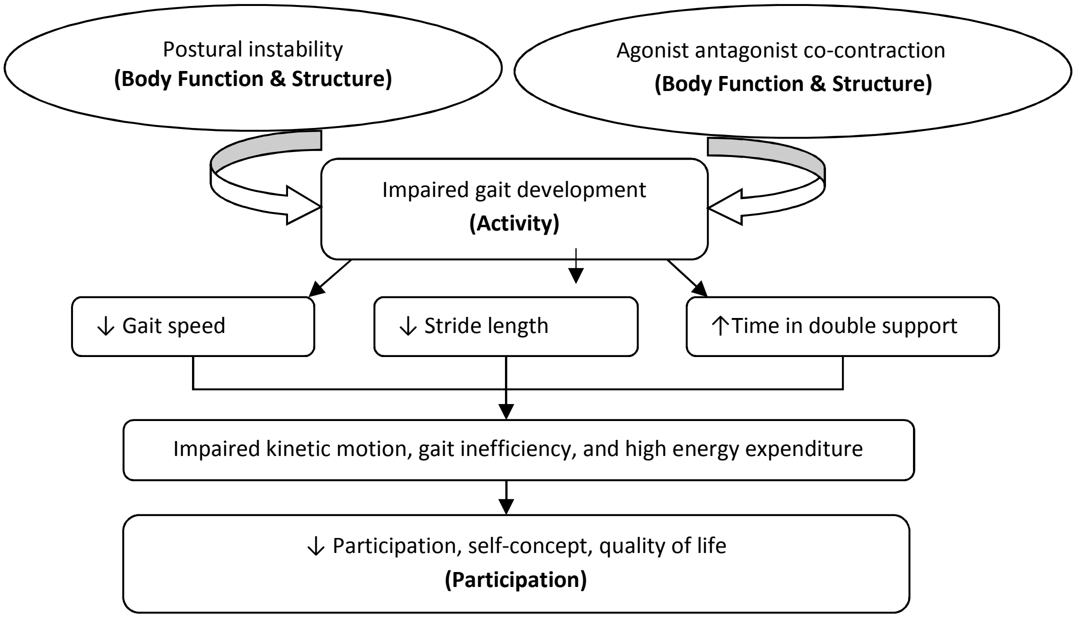


Figure 2.3: Deficits of Children with CP and ICF Model of Disability

Neural Plasticity

Motor control principles guide rehabilitation efforts when damage has occurred to the immature or mature brain, as in the treatment of cerebral palsy, however, neural plasticity is necessary to produce a permanent change in skilled motor control.[39] Shumway-Cook and Woollacott describe neural plasticity, or neural modifiability, as

> "a continuum from short-term changes in the efficiency or strength of synaptic connections, to long-term structural changes in the organization and numbers of connections among neurons".[19]

Providing a comprehensive review of relevant research on activity-dependent neural plasticity to guide clinical research and treatment, Kleim summarized the findings by proposing 10 principals of experience- dependent plasticity (Table 2.1).[20]

Table 2.1: Kleim's Ten Principles of Experience-Dependent Plasticity

Principle	**Description**
1. Use it or lose it	Failure to drive specific brain functions can lead to degradation.
2. Use it and improve it	Training that drives a specific brain function leads to enhancement of that function.
3. Specificity	The nature of the training experience dictates the nature of the plasticity.
4. Repetition matters	Induction of plasticity requires sufficient repetition.
5. Intensity matters	Induction of plasticity requires sufficient intensity.
6. Time matters	Different forms of plasticity occur at different times during training.
7. Salience matters	The training experience must be sufficiently salient to induce plasticity.
8. Age matters	Training induced plasticity occurs more readily in younger brains.
9. Transference	Plasticity in response to one training experience can enhance the acquisition of similar behaviors.
10. Interference	Plasticity in response to one experience can interfere with the acquisition of the other behaviors.

Motor Learning/Motor Control

Neural plasticity is necessary for producing a permanent change in skilled motor control. Skilled motor control comes from learned motor behaviors that have been shown to occur through applied motor learning variables. However, it is dosage required to create this permanent change is unclear.[39] Much research has been conducted to determine the most effective motor learning techniques in rehabilitation.[48] Basic concepts in motor learning include variability in practice, practicing components of movement, task attention, feedback and environmental progression.[21]

Variability in practice or contextual interference (CI) focuses on blocked versus random practice. The CI effect hypothesis contends that blocked patterns of practice lead to better same day acquisition but random patterns of practice lead to better learning, retention and transfer.[49] According to King, the most important aspect of the learning process is retention of the skill or movement, which would seem to support random patterns of practice over blocked.[48] However, Jarus and Gutman studied 7 to 9 year old children and found that a complex task, such as ambulation, was too difficult to effectively utilize random practice and advocated blocked initial training.[23]

Practicing components of movement, or whole versus part, refers to breaking down a task into its components and mastering each component before learning the entire task. Ambulation is a complex task and gait components must be practiced within the overall context of gait. Winstein et al. found that standing balance training in adults with hemiplegia changed their ability to perform single leg stance on the effected side but did not significantly change the asymmetry in their gait. Even though standing balance is an important aspect of gait, isolating separate components and practicing them independently did not carry over to functional gait.[50] Seitz and Wilson also found that learning a motor task in a sitting position did not transfer to ambulation. They studied 31 healthy subjects who were divided into three groups. They were asked to learn a synchronous heel-up-heel-down rhythm task in a sitting position and to reproduce it during their gait cycle. They found training a person in a sitting position produced a nonspecific effect on ambulation.[51]

Task attention lends itself to progression in motor learning moving from complete attention to task to automatic or subconscious performance. The three progressive stages are 1) the cognitive stage, with complete attention to task and frequent errors, 2) the associative stage requiring some attention to task and fewer errors and 3) the autonomous stage which occurs with few errors and automatic performance.[21,52] Practicing the task with full concentration can be progressed to practicing while performing cognitive tasks however Huang et al. found that children without disability had greater difficulty performing motor tasks while concurrently processing cognitive information.[24] A study by Lajoie et al. revealed that there are higher demands for attention with complex skills such as walking versus maintaining a sitting or standing position.[53] Thus precaution for slow progression in task attention when working with children on ambulation is required.

According to Shumway-Cook and Woollacott, feedback can broadly be defined as "all sensory information that is available as the result of a movement that a person has produced." Feedback can be either intrinsic (internal) or extrinsic (external or augmented) in nature. Intrinsic feedback is received thru the sensory system from normal performance of the movement, such as the feedback given by proprioceptors. However, extrinsic feedback involves supplemented or augmented intrinsic feedback. Examples of this type of feedback include use of a mirror and verbal or tactile cues from a clinician, which happen concurrently with the movement or at the end of the movement as in reviewing videotaped performance of the task.[19,48]

Research to determine the best type and timing of feedback with adults reveals that reduced feedback conditions enhance accuracy and consistency in performance in delayed retention tests when compared to those who received feedback during every performance trial.[54-57] However, a study by Sullivan et al. reveals that children do not produce the same results. The researchers compared children and adults in the effect of feedback frequency. They verified that adults who practiced with reduced feedback performed with increased consistency during the retention test compared to those who received 100% feedback. However, children who received reduced practice feedback performed with less consistency and accuracy during the retention test than those who received 100% feedback. During the re-acquisition test (one day later), however, the children in the reduced feedback group were able to improve their results comparable to those in the 100% feedback group. The authors concluded that in order to maximize motor learning, children need more practice with gradual reduction of feedback in comparison to adults.[22]

Environmental progression is an essential aspect of motor learning in regard to function within the patient's environment. It requires gradual adaptation of any situation or condition that the patient encounters in his/her environment. It has a strong link to the participation aspect of the ICF model and ultimately weaves rehabilitation treatment into the patient's real life. It needs to address psychosocial as well as physical factors that are unique to the individual in order to positively motivate the patient.[21] Motivation is often difficult with children particularly when practice can be repetitive in nature. Linking the practice with the environmental task can be challenging when dealing with children particularly if the task is complex such as ambulation.

Motor learning and motor control principals based on the ability to make permanent changes in the neural pathways (neural plasticity) are the cornerstone of rehabilitation techniques in adults and children with neurological insult. These principals and techniques are based on extensive research and form the basis of current neurological treatment by physical therapists. Neural plasticity principals are based on practice, specificity, repetition, intensity, salience, age, and transference. Basic concepts in motor learning including variability in practice, practicing components of movement, task attention, feedback and environmental progression, give further clinical guidance for optimal neural plastic change. It must be noted that research has discovered that children and adults vary in their response to the specifics of motor learning concepts and this must be taken into account when working with children.

Present Therapeutic Intervention

Utilizing the ICF model, treatment to improve Body Function and Structure, such as range of motion, balance, and strength, has been the emphasis of rehabilitation therapy for many years with more recent focus on integration into functional daily activities and participation in daily life activities.[36,58] It has been demonstrated that working on components such as range of motion, balance, and strength in isolation does not necessarily carry over to functional activities such as ambulation.[50,51,58] A systematic review by Scianni et al. revealed that strength training alone had no effect on improving strength, increasing walking speed or producing a clinically meaningful change in gross motor function in children and adolescents with CP.[59]

In attempt to focus on function and participation, while taking motor control and motor learning concepts into consideration, recent therapeutic intervention has often involved treadmill training in rehabilitation of children with CP. Treadmills allow for continuous gait in a small area with control of speed and distance and thus are a staple in many rehabilitation facilities.[60] A study by van der Krogt et al. compared overground and treadmill walking in typically developing (TD) children and children with CP. Overall, the authors found that the treadmill walking with a realistic virtual environment revealed more deviation than the walking in a conventional overground gait lab or natural walking outside of a lab environment. Treadmill walking was slower with reduced stride length and increased stride width for both groups of children. Also noted with treadmill walking was decreased peak angle dorsiflexion (CP and TD), increased knee flexion at initial contact (CP only) and increased anterior pelvic tilt (CP only).[60]

In order to address issues such as shorter stride lengths, manually facilitated treadmill training could be utilized. This is accomplished by placing the patient onto the moving belt of the treadmill, where at least two therapists facilitate trunk and limb kinematics. This proves to be labor intensive requiring the work of two or more therapists which also allows for inconsistent motor pattern execution between therapists and within therapists with fatigue, particularly with faster speeds. This human result of attempting repetitive symmetrical movement can risk reduction of movement fluidity and efficiency and decrease temporal and spatial symmetry, thus negatively affecting neuromotor control, neural reorganization and functional carry-over in gait in the pediatric population.[16,17]

Driven Gait Orthosis

The Driven Gait Orthosis (DGO) utilizes robotic assistance to optimize repetitive, task-specific practice through automated treadmill training rehabilitation. A recent option in this novel technology is the Lokomat which was first manufactured by Hocoma Inc. in Volderswil, Switzerland in 2000.   The DGO Lokomat uses a robotic device in coordination with a treadmill to improve walking ability.[15] The subject is suspended in a harness over a treadmill in an exoskeletal robotic frame that is connected to the frame of a body weight support system by a four bar linkage and comprised of two leg orthoses adjustable to the anatomy of each patient (Figure 2.3).

Figure 2.3: Subject and Hocoma Lokomat

Straps attach the exoskeleton to the outside of the subject's legs. Pediatric exoskeleton attachments for children ages 4 years and older have been available since 2006.[15] The legs are moved in a consistent, repetitive, natural ambulatory pattern that is synchronized in timing with the treadmill to promote normalized motor sequencing and gait efficiency. The consistent and symmetrical step lengths are determined by the lower extremity measurements initially input during the customized set up procedure. Dorsiflexion of the ankle joint is facilitated by an elastic foot strap optimizing ankle strategy needed for foot clearance during swing phase.[29]

A counter weight system is used for body weight support and permits individualized, adjustable body weight support within a range of 5 to 80 kg in 5 kg increments. A computer guides walking pace and measures the body's response to movement in response to the DGO.[61] Guidance force adjustment determines how much guidance the Lokomat is giving to the user's movement. A value of 100% corresponds to strict guidance whereas a value of 0% gives no guidance. In rehabilitation, guidance is slowly reduced from 100% according to the user's progress and response.[29] This advanced technology promotes repetitive, normalized motor patterning and gait execution while providing a high degree of safety that can be trained at adjustable gait velocities while incorporating targeted cuing as well as augmented visual feedback.[61]

The visual biofeedback system displays the user's activity in real time on a separate monitor while the user is walking. The monitor can be easily positioned within the user's range of sight giving direct feedback on performance. The smiley face icon reflects the general performance over one step. The more the user supports her own movement, the broader the smile while with less support, the smile turns to a frown. The display range for lower and upper limits are adjustable to allow all users positive feedback.[29]

The interface of advanced robotic technology, task specificity, progressively intense repetition and flexibility in customization facilitates structured progressive task acquisition, needed to optimize motor learning and promote learned gait pattern improvements to environmental carryover.

DGO technology utilizes motor control and motor learning principles to optimize ambulation rehabilitation through intense, measurably repetitive, and task-specific treatment to augment cortical neuroplasticity and promote lasting change in neuromuscular impairment. Utilizing computerized mechanical consistency, DGO training theoretically promotes accurate motor learning of volitional muscle activation and normalized kinematics. No other form of current therapy provides this consistency in treatment. Research has shown that DGO training improves multiple ambulation parameters in the adult stroke and spinal cord injury population but has just recently been shown as an effective treatment for children with CP.[25]

Adult Stroke DGO Training

In a systematic review of studies of locomotor training with robotic assistance in adults with neurological disorders conducted by Tefertiller et al., the authors concluded that locomotor training with robotic assistance is beneficial for improving walking function in adults following stroke or spinal cord injury. Of the 30 articles reviewed, 16 pertained to stroke including a total of 558 subjects. Thirteen studies (515 subjects) evaluated changes in walking speed with all measuring increased walking speed following use of locomotor training; however, significant differences were noted in those receiving robotic therapy in the acute or subacute phase post-stroke versus the chronic phase. When compared to similar patients receiving conventional therapy, the patients in the acute/subacute phase significantly improved their gait speed with robotic intervention whereas those in the chronic phase did not.

Seven studies (399 patients) measured walking endurance using either the 6-minute walk test or the 2-minute walk test. Results were split with several reporting significant increase in endurance following robotic training and others finding conventional therapy to be more effective. Again, the authors found a correlation between the severity and time post-stroke with the more severe at an earlier post stroke time revealing the best results.

Motor function was assessed in 9 studies using the Motricity Index, Fugl Meyer or the Motor Assessment Scale with five reporting a significant improvement in motor function, but no differences noted between the control and experimental groups. Only one study evaluating motor function revealed a significant difference attributed to locomotor training. The authors concluded that the use of robotic devices in rehabilitation of gait after stroke was found to significantly improve walking independence; however, noted that this training may be more effective in the acute and subacute post stroke rehabilitation phases when the patient is unable to walk independently. They also noted that intensity of treatment may correlate with improved results.[16]

A Cochrane review by Mehrholz et al. included 23 trials (999 participants) evaluating electromechanical-assisted training for walking after stroke in adults. They concluded that electromechanical assisted gait training in combination with physical therapy may improve recovery of independent walking in adults after stroke in comparison to those who received gait training without those devices, however no significant increase in walking velocity or capacity was evident. They cautioned interpretation of these results due to studies which were conducted with subjects who were already independent in gait, trials with varying treatment protocols, frequency, and devices used and trials that included use of functional electrical stimulation. As noted by Tefertiller et al., the authors specified that the evidence indicated that electromechanical assisted gait training in combination with physical therapy may improve independent gait in patients who were not initially walking independently and those in the first three months after stroke. In conclusion, the authors stated that further research was needed to determine the effective frequency and duration of electromechanical assisted gait training and how long the benefit can last.[62]

Coenen et al. evaluated the muscle activity of stroke subjects during overground walking and robotic walking and the muscle activity of able-bodied subjects during over ground walking. Utilizing a 16-channel electromyography (EMG) recording system with surface electrodes, muscle activity was measured and recorded on the following muscles of the lower extremity: medial gastrocnemius, tibialis anterior, semitendinosus, rectus femoris, adductor longus, gluteus maximus and gluteus medius. Recordings were collected bilaterally on the stroke subjects and only on the right lower extremity on the able-bodied subjects. A heel switch as used to determine heel strike.

Results of this study revealed lower overall muscle activity in all muscles except the adductor longus during robotic walking (RW) compared to overground walking (OW) in the stroke subjects. The authors suggested that this was due to lower effort necessary during RW compared to OW due to the support given by the robotic device. In addition, a smaller difference in mean muscle activity throughout the phases of gait between the paretic and non-paretic side was noted in the semitendinosus, adductor longus and gastrocnemius muscles, suggesting increased symmetry during RW.

In comparison of subject groups, the authors found that EMG patterns between the stroke subjects walking overground were significantly different than the able-bodied subjects walking overground. However, little to no difference in EMG patterns was noted between the stroke subject robotic walking and the able bodied overground walking, leading the authors to conclude that muscle activity in robotic walking is similar to that in able-bodied gait. It must be noted that this conclusion was based on 20 subjects (10 stroke and 10 able-bodied) with variability in the data collected.[63]

Pediatric CP DGO Training

Studies on the effectiveness and applicability of DGO training in pediatric rehabilitation are very limited.[64] Since the development of the pediatric Lokomat device in 2006[65], an estimated 208 pediatric versions have been distributed worldwide.[65] It's effectiveness in adult rehabilitation[66] led to the obvious question of its ability to provide the same result in pediatric rehabilitation. Due to the relative novelty and limited availability in the pediatric population, studies are scarce and rather inconclusive.

Borggraefe et al. reported improved gait parameters after utilizing robotic assisted locomotor treadmill therapy with a 6-year-old subject with bilateral spastic CP. Twelve therapy sessions over a 3 week span (4 sessions/week) were conducted on the Lokomat. In the treatment sessions, speed was increased from 1.1 km/hr to 1.8 km/hr. Body weight unloading started at 50% and was reduced to almost zero by the end of the sessions. Guidance force was at 50%. The treatment sessions averaged 34 minutes in length with a mean walking distance per session of 927 m. Outcome measures were taken before and after the 12 sessions and revealed improvement of self-selected overground walking speed from 0.25 m/sec to 0.6 m/sec in the 10 m walk test. Four months later, this velocity persisted. The 6-minute walk test revealed improvement from a distance of 55 m to 115 m after the 12 treatment sessions. Four months later this increased to 152m in 6 minutes.

The authors used the Gross Motor Function Measure (GMFM) to assess motor function. The subject doubled his percentage score in the assessment of standing ability (12.8% to 25.6%) and in the “running, walking and jumping” dimension, the score improved from 18.1% to 26.4%. These results were preserved over four months. In this single case study, the positive effects of DGO intervention is revealed in functional aspects which influence ambulation speed and endurance and thus positively impact participation.[67]

Patritti et al. presented a case series of four children with CP (spastic diplegia) who were treated with DGO Lokomat gait training. Two children were classified as GMFCS level II and the other two were classified as GMFCS level III. One child in each group received DGO training supplemented with augmented feedback (subjects #2 and #3) while the other child received DGO training without feedback (subjects #1 and #4). Each child participated in DGO gait training 3 times per week for 6 weeks. They were assessed pre- and post- training and at 3 months post-training.

The authors found that the GMFCS level II children showed small changes in Dimension D (standing) of the GMFM increasing 10% in subject #1 and 13% in subject #2 without further changes at follow-up. Larger improvements were seen in Dimension E (walking) of the GMFM with a 70% and 30% increase in subject #1 and subject #2 respectively. At the 3 month follow up, subject #1 showed a small increase and subject #2 showed a small decrease. Both subjects showed faster comfortable walking speeds post training with a 23% increase for subject #1 and 16% for subject #2. At follow up subject #1 showed a further increase of 10% while subject #2 decreased 7.2% of the post-training gain. In walking endurance, subject #1 showed a 53% increase after training and a further increase of 26% at the follow up. Subject #2 remained essentially unchanged throughout the study in walking endurance.

