SURGICAL OUTCOMES FOR THE AMBULATORY CHILD WITH CEREBRAL PALSY

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ABSTRACT

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Cerebral Palsy (CP) is one of the most common neurologic conditions treated by physical therapists (PTs); and, improving the ambulation ability of these children is often the most common goal of treatment. Orthopedic surgical intervention can improve the gait of children with spastic CP that have difficulty with walking. Finding which surgical procedures or combination of procedures are the most effective for improving the walking ability of these children is a complex task. This three study dissertation examines the surgical outcomes, and the measures used to determine surgical outcome, of children with spastic CP undergoing orthopedic surgical intervention to improve their gait.

All three studies were retrospective in design, and utilized a sample of convenience at a motion analysis laboratory of a hospital that specialized in orthopedic surgery for children with CP. The data reviewed and contained within these studies spanned the years 1994 to 2011. The subject's' ages ranged from 4.5 years to 18. 2 years.

There are several findings within these studies. The first finding is that orthopedic surgical intervention used in conjunction with a motion analysis laboratory improves the gait of children with spastic CP as noted by the consistent improvement in the Gait Deviation Index (GDI). The second finding is support for the belief that an accurate gait outcome assessment for a given intervention should include both functional and technical gait measures. The third finding suggests that when conducting and analyzing gait outcomes in children with CP, their Gross Motor Function Classification System (GMFCS) level; pre-intervention GDI; and, pattern of involvement should be considered. The fourth finding is a suggestion that increased velocity may not always accompany improvements in the gait of children with spastic CP. Therefore increased velocity may not always be an accurate outcome measure for this particular population after undergoing orthopedic surgery to improve their gait. The fifth finding of this study is support for the use of the GDI along with surgical technical achievement goals (TAGs) as a pair of technical outcome measures for ambulatory children with CP having lower extremity orthopedic surgery to improve their ambulation.

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CHAPTER I

INTRODUCTION

STATEMENT OF THE PROBLEM

Cerebral Palsy (CP) is the neurologic condition most frequently encountered by pediatric physical therapists.[1] CP is a condition caused by a defect or lesion to the brain that can occur in utero, during birth, or shortly after birth with resultant motor impairment and possible sensory deficits.[2] Some of the possible long term effects of this brain lesion include: abnormal muscle tone, impaired voluntary muscle control, increased muscle tightness, muscle weakness, sensory impairments, vision impairments, and cognitive impairments.[1,3,4] Physical therapists who work with children with CP are familiar with how these deficits impair the ability of the child with CP to walk and to balance; and therefore, to function.[1,3,5]

Many ambulatory children with CP require orthopedic intervention to improve their ability to stand, to balance and to walk.[5] These orthopedic interventions can range from stretching, botulinum toxin (Botox) injections, orthotic intervention and surgical intervention.[5-10] Orthopedic surgical intervention is often needed in these children to correct muscle imbalances and skeletal deformity in their lower extremities, in order to improve their standing and walking ability.[5,6,8] Single event multiple level surgery, called SEMLS, is the new standard of care for orthopedic surgical intervention for the ambulatory child with CP.[11,12] SEMLS refer to the surgical correction of more than one lower extremity orthopedic impairment at the level of the hip, knee or ankle in the form of soft tissue or bony intervention, during one single surgery rather than putting the child through multiple separate surgical events. Since SEMLS attempt to address the orthopedic issues at the level of the hip, knee, and ankle that are adversely affecting gait, a number of surgical procedures can be performed to the child. The number of surgical procedures performed during a SEMLS varies depending on the type of CP (bilateral versus unilateral involvement) and functional level of the child. There is currently no uniform consensus on which specific orthopedic surgical procedures work best to improve the ability of these children to ambulate.[11] For instance when the ambulatory child with CP has bony malformation in addition to muscular impairments, some surgeons advocate addressing both the bony and soft tissue intervention concurrently during one single surgical event. While other surgeons prefer to separate the bony intervention from the soft tissue intervention in staged surgical events. While still other surgeons, vary in their approach.

Various surgical soft tissue interventions are needed for the ambulatory child with CP. Four common soft tissue interventions performed by pediatric orthopedic surgeons to improve the gait of the child with CP are: hamstring lengthenings; adductor tenotomies; rectus femoris transfers; and gastrocnemius lengthenings.

One or more of these two joint muscles are often found to be shortened in the child with CP, so much so that it affects their ability to ambulate. Lengthening these muscles, often leads to improved gait.[13,14]

Bony malformation of the femur and tibia in children with CP is another common problem and is referred to