In Dimension D (standing) of the GMFM, the GMFCS level III children increased 333% for subject #3 and 200% for subject #4. At follow up subject #3 maintained the gain and subject #4 demonstrated a further increase of 22%. Dimension E (walking) increased 50% for subject #3 while a small decrease was noted for subject #4. An additional gain of 11% was seen at follow up for subject #3 while subject #4 showed a further 8% decrease. Walking speeds increased 17% for subject #3 and 11% for subject #4 post training and at follow up, an additional 6% increase was measured for both subjects. Walking endurance increased 22% for subject #3 and 10% in subject #4 with a further 11% increase at follow up while subject #4 revealed a 7% loss of post training gain at follow up.

After training, overground gait evaluation of subject #1 revealed improved hip extension in mid to terminal stance, larger and symmetrical knee extension at initial contact and during midstance. Also increased ankle plantarflexion was noted during push-off. Subject #2 also revealed improved hip extension during stance and improved knee extension during mid-stance bilaterally. The excessive ankle dorsiflexion during mid to terminal stance noted in the pre-training gait evaluation improved significantly. After training, over ground gait evaluation of subject #3 was unchanged. Subject #4 also revealed no change in gait kinematics after training.

The authors concluded that the less severe diplegic children in the GMFCS II group could improve more significantly than the children in the more severe GMFCS III group in both clinical outcomes and gait biomechanics. They also concluded that the augmented feedback module appeared to provide benefits to the child in the GMFCS level II group compared to the child who did not receive augmented feedback in the same level group.[7]

This study introduces the idea that the baseline functional level of the child with CP may influence the benefit of DGO training with the less severe able to obtain more benefit. This same conclusion was drawn by Borggraefe et al. in their 2010 study.

In 2010, Borggraefe et al. conducted a study involving 20 children with bilateral spastic CP to investigate the effect of robotic assisted treadmill training on standing and walking. They utilized the same outcomes measures as in the case series, dimensions D (standing) and E (walking) of the GMFM. In addition, they grouped the children according to severity of gross motor involvement utilizing the Gross Motor Function Classification System (GMFCS). The patients classified in the GMFCS levels of I and II (n=10) were categorized as mildly impaired whereas those classified as levels III and IV (n=10) were categorized as moderately to severely involved.

Twelve therapy sessions of robotic assisted treadmill therapy were conducted utilizing the Lokomat over a 3 week period (4 sessions/week). The walking speed was initially set at 1.1 km/hour and was increased to 1.8 km/hour by the end of the sessions. The duration of therapy sessions was limited to 50 minutes or when the patient complained of physical exhaustion. Initial body weight support was 100% and was reduced as much as possible throughout the sessions stopping when the knee started to collapse into flexion during stance phase of gait. Guidance force was individually adjusted according to clinical judgement. Active participation was encouraged by variation of guidance force, body weight support and speed.

Significant improvement was seen in the standing aspect (dimension D) of the GMFM score revealing an average 5.9% improvement and in the running, walking, climbing aspect (dimension E) revealing a 5.3% increase. According to the authors, these task specific improvements suggest the additional effect of postural stabilization.

As for walking distance and total time walked, the results revealed a difference between the mildly and severely involved groups of participants. The mildly impaired revealed a significant improvement before and after Lokomat treatment whereas the moderately/severely impaired revealed an improvement that did not reach the level of significance. In their study, the authors concluded that patients with moderate to severe cerebral palsy achieve less improvement compared to the mildly involved patient.[68]

In contrast to Patritti et al. and Borggraefe et al., van Hedel et al. found that robot assisted gait training might be beneficial for more severely affected children with CP. In a retrospective study of 67 children with CP, they evaluated dose and GMFCS level response. The outcome measures utilized included the Functional Ambulation Categories (FAC) which assessed the amount of walking assistance required and the Functional Independence Measure for Children (WeeFIM) to assess independence in daily life including self-care, mobility, and cognition. The mobility section included subcategories of transfers, walking and stairs. Also utilized were dimensions D (standing) and E (walking, running, and jumping) of the GMFM. Also recorded were self-selected and maximum gait speed in the 10-meter walk test and gait endurance in the 6 minute walk test.

The authors noted that significant within-group improvements were primarily seen in children with GMFCS level IV (severe involvement). Even though they walked less in an average Lokomat session, they revealed significant improvement in walking – related outcomes. A dose-response relationship was noted for children with GMFCS levels III and IV. However, between-group differences in changes in walking related outcomes were not significant.[64]

Borggraffe et al. looked at sustainability of motor performance after robotic-assisted treadmill therapy in children. Fourteen subjects (mean age of 8.2 years) with central gait disorders (13 bilateral spastic cerebral palsy and 1 spinal paralysis) participated in a 3 week trial of 12 sessions on the Lokomat (4 sessions per week). Initial walking speed was 1.1 km/hr and was gradually increased to 1.8 km/hr. The duration of the sessions was limited to 50 min. Body weight support was started at 100% and then reduced as much as possible until the knee collapsed into flexion stance phase.

Outcome measures were the dimensions D (standing) and E (walking, running, jumping) of the GMFM, gait speed as measured by the 10-meter walk test and endurance as measured by the six-minute walk test. Baseline data was taken 1-2 days before the trial began and outcome measures were assessed following the completion of the 3-week trial and then at six months after the completion of the 3 week trial.

During the 6 month follow up period the subjects received regular physical therapy treatment 1-2 sessions per week with seven of the fourteen subjects receiving an additional robotic assisted treadmill therapy session (2-3 sessions/months).

Evaluation immediately following the 3-week trial revealed significant improvement for the standing dimension D of the GMFM from 49.5% (±36.8) to 54.4% (±35.7, P=0.008), with less improvement noted in the walking, running and jumping dimension E from 38.9% (±31.7) to 42.3% (±34.4, P=0.012). Gait speed increased from 0.80 meters/second (±0.62, P=0.006) and endurance as measured by the 6-minute walk test increased from 187 meters (±142) to 226 meters (±142, P=0.033).

Evaluation 6 months after the 3-week trial revealed a gain of 7.3% (from 49.5% to 56.6%, P =0.002) in dimension D from the baseline visit to the 6 month visit. Dimension E revealed an increase of 4.4% (from 38.9% to 43.3%, P=0.033). Gait speed increased from 0.80 meters per second (±0.60) at the baseline visit to 1.11 meters per second (±0.85, P=0.046). Endurance increased but did not reach statistical significance (P=0.099). Separate analysis of the subjects who received continuing robotic assisted treadmill therapy during the 6 month follow up period revealed no statistically significant differences of changes of all outcome measures between the baseline visit and the 6 month follow up visit.

This study of 14 subjects revealed overall improvement in motor performance after a relatively short program of robotic assisted treadmill therapy (12 sessions in 3 weeks) which exhibited sustainability over a period of six months.[69]

Druzbicki et al. assessed the effect of DGO treatment on balance in children with spastic diplegia. Eighteen children (ages 6 – 14 years) with the diagnosis of spastic diplegia were randomly divided into two groups. The experimental group (9 subjects) received physical therapy and DGO treatment in the Lokomat once a day, five times a week for four weeks. The control group began with 9 subjects and ended with 5 subjects. They received physical therapy one time per day, five days a week for four weeks.

Balance was assessed with eyes open and eyes closed using the stabilometric Zebris platform. Statistically significant improvement in balance was found in the experimental group in the following with eyes open: confidence ellipse width, confidence ellipse height and vertical deviation and with eyes closed: confidence ellipse width, confidence ellipse area, total track length and vertical deviation. The control group revealed improvement but not statistically significant in any dimension in either condition. The authors concluded that the study suggests that therapy with DGO may have beneficial influence on the improvement of balance in children with spastic diplegia.[70]

In 2013, Druzbicki et al. studied 52 children with spastic diplegia to assess the impact of DGO treatment on gait. Fifty-two children (ages 6 – 13 years) with the diagnosis spastic diplegia were enrolled in the study. They were randomly divided into two groups of equal size. The experimental group (26 subjects) participated in a rehabilitation program using the Lokomat and physical therapy exercises. The control group (started with 26 subjects and ended with 9 subjects) received only physical therapy exercises. Both groups participated in 20 therapeutic sessions. Individual exercises in both groups were designed to increase stability in sitting and upright positions, improve motor control and walking skills. The time allowed for exercise was the same for both groups.

Assessment occurred twice, once before and once after complete therapeutic intervention. Gait analysis was performed utilizing motion analysis and temporal spatial and kinematic gait parameters were obtained from 3-dimensional gait analysis. Results revealed no significantly different changes between the groups in temporal spatial gait parameters. Also, the difference between the initial and final measurements in both groups was not statistically significant. The mean gait speed increased slightly in both groups and did not differ significantly between groups.

In the sagittal plane the range of pelvic motion measured in the initial measurements was similar for both groups for both the right and left side. The range of motion decreased slightly after the final treatment, but the difference was not statistically significant (p=0.8676). In the frontal plane, a smaller range of motion was noted on the left side in both the initial and final examination, but there was no statistically significant difference between the groups at the initial measurement. In the final evaluation, however, the experimental group revealed a significantly greater increase on the right side in the mean value of the range in pelvic motion in the frontal plane (p=0.0130).

Selected range of motion assessments at the hip joints did not reveal significant changes after completing the therapeutic program nor were significant changes noted between the experimental and control groups.

The authors did not find statistically significant improvement in temporal spatial or kinematic gait parameters in children with spastic diplegia who participated in therapy with the Lokomat. The only statistically significant change noted after Lokomat therapy was the range of pelvic motion on the right side in the frontal plane. It must be noted that the large dropout rate in the control group and the small and unequal group sizes were limitations.[71]

Meyer-Heim et al. studied the DGO treatment in children with central gait impairment. The study included 26 children, eleven females and 15 males with a mean age of ten years one month. Diagnoses comprised of cerebral palsy (19), traumatic brain injury (1), Guillain –Barre syndrome (2), incomplete paraplegia (2), and hemorrhagic shock (1). Ten children were treated on an outpatient basis and sixteen were inpatients. Two subjects out of the 26 did not complete the study. A mean of 19 sessions were completed in the inpatient group (two to five sessions of 45 minute duration of DGO training per week) and 12 sessions in the outpatient group (three to four sessions of 25 -45 minute duration of DGO training per week). The inpatient group participated in a multi-modal rehabilitation program including physical therapy, occupational therapy and speech therapy. Physical therapy included balance training, stretching, COGT, and functional exercises). The outpatient group stopped their usual physical therapy sessions due to time constraints. Eight of the ten patients stayed on their usual botulinum toxin A injection schedule to the lower extremities during this time.

Fifteen of the sixteen inpatients completed DGO training with a mean of nineteen training sessions per patient walking a mean of 649.1 m per session. Mean training duration was 23 minutes 48 seconds and mean walking speed was 1.6 km/hr with unloading of 38.2% body weight. Overall walking parameters improved for the majority of inpatients. Thirteen of the 15 increased their gait speed on the 10-meter walk test. Mean gait speed increased significantly from 0.53 m/s to 0.82 m/s. Eleven of the 13 able to complete the 6-meter walk test revealed a mean walking distance increase from 151.5m to 251.3m. Nine of the thirteen children improved their scores on Dimension D (standing) of the GMFM and twelve of the thirteen in Dimension E (walking). Significant increases were noted for Dimension D scores improving from 57.6 to 66.3 and Dimension E from 38.2 to 54.5. Walking ability was assessed by Functional Ambulation Categories which showed improvement in six of the sixteen children, one child regressed and nine remained the same. The mean score changed significantly from 3.1 to 3.9.

In the outpatient group, nine of ten patients completed the DGO training with the mean number of training sessions on the DGO equaling 12 and the patients walking a mean of 1158m per session. Mean training duration was 28 minutes 42 seconds and mean walking speed was 1.7km/h with unloading of 14.4% of body weight. Over-ground walking parameters improved in the seven patients assessed revealing significant mean gait speed increase from0.87m/s to 1.09m/s. Seven of the nine revealed improvement in Dimension D (standing) with scores increasing from 46.7 to 52.4 and in Dimension E (walking) from 39.5 to 42.2. Walking ability, assessed with the Functional Ambulation Categories, showed no change.

In order to more specifically compare the impact of DGO training on children (inpatient versus outpatient) with cerebral palsy, the inpatients with CP were analyzed separately. All outpatients were children with CP. The inpatient CP group revealed significant improvement in all areas except GMFM Dimension D and the Functional Ambulation Categories. Gait speed improved by 47.1%, from 0.53m/s to 0.78m/s whereas the change in the outpatient group was 23.6%. The largest difference was observed in the GMFM Dimension E score and the Functional Ambulation Categories with the inpatient group improving 47.8% in the GMFM Dimension E score and 43.3% in the Functional Ambulation Categories. GMFM Dimension E score for the outpatient group changed by 6.8% and the Functional Ambulation Categories score remained unchanged.[18]

The authors concluded that DGO training is a “promising tool” for use with children with central gait impairment. However, since no control group was included in this study, the effect of DGO training cannot be isolated and the small sample size adds additional limitation. The greater improvement noted in the inpatient group who also received physical therapy treatment suggests that physical therapy treatment played a role. However the complication of botulinum toxin A injections to the lower extremities in the majority of outpatients during the study puts that conclusion at risk. This study contained many factors that prevent decisive conclusion.

In 2009, Meyer-Heim et al. conducted a similar study with 22 children with CP (11 inpatients and 11 outpatients) ages 4.6 – 11.7 years of age. The authors' objective was to measure functional gait improvements of DGO training in children with CP. Intervention on the Lokomat included a total of 10 sessions of 45 minutes each over 4-5 weeks for the inpatients and 12 sessions of 60 minutes over a 3-4 week course for the outpatients. The inpatients received additional therapy sessions according to need in physical therapy, occupational therapy, speech therapy and hippotherapy. The outpatient group had no other therapeutic treatment.

Results were calculated for the entire study group. A mean of 15.1 training sessions occurs with patients walking a mean of 842m during a mean of 31.5 minutes per session on the DGO. The assessed outcome parameters improved for the entire study group. The mean maximum gait speed in the 10-meter walk test improved 0.12 m/s (15.9%) from 0.78 to 0.91 m/s. The distance covered in the 6-minute walk test improved from mean 176.3 m to 199.5 m or 13.1% increase. The scores in Dimension D (standing) of the GMFM increases significantly by 6.3% from mean 40.3% to 46.6%. Dimension E (walking) showed a non-significant increase of 2.1% from mean 29.5% to 31.6%. An assessment of walking ability measured by the Functional Ambulation Categories revealed a mean score increase from 2.6 to 3.0. Between group analysis was conducted and it did not reveal any significant differences between the results of the inpatient group and the outpatient group.[25]

This study's most prominent limitation is the lack of a control group. Without the ability to compare to standard treatment of CP, there is no way to conclude that

DGO treatment is more or less effective than standard treatment. The small sample size and the admitted non-blinding of the outcome assessors in the pre- and post-training conditions limit the strength of this study's conclusions.

Sarhan et al. studied twelve children ages 3 – 5 years with spastic diplegia who were being treated as either an inpatient or an outpatient in pediatric clinics. They were randomly divided into two equal groups. The control group received manual treadmill therapy and the experimental group received intensive loco-motor treadmill training using the Lokomat. Treatment for both groups included sessions lasting 30-40 minutes, 3 times a week for 10 weeks. Each subject was provided body weight support with the "lowest possible body weight support" to prevent knee buckling and the treadmill speed was adjusted to individual preferred speed.

In the experimental group ($n=6$), mean stride length improved 11% which revealed a highly statistically significant difference ($t = 7.92$, $p < 0.001$) whereas the control groups ($n=6$) mean stride length improvement was 4% and not statistically significant ($t=2.714$, $p<0.025$). In cadence, the experimental group revealed a highly statistically significant improvement (74.16 ± 7.386 steps/min) to 80.92 ± 6.369 steps/min) whereas the control group did not (74.96 ± 7.295 steps/min to 79.57 ± 8.135 steps/min). In the experimental group, mean gait velocity showed an improvement that was highly statistically significant increasing from 36.03 cm/s ± 4.495 cm/s to 41.8 ± 3.705 cm/s whereas the control groups improvement was 38.45 ± 4.272 cm/s to 39.67 ± 3.637 cm/s, not statistically significant. Both groups revealed statistically significant improvement in grades of stability assessed by the Balance evaluation using the Bruininks-Oseretsky Test of Motor Proficiency Subset 2.

The results at the end of the treatment period indicated significant improvement in cadence, stride length, gait velocity and balance for the experimental group who received training with DGO with body weight support system whereas the control group (treadmill with body weight support training) only showed significant improvement in balance. The authors concluded that CP children who receive DGO training show slightly better improvement in all gait variables tested except balance when compared to those trained with body weight support treadmill training.[15]

This study has many limitations greatest of which is small sample size. Parametric statistics were utilized which could be misleading. It appears to be a more significant statement about the treadmill training results than the DGO training. No true control group was utilized thus the positive effect of the DGO training is not validated.

Schroeder et al. studied 83 patients aged 4 to 18 years of age (mean age 10 years 8 months) who were treated with robot-enhanced repetitive treadmill therapy on the Lokomat over 12 sessions during a 3-week period. The children were diagnosed with early-developed movement disorders including bilateral spastic CP (n=69), unilateral CP (n=3), ataxic CP (n=3), hereditary spastic paraparesis (n=6) and genetic syndrome including spasticity (n=2). Twenty-four subjects received botulinum toxin injection 2-4 weeks before visit 1.

The subjects were assessed at visit one which was a day before the training began and then at visit 2, a day after the 3-week training ended. The outcomes measures included GMFM-66 total score, GMFM-D score (standing), and GMFM-E score (walking, running and jumping). Potential differences in improvement were assessed by GMFM-66 baseline total score at visit 1, age, etiology of movement disorder, sex, and botulinum toxin therapy 2-4 weeks before visit 1.

This study took place over 6.5 years with mean distance during treatment equaling 12.6 km, mean duration of therapy session equaling 37 minutes, and mean treadmill speed was 0.49 m/s. The mean group differences at visit 2 showed significant improvements in the range of +2.5 points (95% CI 2.0-3.0; MCID of large effect size), +5.5 points (95% CI 3.8-7.2, MCID of large effect size) and +4.1 points (95% CI 2.9-5.3, MCID of large effect size) for GMFM-66, GMFM-D, and GMFM-E scores respectively. However, great variability was noted in individual improvement from no improvement, or even a decline in some subjects, to large improvement in others.

Significant improvement in overall gross motor abilities as well as standing and walking ability for the whole group of subjects was noted. The focus of this study was on patient-related determinants of the size of the therapeutic effect. The GMFM-66 baseline total score was found to be an important determinant with a linear association for overall gross motor improvement, whereas no association with age, sex, diagnosis or botulinum toxin therapy was observed. The linear association implies that patients with higher motor abilities at baseline improved more during DGO treatment than did those with lower motor ability.

With regards to standing abilities, age was the only significant determinant identified with an inverse linear association. Clinically significant improvements in standing abilities can be expected with a 95% probability in children up to 14 years of age. Walking abilities revealed a significant hyperbolic association between GMFM-66 score and effect size of improvement. Children with lower GMFM-66 scores are very unlikely to reveal improvements large enough to enable them to gain even basic walking skills while those with higher scores who are already independently mobile, will have a greater opportunity to score higher after treatment.

In conclusion, the authors proposed that GMFM-66 scores and age were relevant predictors of responsiveness to robot-enhanced repetitive treadmill therapy whereas no association was noted for sex, diagnosis or botulinum toxin therapy.[72]

Schroeder et al. conducted a study that assessed gross motor function, activity and participation in subjects with bilateral spastic CP after robot-enhanced repetitive treadmill therapy on the Lokomat. Eighteen subjects with bilateral spastic CP with an age range of 5.0 – 21.8 years (mean 11.5 years) participated in twelve treatment sessions over a three-week period with initial assessment one day prior to initiation of treatment and post assessment one day following the last treatment. In order for each subject to serve as his own control, the first assessment was conducted 3 weeks before treatment (V1), the second on the day before treatment began (V2), the day after treatment ended (V3) and 8 weeks after treatment ended (V4). Between V1 and V2, each subject received their regular home-based therapy program once or twice a week.

The outcome measures included the 6 minute walk test, 10 meter walk test, maximum walking speed, step length, GMFM-66, GMFM-66 Dimension D (standing), GMFM-66 Dimension E (walking, running, jumping), and the Canadian Occupation

Performance measure (COPM) to assess participation. Between V1 and V2, GMFM scores did not change significantly, but showed significant improvement comparing V1 or V2 to V3 (GMFM-66 score: $p<0.001$, GMFM-D score: $p<0.01$, GMFM-E score: $p<0.01$). Mean GMFM-66 score improved by 2.7 points (95% CI 0.97-4.42), Dimension D by 3.8 (1.62-5.90), and Dimension E by 3.1 (1.01-5.09).

COPM score for Performance and Satisfaction ratings improved significantly. Improvements were maintained at the eight week follow up, V4. For self-selected and maximum walking speed (SSWS, MWS) no significant changes were noted between V1 or V2 and V3. Step length revealed a decrease of 7.7% and walking distance during the 6-minute walk test increased by 6.8% (both comparing V2 and V3), but this lacked significance (p:0.057 and 0.076 respectively).

In subjects 10 years and older, subjects with increasing GMFCS levels 1-3, and subjects receiving their first robotic therapy, the mean changes of GMFM-66 total score between V1 and V3 showed decreasing responsiveness, however, improvements remained statistically significant as well as clinically meaningful in all subgroups. A significant negative correlation was found when comparing increasing GMFCS levels and GMFM-66 total score changes (Spearman's *rho*= -0.636, p=0.005) as well as repetitive robotic treatment and GMFM-66 total score changes (rho= -0.500, p=0.034). Correlations of any of the GMFM scores and age showed no statistical significance.

The authors summarized the results of their study stating that intensified robotic-enhanced repetitive treadmill therapy in subjects with bilateral spastic CP of different ages reveals improvement of gross motor function in the ICF domains of

Activity and Participation, represents clinically meaningful effect sizes across GMFCS levels 1-3 throughout childhood and adolescence with a tendency toward better response in the Activity level in the first robotic therapy experience in younger and less severely impaired subjects which is not seen in the self-reported Participation ICF domain.[73]

As demonstrated, the investigative studies on the effectiveness of DGO therapy in pediatric rehabilitation are few and inconclusive. Many of the studies were plagued with small sample sizes, lack of control group, lack of blinding, and interfering variables. Most authors found a positive result from the use of DGO therapy with children, however, neither the result nor the patient population which benefitted was consistent between studies. The only common thread in each conclusion is the need for more research to clarify the possible role of DGO therapy in pediatric rehabilitation.

DGO Treatment and EMG

Very few studies have examined the effect of DGO treatment and its effect on muscle activation patterns in adults or children. The first was conducted by Hidler and Wall. They studied seven healthy adult subjects with no known history of neurological injuries or gait disorders who ranged in age from 24 – 30 years (mean age26.8 years). Surface EMG was recorded from the gastrocnemius, tibialis anterior, hamstrings, rectus femoris, adductor longus, vastus lateralis, and gluteus medius. A heel switch was utilized to determine position in the gait cycle.

After the electrodes were placed and the subjects given time to accommodate to the treadmill, they were asked to walk on the treadmill at four different walking speeds

(0.42, 0.53, 0.64, 0.75 m/s), with the order randomly selected. EMG and kinematic data were collected for 60 seconds during the second minute of walking at each speed identified. The subject was then placed in the Lokomat and the procedure was repeated. The subjects were given the same time to acclimate to walking with the Lokomat and then EMG and kinematic data were collected for 60 seconds during the second minute of walking at each of the four randomly selected speeds. No body weight support was provided in either condition.

Individual stride cycles were determined by the heel switch data with the stride considered the period between successive heel strikes on the same leg. The muscle activation (EMG) pattern was then time normalized for each stride expressed as a percentage of the total gait cycle. The average EMG profile was calculated for each muscle for all eight trials and the data was divided into seven phases of gait. Within each phase, the integrated EMG activity was calculated for each muscle.

The results revealed significant changes in muscle activation patterns in numerous muscles. There was higher muscle activation in the quadriceps (rectus femoris and vastus lateralis) and the gluteus muscle groups during Lokomat walking than during treadmill walking, while there was often less activation of the gastrocnemius, adductor longus and tibialis anterior during Lokomat walking. Increased quadriceps muscle activation was noted in Lokomat walking compared to treadmill walking throughout all phases of the gait cycle, particularly in the rectus femoris. The hamstrings also revealed increased muscle activation in Lokomat walking particularly noted in the mid-stance phase through the mid-swing phase. This results in co-activation with the antagonist muscle (quadriceps). The adductor longus also revealed increased muscle activation throughout all phases of the gait cycle on the Lokomat in comparison to treadmill walking.

Statistical comparison of muscle activity of the treadmill and Lokomat walking revealed significance, $P<0.05$ in initial loading in the gastrocnemius and gluteus maximus; in mid-stance in the gluteus maximus; in terminal-stance in the gluteus maximus, anterior tibialis and adductus longus; in pre-swing in the gluteus medius; in mid-swing in the anterior tibialis, and in terminal-swing in the adductor longus. Significance at the $P<0.01$ level was noted in mid-stance in adductor longus and rectus femoris; in pre-swing in the vastus lateralis; in initial-swing in the vastus lateralis and gluteus medius; and in terminal-swing in the rectus femoris. Significance at the $P<0.001$ level was noted in initial loading in the vastus lateralis; in mid-stance in the tibialis anterior, in terminal-stance in the rectus femoris; in pre-swing in the adductor longus, rectus femoris, gluteus maximus, and the hamstrings; in initial-swing in the gastrocnemius, rectus femoris, hamstrings and gluteus maximus; in mid-swing in the rectus femoris, hamstrings and gluteus maximus and tin terminal-swing in the vastus lateralis and gluteus maximus.

The authors felt that the observed changes in muscle activation patterns in the Lokomat were a result of the device's restrictions of leg movements in the sagittal plane and restrictions in pelvic movement. They proposed that since the Lokomat limits movement of the pelvis and prevents lower extremity abduction movement, that the subject would increase compensatory muscle activity in response. The authors suggested further study to determine whether a subject would “learn” the Lokomat’s gait pattern over an extended period of time and thus reduce the amount of co-activation of antagonistic muscles.[74]

This study which was conducted on healthy adults cannot be extrapolated to children or children with CP. Adult normal gait patterns and muscle activation patterns in gait are developed throughout childhood and thus are different than those of children.[75,76] Also, this study does not take into account any differences in muscle activation patterns between overground walking and treadmill walking which could produce further discrepancy in comparison. Since activity and participation depend on typical overground walking ability, this component is essential.

Schuler et al. investigated the muscle activity patterns of healthy children and children with motor impairment during robotic-assisted gait training and treadmill walking. The study included 17 children, 9 with motor impairments and 8 healthy children, ranging in age from 8 – 17 years. The children with motor impairments were in and out patients including spastic diplegia CP (n=3), hip dysplasia (n=1), cerebral hemorrhage (n=1), multiple sclerosis (n=1), encephalopathy (n=1), spastic tetraplegia CP (n=1) and transverse myelitis (n=1).

The study focused on surface EMG pattern and duration of stance and swing phases in three walking conditions: 1) DGO walking, 2) DGO walking motivated by therapist and 3) walking unassisted on a conventional treadmill. Surface EMG recordings (sEMG) were taken from four muscles on the dominant or less affected leg including tibialis anterior (TA), gastrocnemius lateralis (GL), vastus medialis (VM) and biceps femoris (BF). The surface electrodes were placed and the subject walked at least 5 minutes in the Lokomat to become familiar with it. Measurements were taken without breaks between conditions. The DGO was then removed and the subject took a 5 minute break before walking on the treadmill. Two minutes of walking on the treadmill was followed by measurement recording in unsupported treadmill walking. The therapist's protocol to motivate the subjects was standardized and strictly adhered to.

In the DGO, unloading was set for 30% of the subject's weight. The DGO treadmill speed was set at the subject's comfortable walking speed. Each subject wore passive foot lifters that provided sufficient ankle dorsiflexion for adequate toe-clearance during the swing phase.

In regard to stance and swing phase distribution, the average percentage of total stance time in the subjects with motor impairment was 57% ± 2% in DGO walking, 56% ± 4% in DGO with motivation and 74% ± 5% in treadmill walking. In healthy subjects the stance phase duration percentage was 54% ± 3% in DGO walking, 53% ± 2% in DGO with motivation and 67% ± 4% in treadmill walking. Relative stance duration was significantly longer during treadmill walking compared to the DGO conditions (p=0.012 for all comparisons). For all three walking conditions, the healthy subjects had a shorter relative stance phase when compared to those with motor impairment (p=0.008 for each DGO condition and p=0.003 for treadmill walking).

Within walking conditions, significant sEMG amplitude differences were observed in the TA muscle (swing phase) and the VM muscle (stance phase) during treadmill walking as well as in the BF muscle (stance phase) during DGO with motivation. When comparing the sEMG patterns of all the conditions to overground walking reference data from Chang et al.,[26] DGO and DGO with motivation conditions correlated well to very well in general. However, sEMG data from treadmill walking was often negatively correlated with the reference data in both healthy children and children with motor impairment.

This study has illuminated that step duration can be influenced by the subject (healthy or motor impaired) when walking in the DGO. Although the Lokomat is position controlled, differences in stance and swing phase duration were observed between the healthy subjects and those with motor impairment. Furthermore, during DGO, the relative duration of the stance phase of the subjects with motor impairment resembled previously reported percentages for healthy children walking overground.[26,76]

When comparing muscle activation patterns during different walking conditions, the authors found that the TA in the DGO and treadmill walking appeared less active in the loading response and terminal swing compared to normal. The authors presumed that the foot lifters used during DGO might have facilitated eccentric muscle activity during heel strike.

The GM revealed early onset of activity during the end of swing phase as well as prolonged activity in stance particularly noted in the healthy children during treadmill walking and DGO with motivation. According to the authors, this is known as the plantar flexion-knee extension couple to control the second rocker and an upright position. In the subjects with motor impairment, the GM amplitudes were small. The authors felt this could be due to the 30% body weight support during DGO walking which may have reduced the anti-gravitational activity of the already weakened GM muscles. The best GM muscle activity pattern was found in both groups during DGO walking and in the subjects with motor impairment during DGO walking with motivation.

Normally the VM is active from mid-swing to mid-stance. However, in this study, during the treadmill condition, particularly among the subjects with motor impairment, the VM showed activation in terminal stance, which the authors thought might indicate co-contraction for stabilization of the knee joint before entering pre-swing. Another finding of the study was that the VM activity was quite variable in the subjects with motor impairment. However, that group revealed the most similarity to normal in the VM muscle activation pattern in the DGO walking condition as well as the DGO with motivation.

Normally the activation of the BF starts during mid-swing and continues to mid-stance. In this study, the BF was remarkably silent in the DGO and treadmill conditions but highly active during DGO with motivation, particularly in late loading and mid-stance as well as in terminal swing. The authors explained that this could be due to the excessive backward push of the subject’s leg after heel strike and the resistance of the DGO to this movement.

The authors listed several limitations of their study. They noted that the number of subjects was small and relatively inhomogeneous. They also questioned whether the

2 minutes given to the subjects to accommodate to the treadmill and the 5 minutes for the DGO may not have been enough to ensure habitation and could have influenced gait pattern. The authors indicated that it was sometimes difficult to trigger “heel strike” and “toe off” especially during treadmill walking, as this was accomplished manually through video synchronization. The authors used video synchronization rather than foot-switches since normal heel-toe gait is often variable or absent in the subjects with motor impairment. The last limitation noted was that the sEMG data was gathered with 2000Hz, the video recordings were made with 50 Hz only, thus possibly influencing the accuracy of identifying stance and swing phase.

The authors concluded that walking in the DGO resulted in physiological activation patterns for most of the muscle recorded (TA, GM, VM during stance and BF) in the subjects with motor impairment which indicates that a DGO system is able to influence the gait pattern of children with motor impairment in a positive and physiological manner.[27]

This study opens the door to many questions concerning the use of DGO therapy to influence muscle activation patterns in children with motor impairment. With the variability noted in gait maturation in children, the use of reference sEMG muscle activation patterns as “normal” decreases the accuracy of comparison. Also, the authors made many suppositions to explain unexpected results. With only 3 walking conditions for reference, the influence of other contributing factors is left unknown. The choice of monitored muscles did not allow adequate investigation of interaction. The GM and TA could have been greatly influenced by the foot lifters on the DGO. The questions concerning co-contraction of the BF and VM should be further investigated particularly since co-contraction of antagonist muscle is a common problem in gait in children with CP.[7,13,14]

Conclusion

Ambulation ability is a critical component of participation in peer related activities across the life span.[1-3] Limitation in walking proficiency has been identified as the primary physical disability in children with cerebral palsy (CP)[7] and thus inhibits participation in peer activities, threatening the development of independent mobility. Abnormal walking in children with CP is due to alterations in gait characteristics such as agonist-antagonist co-activation, crouched posture, and impaired kinetic motion. These limitations foster inefficient, high-energy expenditure during gait.[7,13-15]

Current therapeutic strategies in overground gait training demonstrate inconsistent effects on correcting these abnormal kinematics.[16,17] Newer approaches such as driven gait orthosis (DGO) training for children with CP have been found to provide consistent, measurably repetitive, task specific training which is necessary for neuroplastic change that could foster volitional muscle activation and normalized kinematics.[15,18] No other form of current therapy provides a training environment with the consistent, repetitive approach found on the DGO.[15]

Significant gaps in knowledge concerning the impact of DGO training on children with CP exist as much of the initial research has been performed on adults and the available research with children is poorly controlled and relatively inconclusive. There is limited knowledge concerning the effects of DGO application with various training parameters on the volitional muscle activation patterns of typically developing children and children with CP in gait. The findings from this research will enhance the evidence and thus the clinical decision making for therapists seeking to maximize functional independent ambulation which will also maximize overall functional independence and quality of life for children.

Chapter 3 : Methodology

Study Overview

This study is intended 1) to determine if the lower extremity muscle activation patterns of children with CP are dissimilar to age-matched TD children in overground walking, 2) to determine if DGO training replicates unimpaired muscle activation patterns in overground ambulation in typically developing children, 3) to determine if the lower extremity muscle activation patterns in overground walking of children with CP are dissimilar to their muscle activation patterns with DGO assistance, and 4) to determine if DGO training promotes unimpaired muscle activation patterns in children with CP.

Study Participants

Inclusion Criteria

Inclusion criteria for the children with CP included diagnosis of cerebral palsy, ages 4-12 years, minimum femur length of 21 cm, ability to ambulate barefoot with or without an assistive device for at least 20 feet, and ability to follow one-step verbal directions. Inclusion criteria for the typically developing (TD) children included ages 4 - 12 years and a minimum femur length of 21 cm.

Exclusion Criteria

Exclusion criteria for the children with CP included Botox to the lower extremity in the past 3 months, history of tendon transfer and presence of a severe deficit in visual acuity and/or visual field.

Exclusion criteria for the TD children included presence of a severe deficit in visual acuity and/or visual field.

Recruitment/Consent/Retention

Children with CP were recruited through the Pediatric Rehabilitation Department at Indiana University Health, the Cerebral Palsy Clinic at Riley Children's Hospital at Indiana University Health and by email, phone calls and flyers. The TD children were recruited through therapists at Indiana University Health, and by email, phone calls and flyers.

The two subject groups were age-matched with the children with CP recruited first and age-matched typically developing peers last (Table 3.1). Age-matching the groups assisted in decreasing the effect of documented variability in children's muscle activation patterns in gait as they mature[76,77] and provided specific age group norms.

The subjects were pre-screened by phone to determine eligibility with final study admission at the initial visit to verify inclusion and exclusion components.

Human Subjects Involvement and Characteristics

All procedures were reviewed and approved by the Indiana University Purdue University at Indianapolis Institutional Review Board (IRB), study number 1603070352 prior to initiation of the study.

Table 3.1: Subjects' Demographics

Subject #	Age	Category	Match	Gender	Diagnosis	GMFCS
01_05	4	TD	02_17	F	TD	
02_17	4	CP	01_05	M	Hemi	I/II
01_16	5	TD	02_16	M	TD	
02_16	5	CP	01_16	F	Hemi	I/II
01_04	6	TD	02_04	M	TD	
02_04	6	CP	01_04	F	Spas quad	III/IV
01_01	7	TD	02_01	F	TD	
02_01	7	CP	01_01	F	Hemi	II
01_19	8	TD	02_19	M	TD	
02_19	8	CP	01_19	F	Spas di/quad	III/IV
01_03	9	TD	02_03	F	TD	
02_03	9	CP	01_03	M	Spas di	II/III
01_18	10	TD	02_18	F	TD	
02_18	10	CP	01_18	M	Spas di/quad	III
01_20	10	TD	02_20	F	TD	
02_20	10	CP	01_20	M	Spas di	II
01_08	11	TD	02_08	M	TD	
02_08	11	CP	01_08	M	Spas di	II/III
01_09	11	TD	02_06	M	TD	
02_09	11	CP	01_09	M	Hemi	I

Benefits of Research to Human Subjects and Others

Participants were informed via the consent process that they should not expect any benefits from the study and that taking part was completely voluntary and would not reflect on any services received at Indiana University Health should they change their mind and withdraw from the project.

Study Design

EMG Data Collection

A Delsys Trigno wireless system with 16 channels was used to record all muscle activity using self-adhesive Trigno sensors. The standard sensor specifications are listed in Table 3.2. The sensors were placed according to recommendations of Cram's Introduction to Surface Electromyography[78] (Table 3.3) for the lower extremity on the following muscles of the dominant (TD) or least affected side (CP): rectus femoris, medial hamstring (semitendinosus), gluteus maximus, and gluteus medius. These lower extremity muscles are major contributors to normal ambulation ability and are readily monitored by surface electrodes. The dominant (TD) or least affected side (CP) were determined by the foot used to take a step forward[79] by TD children and by the affected side that bears the most weight in standing in children with CP. A foot switch with 4 sensors was utilized to allow the synchronization and identification of position in the gait cycle. The sensors were placed on the plantar surfaces of the great toe, the first metatarsal head, the fifth metatarsal head and the heel. This allowed for accurate timing of first contact whether it be heel, toe or forefoot in supination or pronation.

Table 3.2: Delsys Sensor Specifications

Resolution (EMG Signal)	168 nV/bit (LSB)
Bandwidth (EMG signal)	20 ± 5 Hz > 40 dB/dec 450 ± 50 Hz > 80 dB/dec
Passband Ripple	⍰2%
Overall Channel Noise	⍰0.75uV
CMRR	>80dB
Sampling Rate	1926 samples/sec

Table 3.3: EMG Sensor Placement

Muscle	**Sensor Location**
Rectus Femoris	*Patient position:* Supine *Location:* Center of the anterior thigh, ½ the distance between the knee and the iliac spine *Sensor orientation*: Vertical *Movement test:* SLR
Semitendinosus (medial hamstring)	*Patient position:* Prone *Location:* medial aspect of the posterior thigh about ½ the distance from the gluteal fold to the back of the knee *Sensor orientation:* Vertical *Movement test:* Knee flexion
Gluteus Maximus	*Patient position:* Prone *Location:* Half the distance between the greater trochanter and the sacral vertebrae at the level of the trochanter or slightly above *Orientation:* Oblique *Movement test:* Hip extension
Gluteus Medius	*Patient position:* Side lying *Location:* Proximal 1/3 of the distance between the iliac crest and the greater trochanter (must be anterior to the gluteus maximus) *Orientation:* Vertical *Movement test:* hip abduction
Foot Sensors	#1 - Great toe #2 - Base of first met head #3 - Base of fifth met head #4 - Heel (center)

Robotic Device

The Hocoma Lokomat was utilized for the condition requiring DGO assistance. (Figure 3.1) For the DGO use, 30% body weight support (BWS) was provided through the Lokomat suspension system, if the subject was able to maintain enough hip and knee extension to hold his body weight. In several instances more than 30% BWS was necessary to give the subject enough support to walk (Table 3.4). BWS is provided to decrease the demand on the child as an unnatural walking condition is imposed. Thirty percent support supplied assistance while allowing at least half the body weight, thus simulating a more normal condition. Each subject utilized passive foot lifters that provided sufficient ankle dorsiflexion for adequate toe clearance during swing phase.

Figure 3.1: Subject with Hocoma Lokomat

Table 3.4: Subjects' Body Weight Support

BWS	30%	33%	41%	43%	44%	50%
Subject number	01_01, 01_03, 01_04, 01_05, 01_08, 01_09, 01_16, 01_18, 01_19, 01_20, 02_01, 02_08, 02_09, 02_17, 02_20	02_16	02_18	02_04	02_03	02_19

Monitoring EMG activity occurred with 100% guidance force in the Lokomat. Guidance force is the percentage of work that the Lokomat provides for the subject. Thus, at 100% guidance force, the Lokomat is providing 100% guidance. Most treatment protocols start a patient at 100% guidance force and slowly progress through many treatment sessions to 50%, if possible. Low guidance forces (below 50%) allow the subject to deviate from the pre-defined gait pattern reducing the accuracy of the repetitions.

Intervention

The study required two separate visits in the same week for each subject. Day 1 included signing consent forms, placement of EMG sensors, walking overground and walking with the Lokomat. This allowed determination of the subject's self-selected comfortable walking speed with the Lokomat which was replicated in overground walking on Day 2. It also allowed introduction to the feel of the EMG sensors and to the DGO experience. On the second day, all EMG data was collected. This process eliminated the influence of the novel experiences of EMG sensor application and walking in the Lokomat on the EMG output. The second day included placement of the EMG sensors, overground walking and walking with the Lokomat.

Gait was performed in shoes without braces in both conditions: overground ambulation and ambulation with DGO with 100% guidance force. The overground ambulation condition provided the muscle activity pattern of the subjects' normal walking EMG muscle activation patterns. Gait in each condition occurred at the same speed determined by self-selected comfortable walking speed in the DGO. Since EMG profiles can change strikingly with gait speed[80,81] it was necessary for the subjects to walk at the same speed in each condition. The walking speed in the DGO was always slower than overground, thus a pacer was used to maintain the same speed in overground walking. EMG activity was recorded for 10 second intervals. For each child, for each muscle and each condition, the raw EMG data was automatically filtered by the Delsys built-in filtering process (20-450 Hz band-pass Butterworth filter). No additional filtering was performed. Three intervals were collected for every walking condition.

Overground walking was performed as normal for each subject at the speed matching the DGO, with or without an assistive device. The subjects were asked to ambulate in straight 10-meter paths.

Data Processing

Data processing was executed in Excel. In each 10 second gait capture, the point of initial contact was determined by individually examining the foot switch data to precisely identify the point at which there was a constant and consistent increase in pressure following a constant and consistent lack of (or decreased) pressure. Once the initial contact value was identified, the full gait cycles were numbered from each initial contact to the next. The EMG data from the middle 3 gait cycles were selected for analysis.

The data from each of the 3 gait cycles was copied and pasted to further process with wave rectification (absolute value) and then time normalization to express percent of total gait cycle. Once time normalized, the 3 sets of gait cycle values were averaged to determine the final product for that trial. This process was repeated for each of the trials. The final 3 trials for each condition were then averaged to produce the final average percent gait cycle time normalized values.

Data Analysis

For the between group analyses (questions #1 and # 2), Excel was utilized to determine relative EMG activity across the gait cycle with confidence intervals (Table 3.5). Relative EMG was determined to allow true comparison without consideration of amplitude. Since maximal contractions were not utilized to determine percent of maximal contraction, muscle power or strength cannot be inferred. The confidence intervals are represented by the colored bars. Where they do not overlap, the 2 values are statistically different with $p < .05$.

Coefficient of variation (CV) is a non-parametric analysis used when significant variation in the patient population is noted.[27] Previous studies reveal a large variability in muscle activation patterns in gait in children,[76,77] thus CV was determined for each comparison between groups reflecting the percent of variation of EMG measurement throughout the gait cycle across the subjects in that group.[82]

For the within group analysis (questions #3 and #4), the Wilcoxon Signed Rank Test was utilized (Table 3.5). The Wilcoxon Signed Rank Test is a non-parametric test which compares the means of two related groups on the same continuous dependent variable. It does not assume normality in the data and is analogous to the parametric dependent t-test.[83] Again, the relative EMG values were determined and utilized for comparison to eliminate the influence of amplitude in the statistical difference. When walking in the Lokomat, the subjects were unweighted and the guidance force utilized was 100%, both of which could affect the number of muscle units recruited when compared to overground ambulation.

Table 3.5: Research Questions with Statistical Analysis

Research Question	**Data Analyzed**	**Statistics Used**
1. Are the muscle activation patterns of the rectus femoris, semitendinosus, gluteus maximus and gluteus medius of children with CP dissimilar to age-matched TD children in OG walking?	TD overground compared to age-matched CP overground Between group comparison of muscle activation patterns	coefficient of variation Relative EMG with confidence intervals
2. For children with CP, does ambulatory training with DGO assistance at 100% guidance force replicate age-matched TD children's muscle activation patterns of the rectus femoris, semitendinosus, gluteus maximus and gluteus medius in OG ambulation?	CP DGO 100% GF compared to age-matched TD overground ambulation Between group comparison of muscle activation patterns	coefficient of variation Relative EMG with confidence intervals
3. For TD children, does ambulatory training with DGO assistance at 100% guidance force replicate their muscle activation patterns of the rectus femoris, semitendinosus, gluteus maximus and gluteus medius in OG ambulation?	TD DGO GF 100% compared to TD overground ambulation Within group comparison of muscle activation patterns	Wilcoxon Signed Rank Test
4. For children with CP, are the muscle activation patterns of the rectus femoris, semitendinosus, gluteus maximus and gluteus medius in OG walking dissimilar to their muscle activation patterns with DGO assistance at 100% guidance force?	CP overground compared to CP DGO GF 100% Within group comparison of muscle activation patterns	Wilcoxon Signed Rank Test

Mitigation of Risk

The Lokomat is a machine capable of independent motion, thus numerous safety precautions were implemented through built-in emergency shut off and manual shut off switches. The investigator had one manual switch and the other was positioned next to the subject. Immediate shut off the Lokomat occurs when the switch is deployed. The manual switches were never engaged during this study. Internal software monitoring of excessive speed, acceleration or force exerted could also result in stopping the Lokomat. If a child resisted the movement either volitionally or non-volitionally, the Lokomat would shut down. This happened on occasion with the only risk of needing to initiate the start process again.

Chapter 4 : Results

Introduction

The following chapter presents the results from the analysis performed on the data from the comparison of the muscle activation patterns in gait of the rectus femoris, semitendinosus, gluteus maximus and gluteus medius in TD children and children with CP in overground walking and walking in the Lokomat with 100% guidance force. The results are organized and presented by research questions. Two of the research questions compare between group ambulation results (TD overground compared to CP overground and TD overground to CP Lokomat) and two research questions compare within group ambulation results (TD overground to TD Lokomat and CP overground to CP Lokomat). These comparisons will assist us in evaluating if the Lokomat is replicating typically developing overground muscle activation patterns in both groups.

Participants

Twenty subjects, ten with the diagnosis of CP and ten age-matched TD children met inclusion criteria and were enrolled in this study. All participants completed the study. The demographics for the study participants can be found in Table 3.1.

Data

A Delsys Trigno wireless system with 16 channels was utilized to record all muscle activity using self-adhesive Trigno sensors. The standard sensor specifications are listed in Table 3.2. The sensors were placed according to the recommendations of Cram et al. (Table 3.3) for the lower extremity on the following muscles of the dominant (TD) or least affected side (CP): rectus femoris, medial hamstring (semitendinosus), gluteus maximus, and gluteus medius. For each child, for each muscle and each condition, the raw EMG data was automatically filtered by the Delsys built-in filtering process (20-450 Hz band-pass Butterworth filter). No additional filtering was performed.

Data Processing

Data processing was executed in Excel. In each 10 second gait capture, the point of initial contact was determined by individually examining the foot switch data to precisely identify the point at which there was a constant and consistent increase in pressure following a constant and consistent lack of (or decreased) pressure. Once the initial contact value was identified, the full gait cycles were numbered from each initial contact to the next. The EMG data from the middle 3 gait cycles were selected for analysis.

The data from each of the 3 gait cycles was copied and pasted to further process with wave rectification (absolute value) and then time normalization to express percent of total gait cycle. Once time normalized, the 3 sets of gait cycle values were averaged to determine the final product for that trial. This process was repeated for each of the trials. The final 3 trials for each condition were then averaged to produce the final average percent gait cycle time normalized values.

Data Analysis

For the between group analyses (questions #1 and # 2), Microsoft Excel was used to determine relative EMG activity across the gait cycle with confidence intervals which can be found in Figures 4.1, 4.2, 4.3, 4.4, 4.5, 4.6, 4.7, and 4.8. Relative EMG was determined to allow true comparison without consideration of amplitude. Since maximal contractions were not captured, muscle power or strength cannot be inferred. The confidence intervals are represented by the colored bars. Significance is determined by a lack of confidence interval overlap.

Coefficient of variation (CV) is a non-parametric analysis used when significant variation in the patient population is noted.[27] Previous studies reveal a large variability in muscle activation patterns in gait in children,[76,77] thus CV was determined for each comparison between groups reflecting the percent of variation of EMG measurement throughout the gait cycle across the subjects in that group.[82]

For within group analysis (questions #3 and #4), a Wilcoxon Signed Rank Test was used. The Wilcoxon Signed Rank Test is a non-parametric test comparing the means of two related groups on the same continuous dependent variable. It does not assume normality in the data and is analogous to the parametric dependent t-test.[83] Again, the relative EMG values were determined and used for comparison to eliminate the influence of amplitude in the statistical difference. When walking in the Lokomat, the subjects were unweighted and the guidance force was set at 100%.

Research Question 1

Are the muscle activation patterns of the rectus femoris, semitendinosus, gluteus maximus, and gluteus medius of children with CP similar to age-matched TD children in overground walking?

Rectus Femoris

In comparing the rectus femoris muscle activation pattern across the gait cycle of the TD children and the children with CP in overground walking, the analysis reveals lack of overlap of confidence intervals at one point (18%) indicating significant difference at that one point of the gait cycle (Figure 4.1). The variability in muscle recruitment was greater for the children with CP when compared to the TD group. (TD CV = 38.33%, whereas the CP children's CV = 52.82%).

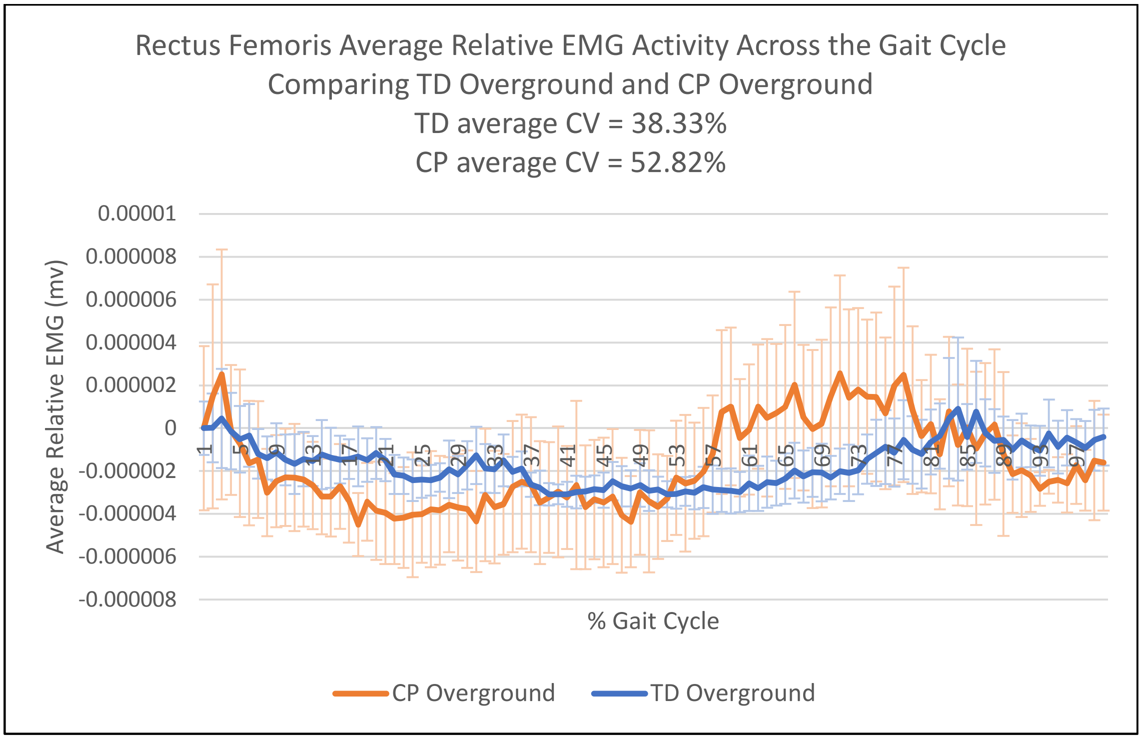


Figure 4.1: Rectus Femoris EMG Comparing TD OG and CP OG

Semitendinosus

In comparing the semitendinosus muscle activation pattern across the gait cycle between the two groups, the analysis reveals overlap of confidence intervals throughout most of the cycle (Figure 4.2). Lack of overlap was noted at 60% and 61% of the gait cycle indicating significant difference (total of 2%). These 2 points are found at the end of the pre-swing phase of the gait cycle according to the Rancho Los Amigos Gait Analysis[84] (Table 4.1). The variability in the confidence intervals for the children with CP were larger than that of the TD children (TD CV = 45.53%, CP CV = 69.20%).

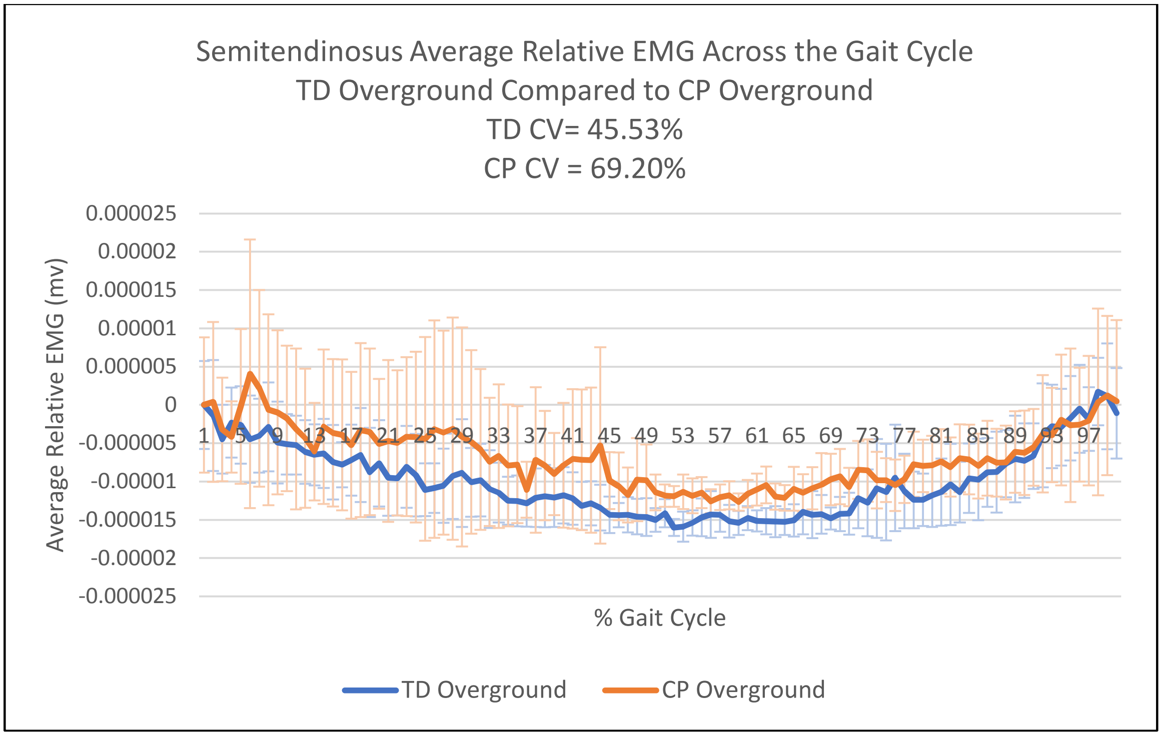


Figure 4.2: Semitendinosus EMG Comparing TD OG and CP OG

Table 4.1: Gait Cycle Phases

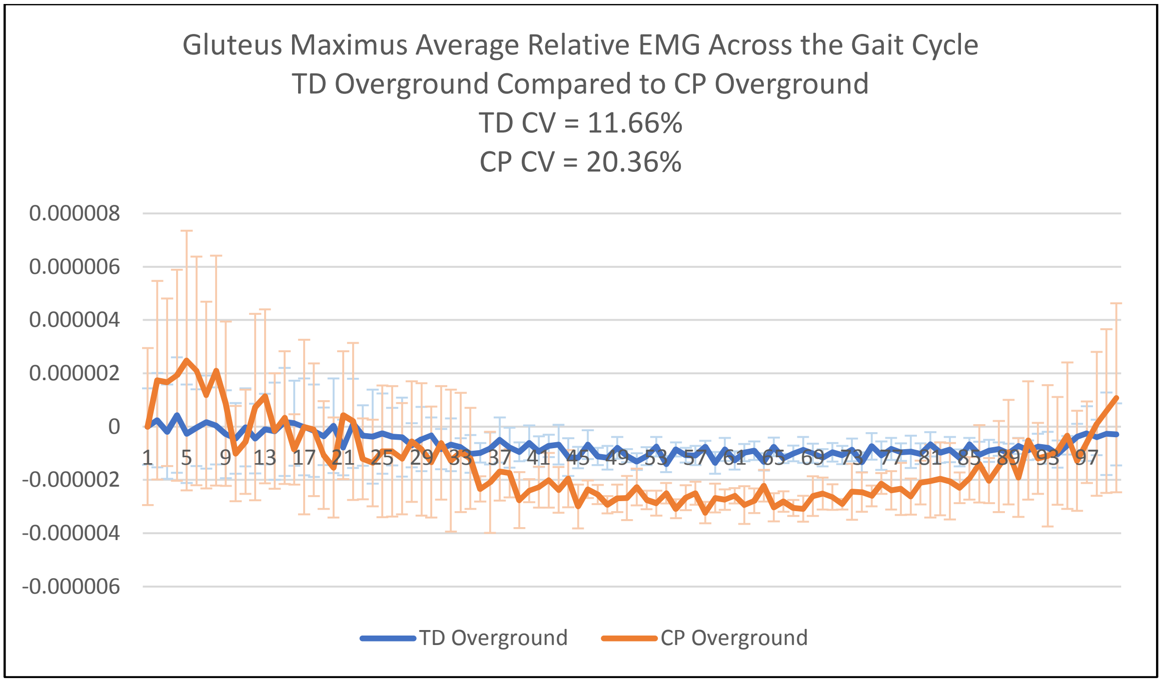
<u>**Gait Cycle Phases**</u>		
Initial Contact (IC)	0%	
Loading Response (LR)	0-12%	
Mid Stance (MSt)	12-31%	Stance = 62%
Terminal Stance (TSt)	31-50%	
Pre-swing (PSw)	50-62%	
Initial Swing (ISw)	62-75%	
Mid Swing (MSw)	75-87%	Swing = 38%
Terminal Swing (TSw)	87-100%	

Gluteus Maximus

Data was also collected and assessed for the gluteus maximus revealing no overlap during 36% of the gait cycle (Figure 4.3). The gait cycle difference corresponded to parts of terminal stance (39%,40%,43%, 45%-51%), most of pre-swing (52%-62%), most of initial swing (62%-74%), and parts of mid swing (75%-80% and 84%). There was less variability noted in the gluteus maximus between TD and CP (TD children's average CV = 11.66%, CP children's CV = 20.36%).

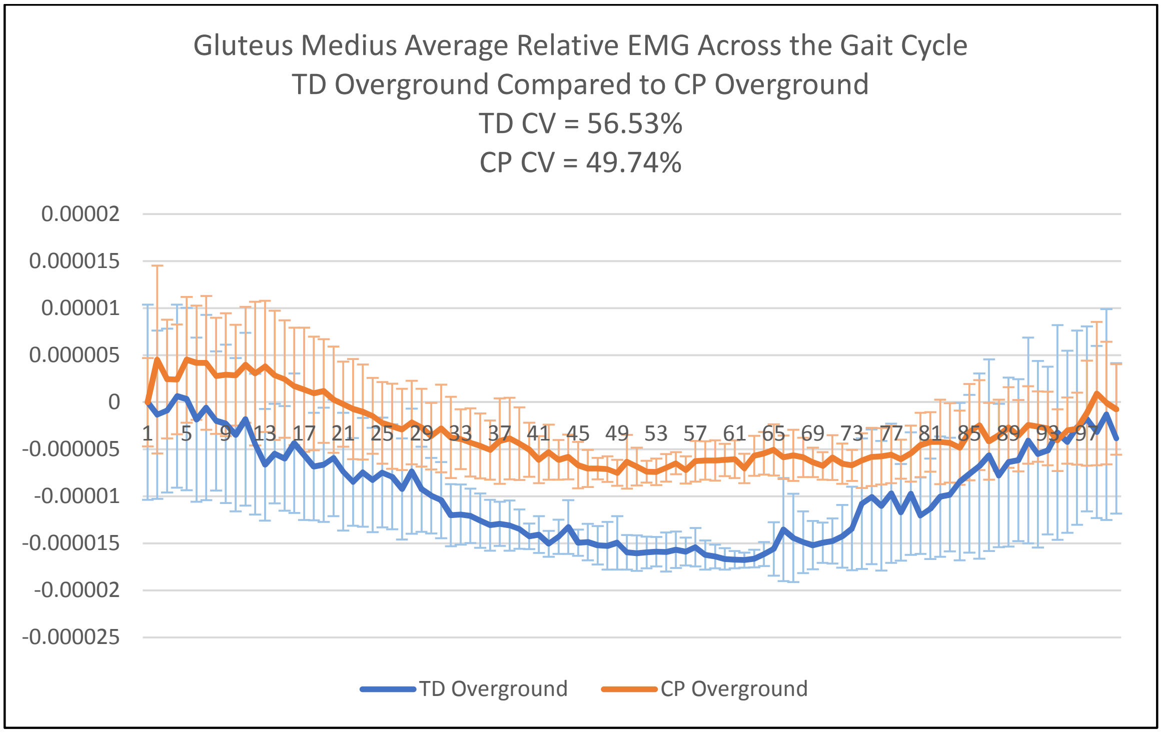
Gluteus Medius

In comparing the gluteus medius muscle activation pattern across the overground gait cycle, the analysis revealed less overlap of confidence intervals totaling 41% of the cycle (Figure 4.4). Differences in the gait cycle corresponded to most of terminal stance (32%-50%), all of pre-swing (50% -62%) and most of initial swing (62-74%). In this case, the confidence interval for the TD children is larger than that of the CP children, which is reflected in the CV (CP children's average CV = 49.74%, whereas the TD children's CV = 56.53%).



Gluteus Maximus Average Relative EMG Across the Gait Cycle
TD Overground Compared to CP Overground
TD CV = 11.66%
CP CV = 20.36%

Figure 4.3: Gluteus Maximus EMG Comparing TD OG and CP OG



Gluteus Medius Average Relative EMG Across the Gait Cycle
TD Overground Compared to CP Overground
TD CV = 56.53%
CP CV = 49.74%

Figure 4.4: Gluteus Medius EMG Comparing TD OG and CP OG

Research Question 2

For CP children, does walking with DGO at 100% guidance force replicate age-matched TD children muscle activation patterns of the rectus femoris, semitendinosus, gluteus maximus, and gluteus medius in overground ambulation? Comparisons of muscle activity patterns between TD children ambulating overground and children with CP ambulating in the Lokomat at 100% guidance force were compared.

Rectus Femoris

The rectus femoris data revealed that 40% of the gait cycle was statistically different. The dissimilar portions corresponded to parts of mid stance (22-28%, 29%), terminal stance (35%, 37%-50%), all of pre-swing (50-62%), and the beginning of initial swing (62%-69%) (Figure 4.5). The CV for the children with CP is larger than that of the TD (TD CV = 38.33%, whereas the CP children's CV = 51.40%).

Semitendinosus

When evaluating the activity of the semitendinosus, the graphic representation of the data illustrated that 49% of the gait cycle did not overlap. The differences total approximately half of the gait cycle and correspond to portions of mid stance (25% and 26%), most of terminal stance (32%-50%), all of pre-swing (50%-62%), most of initial swing (62-74%), and portions of mid swing (78%-82% and 83%) (Figure 4.6). The confidence intervals for the children with TD is larger than that of the CP children which is reflected in the CV (CP children's average CV = 38.50%, whereas the TD children's CV = 45.53%).

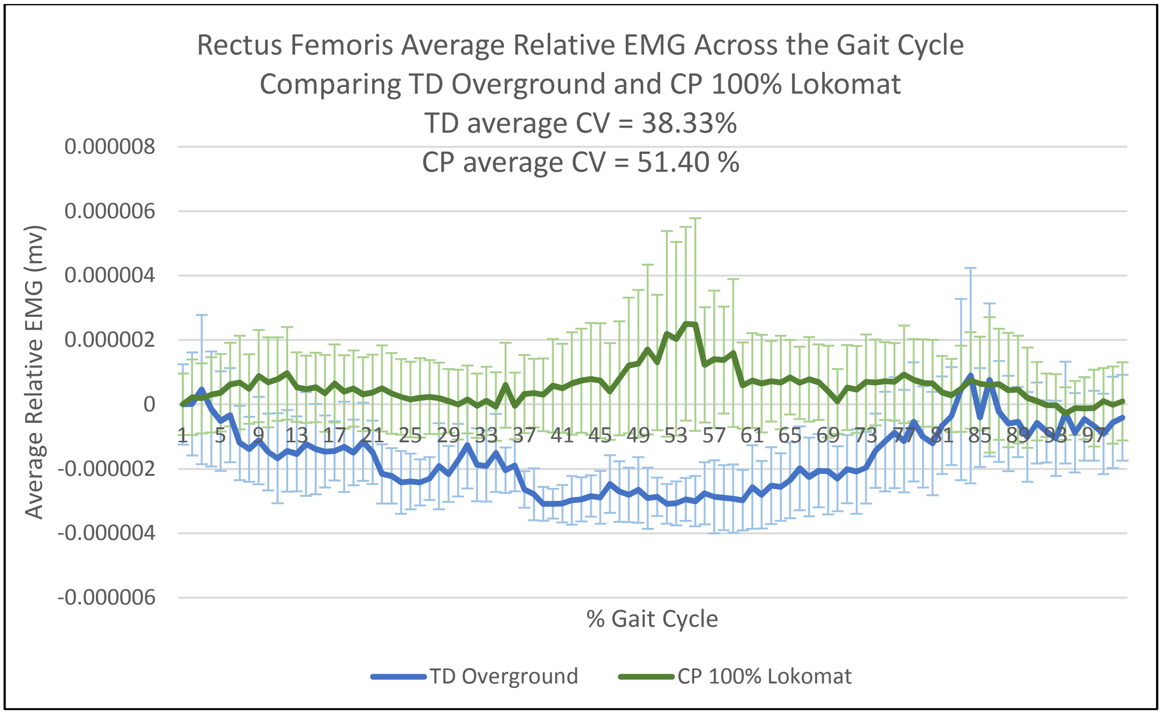


Figure 4.5: Rectus Femoris EMG Comparing TD OG and CP DGO

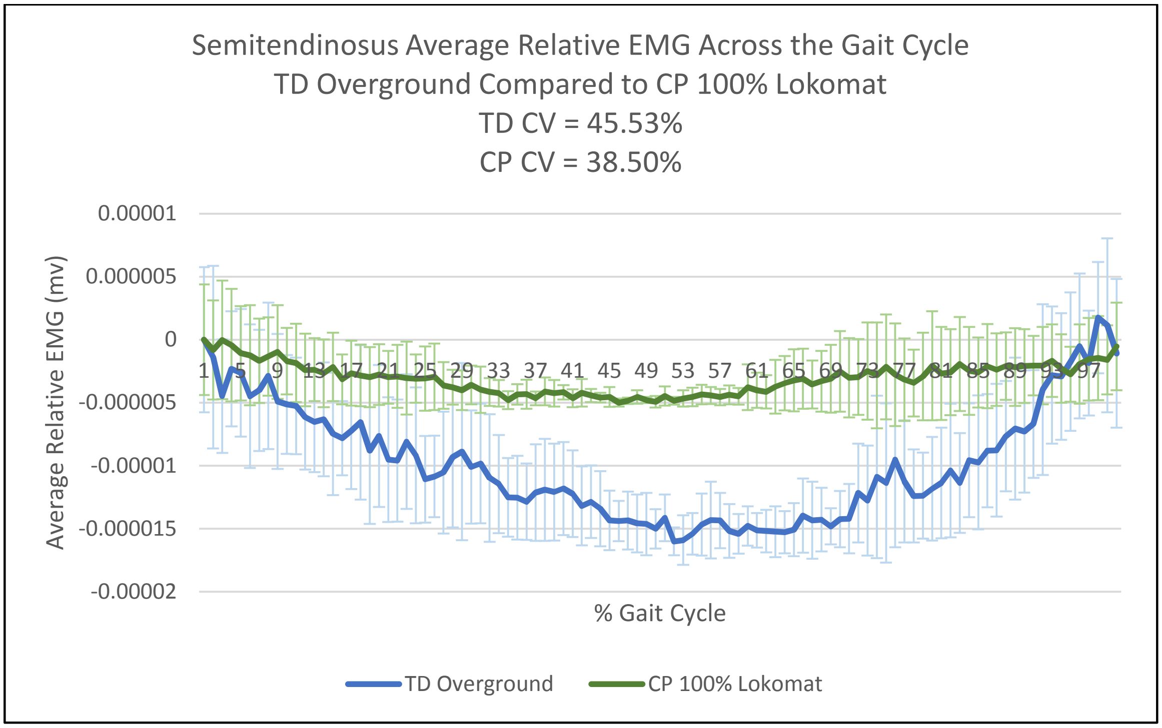


Figure 4.6: Semitendinosus EMG Comparing TD OG and CP DGO

Gluteus Maximus

The analysis reveals 37% variance in confidence intervals across the gait cycle. The difference corresponds to portions of terminal stance (45%, 47%, 48%), pre-swing (50%, 51%, 54%, 56%-60%, 61%), initial swing (62%-65%, 66%-75%), mid swing (77%-81%, 82%-87%) and terminal swing (88%-92% and 100%) (Figure 4.7). The confidence intervals for the TD children are larger than that of the CP children which is reflected in the CV. The CP children's average CV = 5.62%, whereas the TD children's CV = 11.66%.

Gluteus Medius

The analysis reveals 56% lack of overlap throughout the gait cycle indicating that they are statistically different. The difference represents over half of the gait cycle and corresponds to portions of mid stance (22%, 27%, 29%-31%), all of terminal stance (31%-50%), all of pre-swing (50%-62%), all of initial swing (62%-75%), and the majority of mid swing (75%-77%, 78%-84%) (Figure 4.8). The confidence intervals for the TD children are larger than that of the CP children which is reflected in the CV. The CP children's average CV = 37.04%, whereas the TD children's CV = 56.53%.

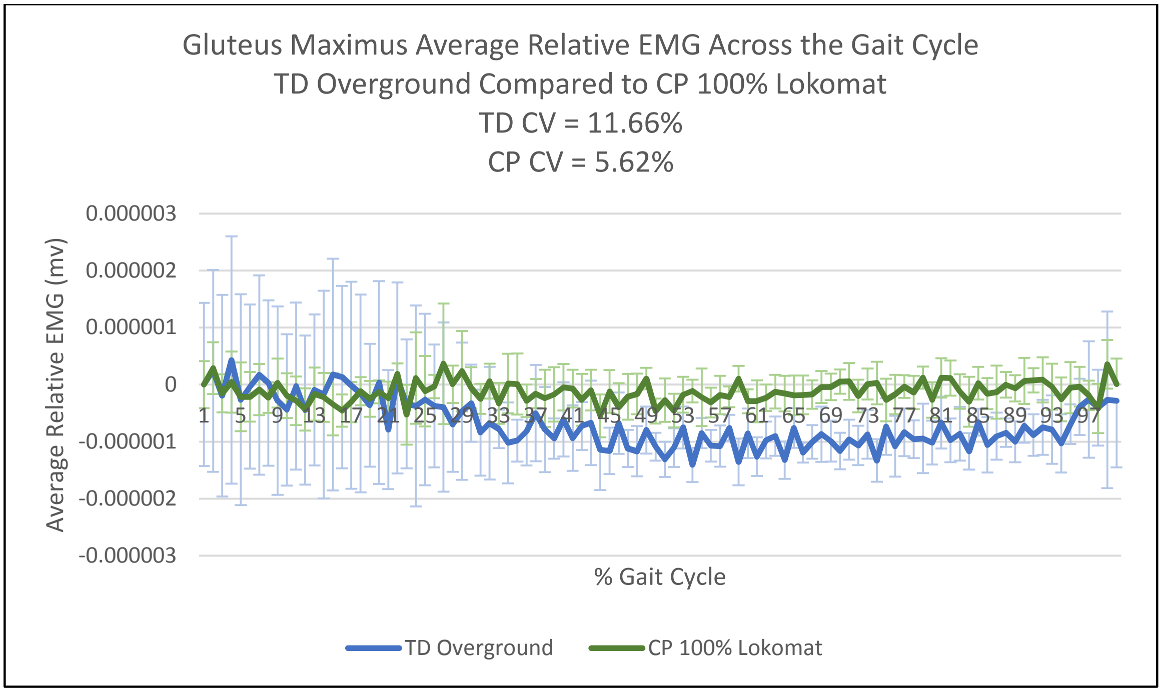


Figure 4.7: Gluteus Maximus EMG Comparing TD OG and CP DGO

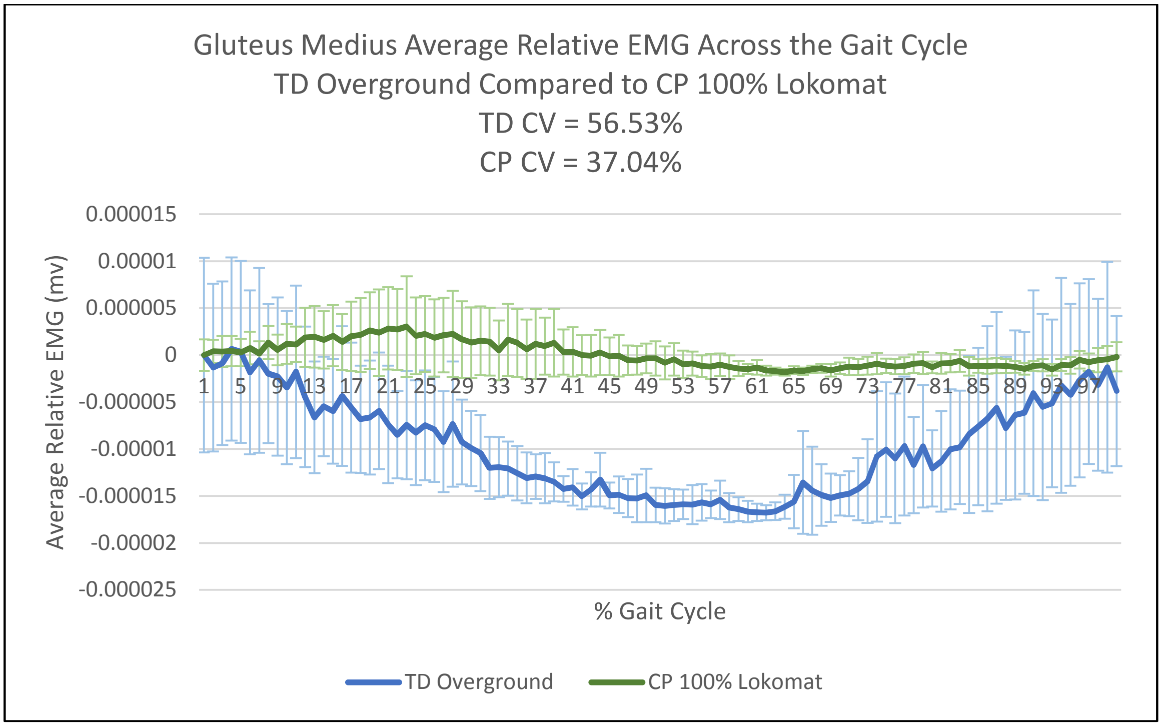


Figure 4.8: Gluteus Medius EMG Comparing TD OG and CP DGO

Research Question 3

For TD children, does walking with DGO assistance at 100% guidance force replicate their muscle activation patterns of the rectus femoris, semitendinosus, gluteus maximus, and gluteus medius in overground ambulation? Statistical comparisons were made using the Wilcoxon Signed Rank Test. Significance was set at $p < .05$.

Rectus Femoris

There was a significant difference found in the activation of the rectus femoris during portions of loading response (8%, 10%-12%), portions of mid stance (12%-14%, 19%, 22%-31%), the majority of terminal stance (32%-50%), all of pre-swing (50%-62%) and part of initial swing (62%-75%). The differences in muscle activation totaled 58% of the gait cycle (Figure 4.9).

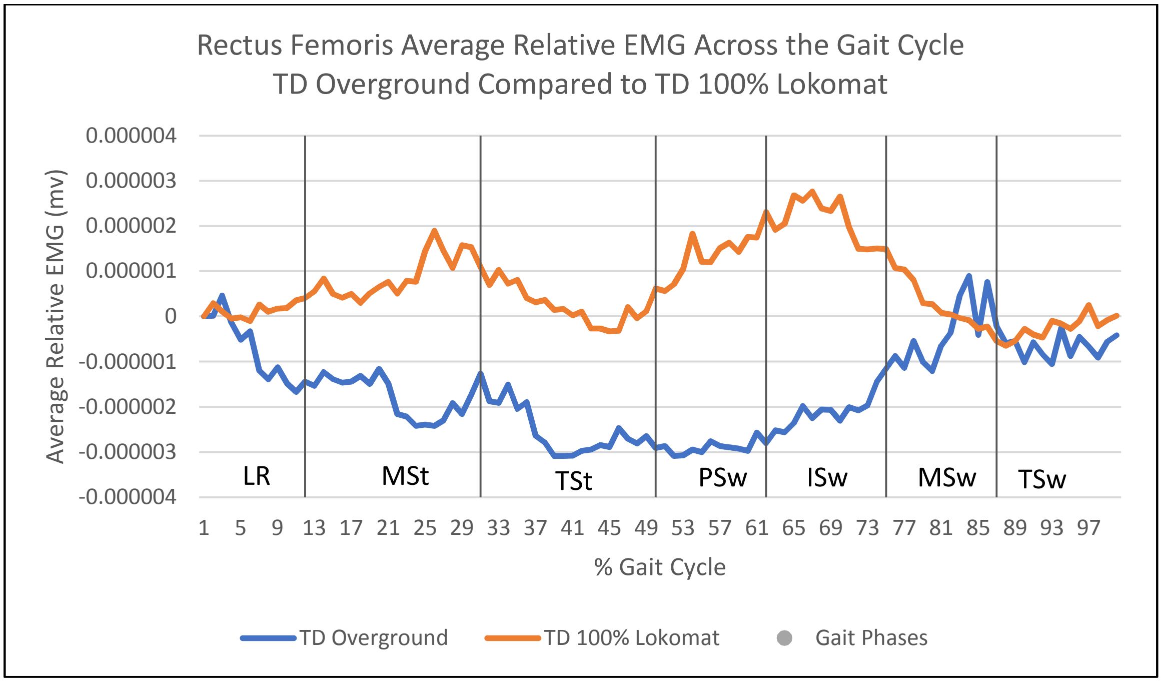


Figure 4.9: Rectus Femoris EMG Comparing TD OG and TD DGO

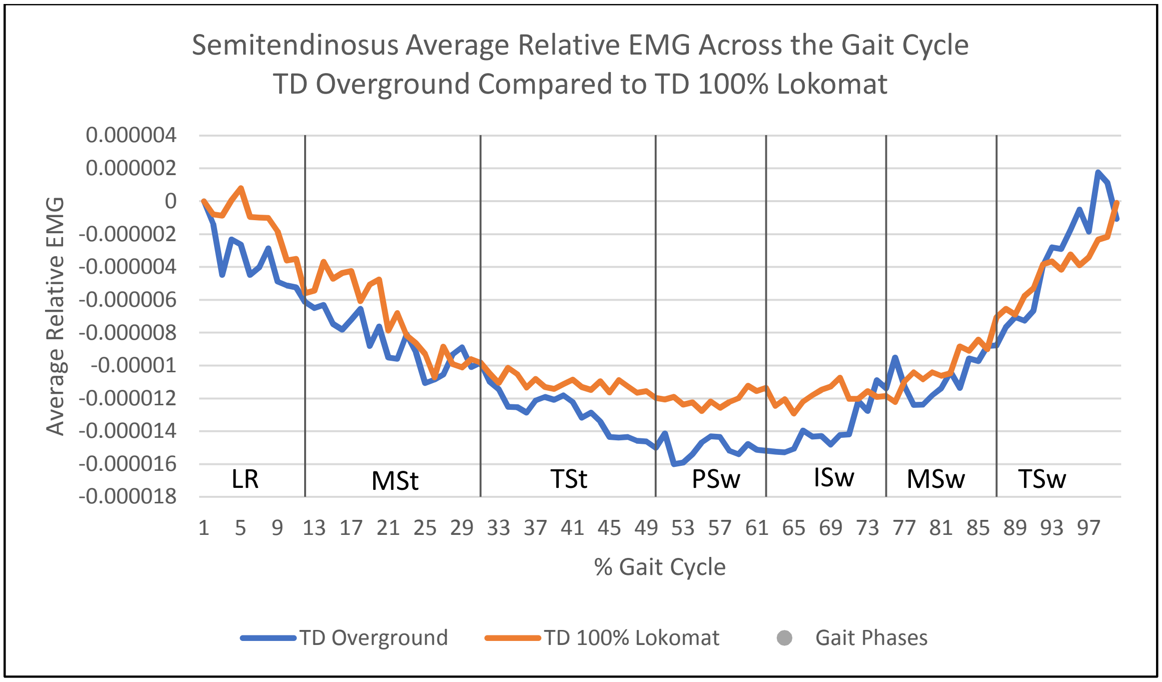


Figure 4.10: Semitendinosus EMG Comparing TD OG and TD DGO

Semitendinosus

In comparing the semitendinosus muscle activation pattern, 10% of the gait cycle was statistically significant corresponding to terminal stance (46%), pre-swing (50%, 52%, 59%-62%), initial swing (62%), and mid swing (64%, 68%, 69%) (Figure 4.10).

Gluteus Maximus

The muscle activation pattern was significantly different across 19% of the cycle. The statistically different points occurred in portions of terminal stance (32%, 35%, 38%, 39%, 41%, 47%), portions of pre-swing (51%, 52%, 54%, 56%, 59%), parts of initial swing (62%, 64%, 66%, 67%, 74%), part of mid swing (84%) and part of terminal swing (89%, 91%) (Figure 4.11).

Gluteus Medius

The muscle activation pattern of the gluteus medius had the largest amount of activation difference with a total of 72% of the cycle. This variance occurred during parts of mid stance (13%-16%, 17%-31%), all of terminal stance (31%-50%), all of pre-swing (50%-62%), all of initial swing (62%-75%), part of mid swing (75%-85%) and one point in terminal swing (88%) (Figure 4.12).

Research Question 4

For children with CP, are the muscle activation patterns of the rectus femoris, semitendinosus, gluteus maximus, and gluteus medius in overground walking dissimilar to their muscle activation patterns with DGO assistance at 100% guidance force? For this set of data statistical comparisons were made using the Wilcoxon Signed Rank test. Significance was set at $p < .05$.

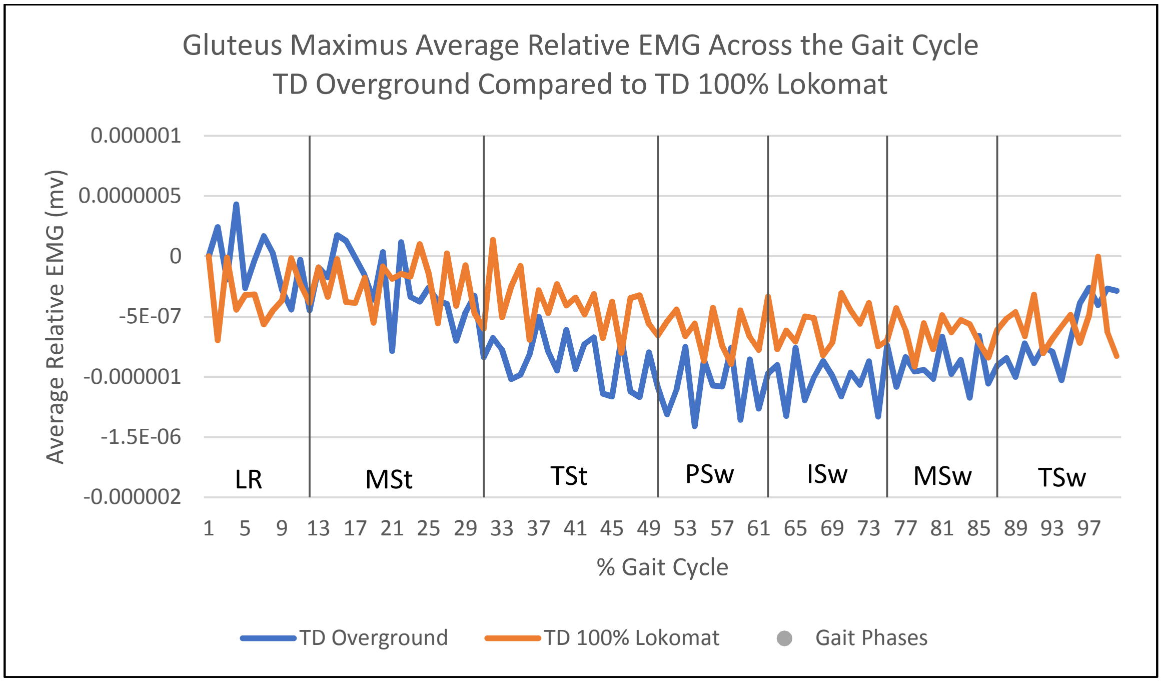


Figure 4.11: Gluteus Maximus EMG Comparing TD OG and TD DGO

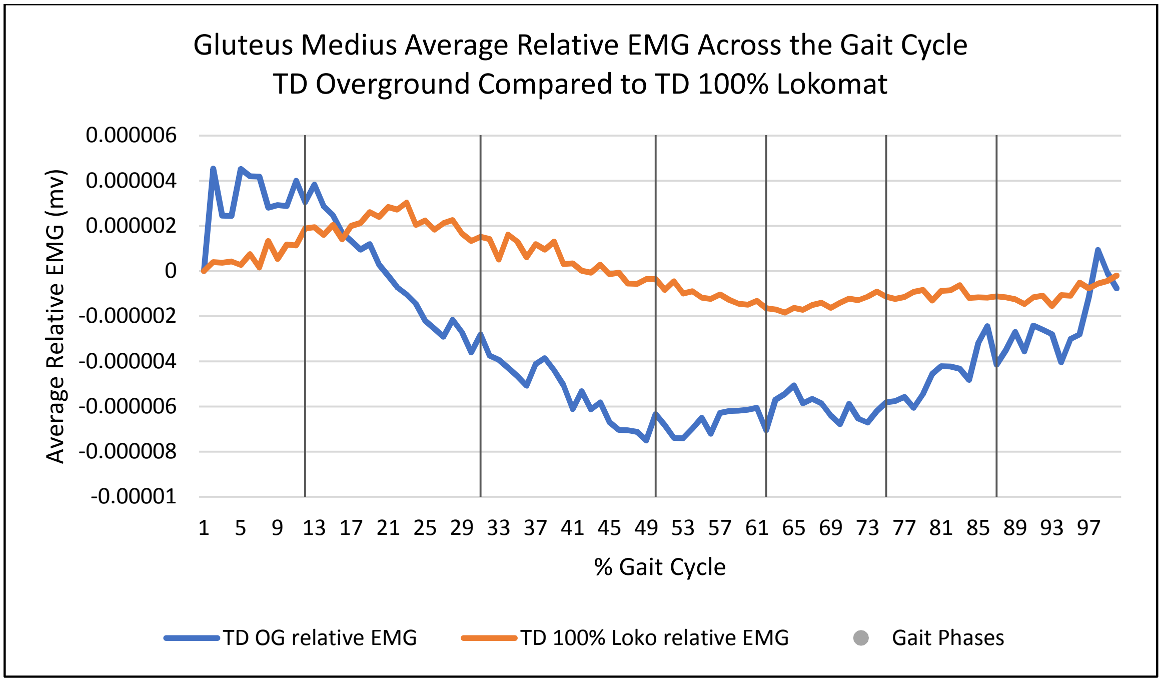


Figure 4.12: Gluteus Medius EMG Comparing TD OG and TD DGO

Rectus Femoris

Statistically significant differences in activation were noted during portions of mid stance (8%-21%, 22%, 23%, 25%, 27%-30%), part of terminal stance (31%, 33%, 34%, 47%, 48%), parts of pre-swing (51%, 52%, 55%, 56%), and parts of terminal swing (93%-99%), totaling 34% of the gait cycle (Figure 4.13).

Semitendinosus

Dissimilarity was noted during 36% of the gait cycle in terminal stance (36%, 45%, 47%, 50%), all of pre-swing (50%-62%), most of initial swing (62%-72%, 74%), portions of mid swing (75%-78%, 80%-84%, 86%) and part of terminal swing (87%, 88%) (Figure 4.14).

Gluteus Maximus

The statistically dissimilar points occurred in 52% of the gait cycle, noted in one point in mid stance, part of terminal stance (35%, 37%-50%), all of pre-swing (50%-62%), all of initial swing (62%-75%), part of mid swing (75%-83%, 84%, 85%), several points in terminal swing (87%, 90%) (Figure 4.15).

Gluteus Medius

Approximately half of the gait cycle was different (46%). This occurred during parts of mid stance (27%, 30%), parts of terminal stance (32%-37%, 40%-50%), all of pre-swing (50%-62%), all of initial swing (62%-75%), and part of mid swing (75%, 76%, 78%, 79%) (Figure 4.16).

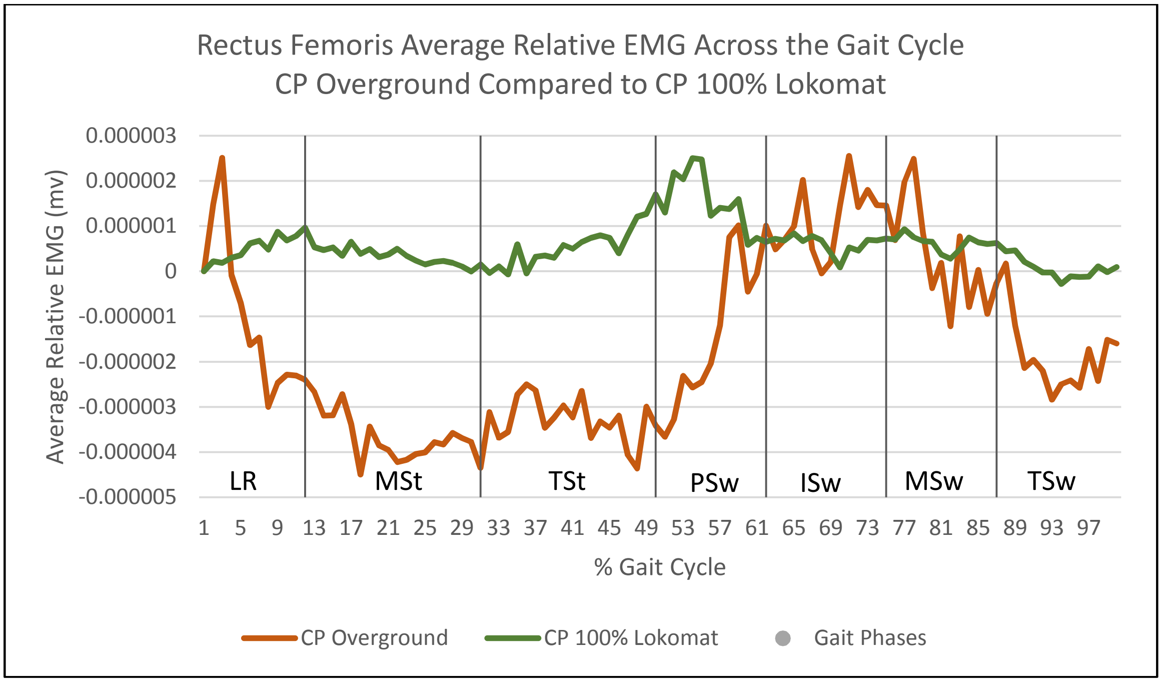


Figure 4.13: Rectus Femoris EMG Comparing CP OG and CP DGO

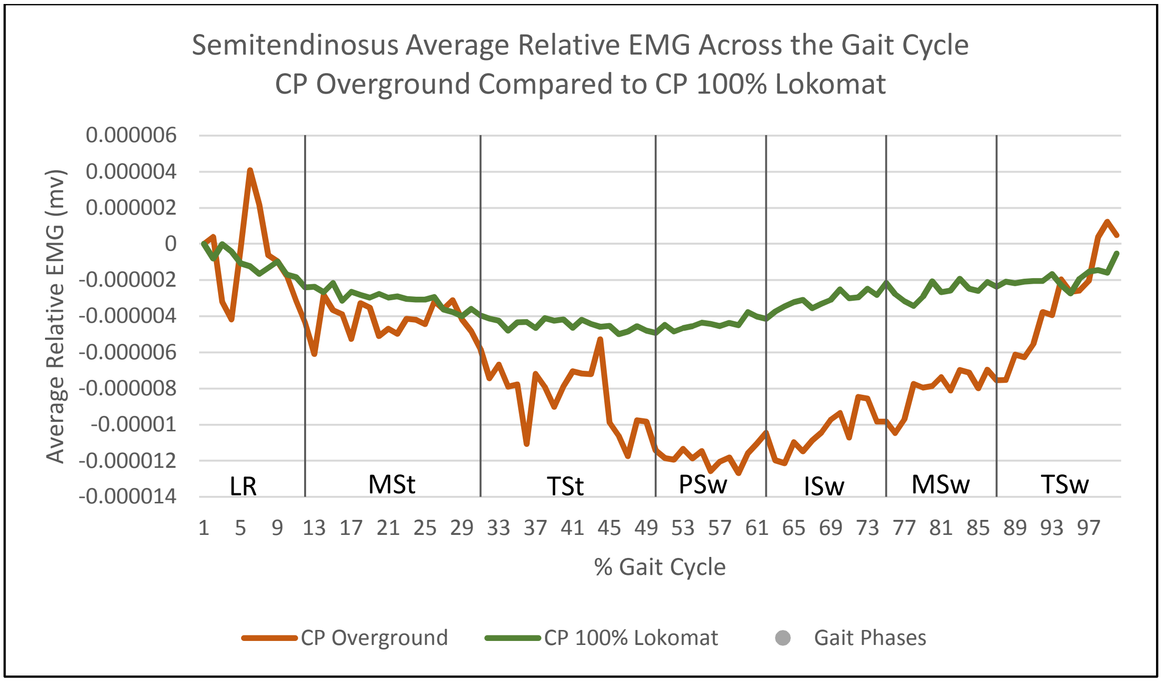


Figure 4.14: Semitendinosus EMG Comparing CP OG and CP DGO

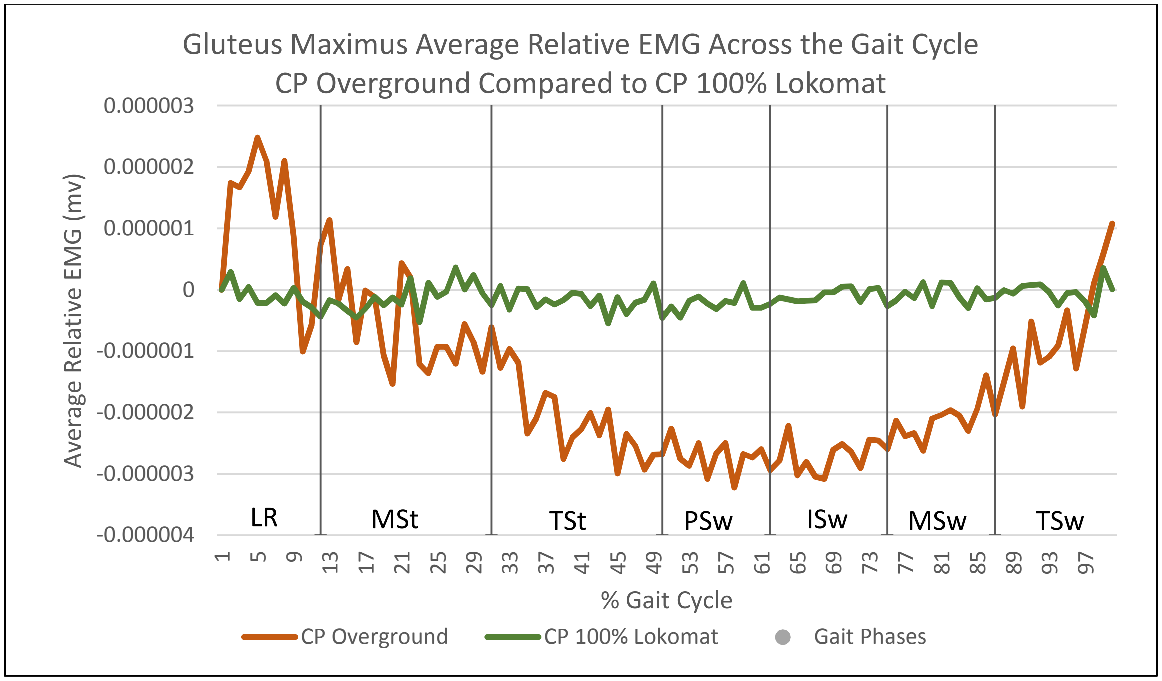


Figure 4.15: Gluteus Maximus EMG Comparing CP OG and CP DGO

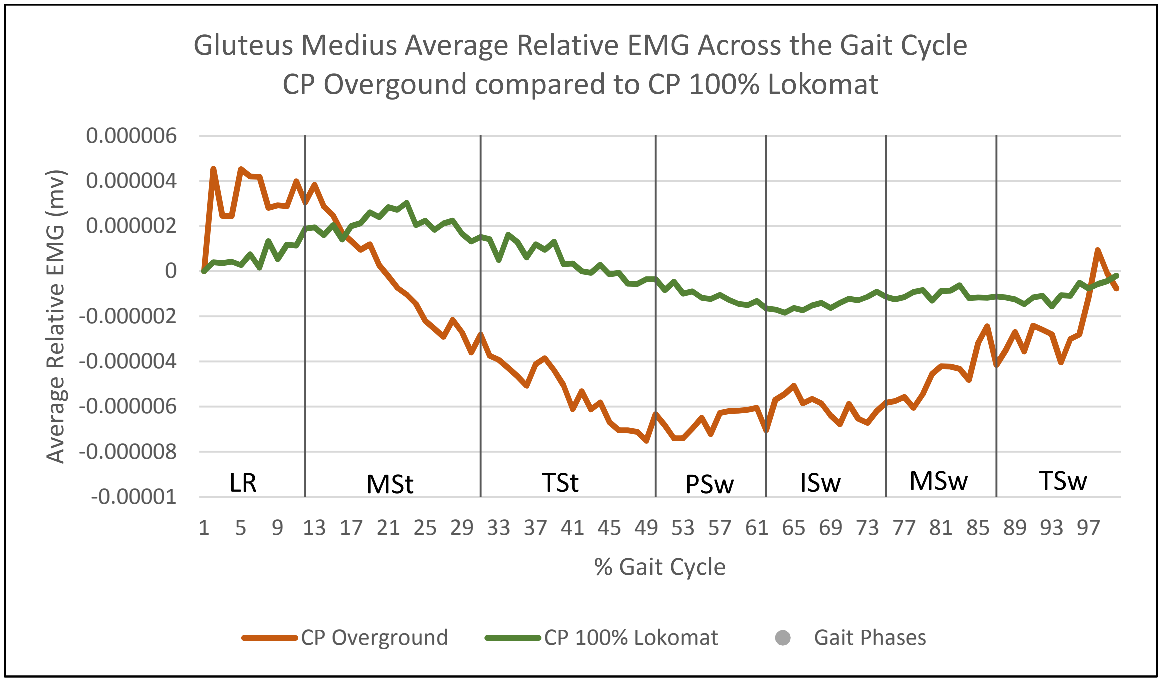


Figure 4.16: Gluteus Medius EMG Comparing CP OG and CP DGO

Chapter 5 : Discussion

Introduction

Ambulation is a critical element to a child's ability to participate,[1-3] develop self-concept, and positive quality of life.[4,5] Children with CP frequently exhibit limitation in walking proficiency[7] with lower scores of activity and participation[1-3] and poor quality of life[32] which can lead to dependent lifestyles and lower rates of employment in adulthood.[8-11]

Impaired walking ability has been identified as the primary physical disability in children with CP.[7] Damage to the central nervous system, resulting in spasticity, muscle weakness, impaired coordination and decreased selective motor control interfere with normal development of ambulation.[40,44,45] Slower walking speed, shorter stride length and more time spent in double support are frequent characteristics of CP gait [45] with significant losses of excursion at the hip, knee and ankle which worsens as the child gets older.[46]

Alterations in gait characteristics such as agonist-antagonist co-activation, hip and knee flexed posture and impaired kinetic motion contribute to diminished walking ability in children with CP. These limitations cause a child's walking ability to be inefficient resulting in high-energy expenditure during gait.[7,13-15,85] Hip and knee flexed posture in gait is present in more than 45% of CP children with a GMFCS level I and in more than 60% with GMFCS levels II to IV. [86] Muscles associated with these gait impairments include the rectus femoris, semitendinosus, gluteus maximus[87] and gluteus medius.[88] These muscles were selected for this study due to their functional importance in gait. Normalizing the muscle activation patterns of these muscles across the gait cycle is a goal of clinical intervention with current therapeutic strategies revealing unreliable results.[16,17]

Other important components of typical gait include passive forces such as ground reaction forces (GRF). These passive forces supplement muscle activity and allow for less energy expenditure and greater efficiency in gait.[89] Williams et al. found that 66% of the children with CP studied revealed decreased GRF in gait interfering with appropriate gait development.[90]

Traditional rehabilitative treatment techniques to improve ambulation for children with CP have been thwart with inconsistency.[16,17] This lack of consistent impact has encouraged the development of innovative treatment approaches. Driven gait orthosis (DGO) training is one such novel approach addressing several experience-dependent plasticity principles that have been shown to foster neural plasticity changes in the brain. These principles include specificity of training ("use it and improve it"), consistent repetitive movement (repetition), intensity of training requiring focus and effort (intensity), and meaningful activity to the individual (saliency).[20] DGO training creates an opportunity to implement gait related motor learning when applied to use with children which may induce more permanent change because plasticity occurs more readily.

Little research has explored the effect of DGO training on the muscle activation patterns of children with cerebral palsy (CP) as well as those who are typically developing (TD). The purpose of this study was to determine the impact of DGO training on muscle activation throughout the gait cycle for CP and TD. In addition, to compare how muscle activation within the DGO and in overground (OG) conditions compare to TD children in the same environments.

EMG Muscle Variability in Gait

Due to significant variation in muscle activation patterns in gait,[76,77,91,92] average coefficient of variation (CV) was determined for each muscle in each group. This was assessed for both overground and robotic walking conditions. The results revealed reduction in variability among CP subjects in muscle activation patterns across the gait cycle in most muscles studied during DGO walking (Table 5.1). Variability was noted overall in CP OG walking ranging from 20.36% to 69.20% across muscles. This variability decreased with DGO walking (5.62% to 51.40%). Considering the principle of consistent, measurably repetitive movement to induce neural motor plasticity, this evidence is supportive of the DGO's ability to provide an environment capable of inducing a consistent recruitment pattern.

Interestingly, the average CV for the TD children overall remained relatively the same when comparing OG with DGO walking. Average CV for OG walking ranged from 11.66% to 45.53% and DGO walking from 8.27% to 43.44%. Winter and Yack found that mean CV for proximal muscles was overall greater than those for distal muscles in TD college-aged subjects suggesting that the proximal muscles have dual roles of balance and support which contributes to variability. They noted that the hip and knee muscles provided anti-gravity control while they were also responsible for correcting posture and balance of the trunk, head, and upper extremities.[91] With this in mind, this study found that the average CV of the muscles in CP DGO walking ranged from 5.62% to 51.40% and more closely resembled the CV of the TD OG walking, which ranged from 11.66% to 56.53%, supporting the effectiveness of DGO training in decreasing the variability across the gait cycle. However, it must be noted that the variability of CP DGO was overall less than TD OG, indicating that the variability necessary to provide anti-gravity control for correcting posture and balance in gait is not normalized in the DGO application for CP.

Table 5.1: Average CV by Muscle and Walking Condition

Muscle	**CP OG**	**CP DGO**	**TD OG**	**TD DGO**
Rectus Femoris	52.82%	51.40%	38.33%	40.94%
Semitendinosus	69.20%	38.50%	45.53%	43.44%
Gluteus Maximus	20.36%	5.62%	11.66%	8.27%
Gluteus Medius	49.74%	37.04%	56.53%	53.11%

TD Overground and DGO Walking

Since the muscle activation patterns of children in gait vary as they mature,[76,77,93] the groups (TD and CP) for this study were age-matched, thus generating TD normative muscle activation patterns for comparison. It has also been found that muscle EMG patterns can be greatly affected by speed of ambulation,[80,81,94] therefore; the OG walking speed was matched to the DGO to allow for increased accuracy in comparison of muscle activation patterns. It must be noted that the activity of muscles and kinetics during each phase of gait has been identified in adults,[84,95] but not in children.[76,77,92] The following discussion will be based on adult norms.

Rectus Femoris

In comparing the rectus femoris muscle activation patterns of TD OG to TD DGO walking, 58% of the gait cycle was found to be significantly different corresponding to the loading response (3%), mid stance (12%), terminal stance (18%), all of pre-swing (12%) and initial swing (13%). The most consistent variance was found in terminal stance, pre-swing and the beginning of initial swing with more muscle unit recruitment noted in the DGO condition.

The rectus femoris is a two-joint muscle, crossing the hip and the knee, acting as both a flexor (hip) and an extensor (knee).[94,96] During the terminal stance phase in gait, the knee reaches its greatest extension, then by the "plantarflexion/knee extension couple" active plantarflexion brings the ground reaction force in front of the knee joint to flex the knee.[95] In pre-swing, the knee moves into flexion and the rectus femoris begins to act eccentrically to slow its rapid movement.[84,92] In initial swing, the rectus femoris acts as a hip flexor to aid knee flexion, such that when the knee flexes, the lower leg is held back by inertia resulting in flexion of the knee.[94,95]

Annaswamy et al. found that the muscle activity patterns of the rectus femoris were primarily active in the pre-swing and initial swing phases and changed with walking speed.[96] In a study by Nene et al., the quantity of rectus femoris activity was also found to be clearly related to speed with the muscle activity increasing with increased walking speed.[94] In this study, TD OG muscle activity was primary noted in mid swing. This difference in phase activity could be due to the variations noted in muscle activation patterns in children's gait as they mature[76,77,93] and the reduced speed of OG ambulation performed to match the speed of DGO gait.[80,81,94]

Semitendinosus

The semitendinosus muscle activity patterns, when comparing TD OG to DGO walking, revealed significant variation in only 10% of the gait cycle with the main differences occurring in pre-swing and mid swing. The variance in pre-swing revealed more muscle unit recruitment in DGO walking than in OG walking. According to Rancho Los Amigos, pre-swing occurs from 50% - 62% of the gait cycle and the semitendinosus is not active during this phase.[84] The semitendinosus crosses two joints and serves to flex the knee and extend the hip showing its greatest activity during deceleration in the swing phase of gait.[97] This study's results illustrated a similar recruitment pattern in both walking conditions with greatest recruitment and similarity in terminal swing.

Gluteus Maximus

In comparing the activation of the gluteus maximus in the two TD walking conditions, significant variance was noted in a total 19% of the gait cycle occurring in terminal stance (6%), pre-swing (5%), initial swing (5%), mid swing (1%) and terminal swing (2%) with the muscle activity in the Lokomat higher than that noted in overground walking. The gluteus maximus extends and laterally rotates the hip joint with the lower fibers assisting in adduction and the upper assisting in abduction.[98] The majority of the difference in muscle activation pattern occurred in terminal stance, pre-swing and initial swing. The hip extends toward its peak as terminal stance moves to pre-swing;[95] however, the gluteus maximus is not normally active at this time and a hip extension torque keeps the hip stable.[84] TD EMG activity in OG walking supported this pattern while DGO walking resulted in an increase in muscle recruitment at this point.

As the hip moves from extension to flexion, active knee flexion reverses the external moment from extensor to flexor.[95] In pre-swing, the highest power generation of the entire gait cycle is created by the external dorsiflexor moment and corresponding high internal plantarflexion moment with immediate effect to accelerate the limb forward in initial swing phase.[89,95] In initial swing, the gluteus maximus is not active as the hip is flexing; however, the inertia of the tibia initially maintains the hip extension torque, which diminishes by the end of the phase.[84] Again, the DGO muscle activation patterns revealed more muscle unit recruitment during these phases of gait in comparison to OG walking.

Gluteus Medius

The largest variance between TD OG and DGO walking occurred in the gluteus medius resulting in differences across 72% of the gait cycle. The key areas of variance were observed in mid stance (17%), all of terminal stance, pre-swing, and initial swing, as well as mid swing (10%). The gluteus medius abducts the hip joint with the anterior fibers providing medial rotation and the posterior fibers contributing to external rotation.[98] According to Rancho Los Amigos, the gluteus medius is active during mid stance but not terminal stance, pre-swing, initial swing or mid swing. During mid stance, substantial muscle activity around the hip occurs in the frontal plane to stabilize it as the opposite foot leaves the ground.[84] The hip’s position is controlled by the hip abductors, of which the gluteus medius is the greatest.[95,99,100] Liu et al. found that the gluteus medius is a significant contributor to the “fore-aft” acceleration in gait. According to the results of their study, the posterior portion of the gluteus medius provides support and slowed progression in the first half of stance and both anterior and posterior portions accelerate the body mass forward in the second half of stance influencing sagittal plane dynamics.[99]

The data in this study revealed activation of the gluteus medius in both walking conditions throughout the first half of the mid stance phase of gait in accordance with the other studies. It then revealed an increase in muscle unit recruitment during the second half of the phase in DGO walking, which continued through terminal stance, pre-swing, initial swing and mid swing.

The four muscles studied are proximal in location and serve multiple roles in support and balance with greater variability and higher CV.[91] Interestingly, the greatest CV is noted in the gluteus medius (TD OG = 56.53% and TD DGO = 53.11%) which also experienced the greatest muscle activation pattern variance between walking conditions spanning from mid stance through mid swing. Since this proximal muscle is less dependent on outside forces during these phases and its muscular action is integral to stability in single leg stance in gait,[95,99-101] the overall variability is to be expected and similar to that reported by Winter.

TD Overground and CP Overground Walking

In this study, each subject’s OG walking speed was matched to their comfortable walking speed in the Lokomat. Their DGO walking speed was determined and a pacer enabled them to perform the same speed overground. This process was consistent across subjects thus allowing more appropriate comparison since muscle activation patterns change with speed of gait.[80,81,94,102] Interestingly, this comparison of conditions revealed the most similarity of muscle activation patterns overall. This could be due in part to the slower OG speed performed to match the DGO walking.

Rectus Femoris and Semitendinosus

The OG muscle activation patterns of the rectus femoris of the TD children were statistically different in 1% of the gait cycle when compared to the CP children. This was also true for 2% of the gait cycle when analyzing the semitendinosus activity. This is a surprising result considering the many documented differences noted in the gait of TD children and children with CP.[7,13-15,103] It may be due to the slower pace of TD OG ambulation and the age of the children. The children in this study were asked to walk at a pace slower than their comfortable walking speed to match the speed walked during DGO application. Tirosh et al. found greater variability during slow walking particularly with children under 10 years of age. The majority of children in this study were age 10 or under indicating the likelihood of observing significant variability. The authors speculated that the increased muscle variability found in the younger children at non-preferred speeds suggest maturity in neuromuscular control at comfortable walking speeds, but further maturation is necessary to accommodate to slower or faster speeds of walking.[102]

Arnold et al. discovered that the hamstring muscles have little effect on stance phase knee motion when analyzing the angular accelerations of the hip and knee. They went on to suggest that decreased range or spasticity in hamstring muscles may not be the direct source of excessive knee flexion during stance in CP gait.[104] Data from this study revealed similarity in the muscle activity of the semitendinosus in both CP and TD walking. Hicks et al. found that a flexed posture markedly reduced the abilities of the major hip and knee extensors except the hamstrings, whose extension ability at the hip was maintained.[88] The results of these two studies explain the lack of significant difference noted between CP and TD semitendinosus muscle activation patterns across the gait cycle in this study.

The CV for the rectus femoris and semitendinosus during OG walking was greater for the children with CP than for the TD children suggesting greater neuromuscular control in the TD children, particularly when considering that the TD CV was relatively unchanged between OG and DGO walking. The unchanged CV in the two walking conditions is evidence of the ingrained muscle activation patterns, balance and stability exhibited in TD gait. On the other hand, the decrease in CV noted between CP OG and DGO walking reveals the unstable nature of the neuromotor system in the children with CP (Table 5.1).

Gluteus Maximus

When comparing the gluteus maximus muscle activation patterns throughout the gait cycle, 37% were significantly different with an 8.7% difference in CV (CP = 20.36%, TD = 11.66%). These differences were noted in terminal stance (9%), pre-swing (10%), initial swing (12%), and mid swing (6%) with more muscle unit recruitment in TD OG than CP OG walking. This lower recruitment in CP OG walking is to be expected due to primary muscle weakness noted in children with CP, particularly in the hip extensors and abductors.[44] In a study comparing the muscle strength of TD children and children with CP, Wiley and Damiano found that in comparison of all the muscles of the lower extremity, the gluteus maximus strength is particularly reduced.[105]

Gluteus Medius

The gluteus medius muscle activation patterns revealed the greatest variance between OG walking patterns of TD and CP children with a total of 42%. This was noted in terminal stance (18%), all of pre-swing (12%), and most of initial swing (12%) with consistently more motor unit recruitment by the children with CP across the gait cycle. Interestingly, the TD children's CV was larger than the CP children's CV with TD = 56.53% and CP = 49.74%. During the phases with significant variance, the confidence interval was smaller, indicating less variation during those phases. The gluteus medius is supposed to be relatively quiet during these phases of gait[84,89] which could explain the reduced variation in muscle activity across the subjects of both groups during this time.

When considering the passive forces involved, internal hip rotation moments spike in terminal stance and pre-swing for TD children while in CP children it is presented as an external rotation moment at the hip.[106,107] This was explained by Brunner et al. as a compensatory response to the external internally rotating moment due to toe or forefoot initial contact and internal rotation of the foot.[107] In this study, the increased gluteus medius activation recruitment by CP children during this time would be consistent with an external rotation moment as outlined by Brunner.

CP Overground and DGO Walking

One third to one half of the muscle activation patterns were different across the gait cycle when comparing CP OG to CP DGO walking. The CV was considerably reduced during DGO walking throughout the gait cycle for the semitendinosus (OG = 69.20%, DGO = 38.50%), gluteus maximus (OG = 20.36%, DGO = 5.62%), and gluteus medius (OG = 49.74%, DGO = 37.04%). The CV for the rectus femoris remained relatively unchanged (OG = 52.82%, DGO = 51.40%). The DGO reduced semitendinosus, gluteus maximus, and gluteus medius variability which was to be expected because the robotic device moves the legs in a consistent and repetitive manner and was giving 100% guidance of that movement. The reduction in variability found during DGO gait was slightly lower than the TD recruitment patterns (Table 5.1). Considering the principle of measurably repetitive movement to induce plasticity, this evidence is supportive of the DGO's ability to provide that application in reducing the variability and allowing consistent practice in a repetitive nature.

Rectus Femoris

The differences between overground and DGO walking for children with CP were found in mid stance (19%), terminal stance (5%), the beginning of pre-swing (4%) and terminal swing (6%) with more muscle unit recruitment in DGO walking noted. The rectus femoris is normally active from mid pre-swing through the beginning of initial swing.[84,89,95] The results of this study found similarity in muscle activation patterns during those phases.

Semitendinosus

The differences in the semitendinosus muscle activation patterns across the gait cycle between CP OG and CP DGO are noted in terminal stance (4%), all of pre-swing (12%), most of initial swing (11%), mid swing (8%) and terminal swing (2%), totaling 37% of the gait cycle with the majority of the difference reflecting more muscle activation in the DGO condition. There was also a significant decrease in variability in DGO walking with the DGO CV = 38.5% and OG = 69.20%.

Gluteus Maximus

The gluteus maximus muscle activation patterns reveal variability in 52% of the gait cycle including mid stance (1%), terminal stance (14%), all of pre-swing (12%), all of initial swing (13%), and mid swing (10%) and terminal swing (2%) with more muscle unit recruitment in the DGO condition. The variability of muscle activation across the gait cycle was considerably lower with DGO walking with DGO CV = 5.62% and OG CV = 20.36%.

Gluteus Medius

Differences in muscle activation patterns were noted across 46% of the gait cycle in mid stance (2%), terminal stance (15%), all of pre-swing (12%), all of initial swing (13%) and mid swing (4%) with more muscle unit recruitment in the DGO walking condition. The variability of the muscle activation patterns across the gait cycle was lower with DGO walking with DGO CV =37.04% and OG CV = 49.74%.

CP Overground Gait

Hoang et al. found that although hip and knee flexion in gait is generally considered to be a disadvantage for children with CP, greater ground reaction forces are generated in this position allowing a biomechanical advantage. The greater ground reaction forces result from an increased capacity of muscular action that is thought to be due to the creation of new movement patterns to compensate for motor control deficits.[108]

Steele et al. found that CP children use the same muscles to support the body in single leg stance when compared to TD; however, they use a different support strategy. They suggested that children who exhibit a flexed posture in stance utilize the support muscles for upward acceleration (soleus, vasti, gastrocnemius, gluteus medius, rectus femoris, and gluteus maximus) and those for forward progression (hamstrings, gluteus medius, and gluteus maximus) relying more on proximal muscles than unimpaired subjects. It was suggested that these different strategies of support and progression during single leg stance may be the reason for abnormal gait patterns in CP.[103]

These studies explain the increased muscle unit recruitment noted in DGO walking in this study. CP OG walking employs different gait strategies including increased double support time and decreased single support in gait.[7,13,15,88,109] With DGO walking, the subjects' lower extremities are regulated in movement to achieve normalized alignment and time in single leg stance which changes the gait dynamics, disrupting their usual strategy, which would explain the increased muscle unit recruitment in the DGO.

TD Overground and CP DGO Walking

In comparing the muscle activation patterns of TD OG and CP DGO walking, the differences ranged from 37% to 56% with the CV of the CP DGO walking lower in three of the four muscles.

Rectus Femoris

The rectus femoris data revealed 40% variance across the gait cycle when comparing these between group conditions. These differences were noted in mid stance (7%), terminal stance (14%), all of pre-swing (12%), and the beginning of initial swing (7%) with the muscle recruitment higher with the children with CP during those identified sections. In this case, the TD children's average CV was lower than the CP DGO with TD OG = 38.33% and CP DGO = 51.4%.

Semitendinosus

In comparing the activity of the semitendinosus across the gait cycle of the two groups, almost half (49%) was variable. These variances were noted in mid stance (2%), terminal stance (18%), all of pre-swing (12%), initial swing (12%), and mid swing (5%) with more muscle recruitment in the CP DGO group. The average CV for the CP DGO was lower (38.50%) than the TD OG (45.53%).

Gluteus Maximus

The least amount of variance in this comparison was noted in the gluteus maximus muscle activity across the gait cycle revealing a total of 37%. These differences were noted in terminal stance (3%), pre-swing (8%), initial swing (12%), mid swing (9%) and terminal swing (5%) with more muscle unit recruitment in the CP DGO condition.

The average CV for the CP DGO group was lower than that of the TD OG (CP DGO = 5.62% and TD OG = 11.66%).

Gluteus Medius

The greatest variance between the two groups was found in the gluteus medius with a total of 56% again with the CP DGO revealing more muscle unit recruitment during the variable times. Differences were noted in mid stance (4%), all of terminal stance (19%), all of pre-swing (12%), all of initial swing (13%), and mid swing (8%). The average CV of the TD OG group was higher than the CP DGO with TD OG = 56.53% and CP DGO = 37.04%.

The comparison of muscle activation patterns in TD OG and CP DGO walking is an important comparison in this study. The ability of the DGO to normalize muscle activity across the gait cycle is expected however, consistent differences are noted in terminal stance, pre-swing, and initial swing with the DGO condition revealing increased muscle unit recruitment during phases of gait when those muscles are not usually active. Further exploration has led to interesting explanations of this surprising result.

Consistent Outcomes

Terminal Stance, Pre-Swing, Initial Swing

This study revealed consistent differences in the muscle activation patterns across most muscles, most conditions and most comparisons during terminal stance, pre-swing, and initial swing phases of gait with the DGO conditions consistently revealing greater muscle unit recruitment (Table 5.2). During these phases of gait, the semitendinosus, gluteus maximus and gluteus medius are normally quiet and the rectus femoris is active from mid pre-swing to the beginning of initial swing.[84,89,95]

Table 5.2: Phases of Gait with at Least 50% Variance

	IC	**LR**	**MSt**	**TSt**	**PSw**	**ISw**	**MSw**	**TSw**
TD OG & TD DGO								
Rec Fem			X	X	X	X		
Semi								
GlutMax								
GlutMed			X	X	X	X	X	
CP OG & TD OG								
Rec Fem								
Semi								
Glut Max				X	X	X	X	
Glut Med				X	X	X		
CP OG & CP DGO								
Rec Fem			X					
Semi					X	X	X	
Glut Max				X	X	X	X	
Glut Med				X	X	X		
TD OG & CP DGO								
Rec Fem				X	X	X		
Semi				X	X	X		
Glut Max					X	X	X	
Glut Med				X	X	X	X	

In normal gait, as the body progresses forward, there is a change from double support in terminal stance and pre-swing to single support in initial swing. The hip musculature seeks to establish postural control (sagittal, frontal and transverse) during the initiation of single leg stance (loading response). Passive forces then substitute for individual muscle effort as the lower extremity moves into single leg stance where the demand on the hip muscles is less intense during opposite limb advancement (terminal stance). These varying requirements of the hip throughout the gait cycle allow for less energy expenditure and an efficient gait.[89]

Ground Reaction Force and Ground Reaction Force Vectors

Ground reaction forces (GRF) are the forces applied by the ground to the foot in response to the forces applied to the ground by the foot when a person takes a step. They are equal in magnitude and opposite in direction.[110] If a person is standing still, the GRF will be equal to the person's body weight, but if the body is in motion, the inertial force involved has to be added to or subtracted from the body weight, depending on the direction of the force.[111] A typical GRF pattern is generated from initial contact to toe off. At first the levels are low but increase to amounts greater than body weight in loading response and terminal stance with lower levels in midstance in the vertical direction.[110] As the individual moves through single leg stance (mid stance) the ground reaction force is less than body weight because the center of mass experiences an upward inertial force due to downward acceleration and reduces the ground reaction force to 85% of body weight. In terminal stance, the propulsive action of push off generates forces greater than body weight which quickly drops at the end of stance phase.[110,111]

GRFs are expressed in three different axes including vertical, anteroposterior and mediolateral. The combination of these force components in the three planes of movement are called ground reaction force vectors (GRFV). In gait, the GRFV is primarily expressed in the sagittal plane. It starts at the center of pressure of the foot and travels up through the joints in a direction dependent on the GRF. [110] According to their relation to the joint position, these vectors can cause external extensor or flexor moments. In terminal stance, the GRFV travels in front of the knee and behind the hip joints creating external extension moments. The external moment is counteracted by an internal moment created by the muscles on the opposite side to stabilize the joint.[112] These vectors and associated moments provide support allowing decreased muscle activity creating an energy efficient gait.

The support moment, described by Winter, is the combination of the hip, knee, and ankle moments which keep the leg from failing during stance phase. They are described as positive or extensor moments at these three joints. It was found that this support moment is present at all walking speeds for both TD individuals and persons with a disability. As stance progresses, increasing support is provided by the plantarflexors until they become the only support of late or terminal stance. The support moment then switches from net extensor to net flexor moment which begins swing phase.[113]

This important support moment in terminal stance and the GRFV in pre-swing and initial swing were reflected in both TD and CP OG gait conditions when compared to walking in the DGO. Significant difference was found in these three phases with the DGO condition consistently recruiting more muscle unit activity, which produces decreased energy efficiency in gait.

Functional Correlation to DGO Use

In this study, it was discovered that the greatest variance in muscle activation patterns were found in terminal swing, pre-swing and initial swing with more muscle recruitment noted in DGO walking. When considering sagittal plane GRF, GRFV, and moments, and the normally inactive muscular activity of the of the muscles studied, the absence of these important passive forces in DGO walking must be considered. The DGO provided body weight support, 100% guidance force, and decreased speed, which interfere with these important passive forces, promoting increased muscle action in the rectus femoris, semitendinosus, gluteus maximus and gluteus medius.

Guidance Force

Lerner et al. examined the effect of a robotic exoskeleton at various degrees of assistance on knee kinematics, kinetics and muscle activity while walking on a treadmill. They found that increased exoskeletal assistance was positively associated with increased knee extension muscle activity at foot contact and mid stance, but negatively associated with the biological knee extension moment during stance and swing. They also noted increased knee flexor activity with increasing amounts of assistance which diminished the increased knee extension noted. The authors proposed that the increased exoskeletal assistance elicited neuromuscular responses that were counterproductive. These results revealed a positive correlation with the degree of assistance suggesting that increasing the amount of assistance with the robotic exoskeleton may be counteractive to rehabilitative efforts.[114] In this study, muscle activity was recorded with DGO support set at the maximum assistance setting (100% guidance force) resulting in increased muscle recruitment. The study by Lerner et al. suggests that a lower assistive force in the DGO may improve the knee extensor moment and decrease the knee flexor activity, thus decreasing the muscle activation recruitment in terminal stance, pre-swing and initial swing and normalizing the pattern.

Body Weight Support

In a study of the effect of body weight support (BWS) on GRF by Barela et al., it was found that as the BWS was increased, the magnitude of GRF decreased. They concluded that different amounts of BWS foster different outputs of GRF parameters even with the same walking speed.[115] In this study, subjects were unweighted from 30% - 50% according to their ability to maintain enough hip and knee extension to ambulate effectively over the treadmill (Table 3.3). In accordance with Barela, this unweighting affected the GRF and resultant external extensor moments needed to assist with extension to flexion in terminal stance, pre-swing and initial swing. Compromising these important passive forces led to increased muscle unit recruitment in the DGO.

Speed

Looking at the effect of speed of gait on hip and knee flexed positioning in children with CP, Cherni et al. found that children with CP can walk 30% faster than their comfortable walking speed and the fast walking required more hip and knee active extension during stance phase and created a more extended posture. It was also noted that they increased their step length and cadence with faster walking. The authors concluded that the increase in knee extension may have been due to forward shifting of the GRF resulting in increased planter flexion/knee extension couple which is a significant knee extensor mechanism.[116] In this study's DGO and OG walking, the speed was slower than comfortable OG walking in order to match comfortable walking speeds in the DGO. Muscle activation patterns were different in most comparisons of conditions in terminal stance, pre-swing and initial swing with increased muscle unit recruitment in all the DGO conditions. Considering the results of the Cherni study, the slow speed would have negatively affected the passive forces noted in these phases of gait creating a need to compensate with greater muscle recruitment.

Guidance Force, Body Weight Support and Speed in the DGO

Guidance force, BWS, and speed are the three DGO parameters that the operator can adjust and progress with treatment.[29] A subject's DGO treatment often begins with 100% guidance force, increased BWS and decreased speed with decrease in guidance force and BWS and increase in walking speed as objective measures of progression in treatment. In this study, 100% guidance force, 30-50-% unweighting and slow walking speed were used in the DGO condition. In comparing the muscle activation patterns across the gait cycle the greatest variance between walking conditions was noted in terminal stance, pre-swing and initial swing with greater muscle unit recruitment in all DGO conditions. These three phases of gait are in sequence and address the transition from dual leg stance to single leg stance during a time when passive forces play an important role.[89,95,110] In light of the research that shows that these three parameters have an effect on GRF in walking, this result should be expected. With that in mind, starting a subject at a lower guidance force, lower unweighting and higher speed may create a greater opportunity for the natural GRF and resultant external moments to normalize the muscle activity patterns.

<u>Limitations</u>

A limitation of this study is the use of a pacer in OG walking to match the walking speed to that in the DGO. This may have affected the subject's natural walking pattern but was necessary to appropriately compare the two conditions since walking speed effects the muscle activation patterns.[80,81,94] Another limitation was the potential influence of walking on a treadmill in the DGO, where the ground moves under the subject, and potentially could change the gait dynamics. At this time, DGO training occurs suspended over a treadmill, not allowing other options.

The use of the foot lifters in the DGO may have inhibited the natural ankle movement necessary in the gait cycle which is identified as the greatest power and the only support in most of late stance by Winter et al..[113] Although the foot lifters have elasticity, enough passive dorsiflexion to clear the treadmill in swing was necessary, particularly in the children with CP who normally wear orthotics and did not wear them in this study, due to EMG sensor placement. This passively held dorsiflexed position could oppose active plantarflexion.

The small subject numbers (10 in each group) was also a limitation. Small quantities give less statistical power to the study. The use of concurrent video would have allowed a visual verification of initial contact and the phases of gait. The foot switch data was used for this purpose but at times the interpretation was unclear and visual verification would have been helpful.

Future Study Considerations

This study is the first step in determining the full effect of locomotor assisted therapy on lower extremity motor performance in TD children and children with CP. This important step identified consistent differences in the muscle activation patterns of four lower extremity muscles across the gait cycle for the first experience with DGO training, however the effect at the completion of training with progression in speed, BWS and guidance force and post training would be necessary to fully explore the changes that potentially occur with consistent exposure.

It was discovered that the current initiation of the parameters of guidance force, BWS and speed may need to be adjusted to optimize kinetic forces in gait. Initial training at a faster speed than comfortable with less guidance force and less BWS would prove to be an interesting adjunct exploration to see if starting with these parameters would progress the muscle activation patterns to more closely match TD. Further study to determine not only the optimal initial setting but the optimal progression of these three parameters would be appropriate.

Another important study consideration would be the introduction of OG walking training to the DGO rehabilitation protocol. Since the GRF, GRFV, and external moments are optimized in OG walking and this study finds consistent difference in muscle activation patterns during phases when these factors are important to gait, when best to introduce OG training would provide crucial rehabilitative insight.

Chapter 6 : Conclusion

This study compared the muscle activation patterns of the rectus femoris, semitendinosus, gluteus maximus, and gluteus medius across the gait cycle of age-matched TD children and children with CP in overground (OG) walking and DGO walking with 100% guidance force.

Surface EMG muscle variability across the gait cycle was analyzed for the same muscles with coefficient of variation (CV) statistics. The results revealed overall greater CV in CP OG walking when compared to TD OG, which decreased considerably with DGO walking. Considering the principle of measurably repetitive movement to induce motor learning and neuroplasticity, this evidence is supportive of the DGO's ability to provide that application in allowing consistent practice in a repetitive nature. Although the CV of CP DGO walking was closer to that of TD OG walking overall, it must be noted that the CV of CP DGO walking was lower than TD OG. Since TD proximal muscles reveal increased CV due to their dual roles of balance and support,[91] it is suggested that initial training in the DGO is necessary to provide consistent, repetitive practice for children with CP, but needs to be progressed to OG walking where that challenge may normalize CV for these proximal muscles. Further study to determine appropriate dosage of DGO treatment versus OG practice is indicated.

This study also compared muscle activation patterns across the gait cycle of the rectus femoris, semitendinosus, gluteus maximus, and gluteus medius finding consistent differences across most muscles and most conditions during terminal stance, pre-swing, and initial swing phases of gait with the DGO condition consistently revealing greater muscle unit recruitment. During these phases of gait, the semitendinosus, gluteus maximus and gluteus medius are normally quiet in TD OG gait and the rectus femoris is active from mid pre-swing to the beginning of initial swing.[84,89,95]

In normal gait, passive forces substitute for individual muscle effort allowing for less energy expenditure and efficiency.[89] GRF and GRFV are important external forces that play a crucial role during terminal stance, pre-swing and initial swing.[89,95,110-113] Guidance force, BWS, and speed are the DGO parameters used to progress rehabilitation in DGO walking. High guidance force,[114] increased BWS,[115] and decreased speed[116] have all been found to have a negative effect on GRF which would negatively affect the GRFV and associated moments. In this study, when considering sagittal plane GRF, GRFV, moments, and the normally inactive muscles, the parameters of DGO guidance force, BWS, and speed are proposed to have had a negative effect on these important passive forces creating the need to increase muscle recruitment to compensate. This could easily explain the differences in muscle activation patterns and increased muscle recruitment noted in terminal stance, pre-swing and initial swing when these passive forces play such an important role.

The ability to ambulate is critical to a child's ability to participate,[1-3] to the development of their self-concept, and to their overall quality of life.[4,5] Impaired walking ability has been identified as the primary physical disability in children with CP[7] and thus rehabilitation of walking is imperative. DGO training is a novel approach to gait rehabilitation for these children and this study supports its use, however attention needs to be given to the possible negative effects on the important passive forces provided by OG walking.

The results of this study suggest the need to initiate treatment in the DGO with lower guidance force, higher speed, and lower BWS or to advance rapidly in treatment in these parameters. It also indicates the need for gait rehabilitation with the DGO in conjunction with OG training. Further study would be necessary to determine the optimal initial DGO parameters and their progression, DGO dosage, and co-treatment with OG walking.

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Curriculum Vitae

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Education

2019	**PhD, Health and Human Sciences** Indiana University (Indianapolis, IN)
1984	**Master of Science, Physical Therapy** University of Indianapolis (Indianapolis, IN)
1981	**Bachelor of Arts, Biology** Purdue University (Indianapolis, IN)

Licensure

1984-present	Physical Therapist-Indiana State License

Positions and Employment

2006-Present	**Physical Therapist** Indiana University Health Riley Hospital for Children Indianapolis, IN
2001	**Physical Therapist** Hamilton-Boone-Madison Special Services Cooperative Sand Creek Intermediate School Developmental Preschool Fishers, IN
1991-1996	**Physical Therapist** James Whitcomb Riley Hospital for Children Indianapolis, IN
1989-1990	**Physical Therapist** University of Indianapolis Developmental Preschool and Foot Clinic Indianapolis, IN
1987-1990	**Physical Therapist** Private Practice Indianapolis, IN
1984-1989	**Physical Therapist** James Whitcomb Riley Hospital for Children Indianapolis, IN

1980-1982	**Lab Technician** Department of Neuroanatomy Indiana University School of Medicine, Indianapolis, IN

Professional and Other Experience:

2012-2015, 2017	Guest Lecturer, Indiana University School of Occupational Therapy, Indianapolis, Indiana
2007 - 2010	Carmel Clay Education Foundation Carmel, IN, Board Member Chair of Governance Committee, July 2008 - July 2010
2007-2010	Guest Lecturer, Indiana University School of Physical Therapy, Indianapolis, Indiana
2002-2006	Carmel Clay School Corporation, Carmel, Indiana Board of School Trustees, President, July 2005 – June 2006
2002-2004	Carmel Clay Parks and Recreation, Carmel, IN, Board Member
1994	Guest Instructor, Indiana University School of Physical Therapy, Indianapolis, Indiana
1988, 1990	Clinical Instructor, Pediatric Neuro Developmental Treatment Certification Course, Indianapolis, IN

Selected Peer Reviewed Publications

1**. Scheidler, C.S.**, Golomb, M.R. An Unusual Presentation of Chiari I Malformation. J Child Neurol. 2013. Nov. 28(11):1527-1530.

Additional Publications

1. **Scheidler, C.S**., Lopes, E., Cardinal, R., Altenburger, P. Ankle-Foot Orthosis Footwear Combination. Indiana University School of Health and Rehabilitation Science Research Summit. Indianapolis, IN 2014
2. **Scheidler, C.S**., Zambon, K., Mathews. C., Zehr, A., Sigmund, S., Denning, N., Cardinal, R., Altenburger, P. The influence of training environment on self-selected gait speed. American Physical Therapy Association Combined Sections Meeting. Anaheim, CA 2016.
3. **Scheidler, C.S**., Bridgeman, K., Fuller, E., Nobbe, J., Hart, A., Jay, K., Stanley, S., Tellus, S., Altenburger, P. Driven gait orthosis influence on the rectus femoris and semitendinosus in a child with crouch gait. American Physical Therapy Association Combined Sections Meeting. New Orleans, LA 2018.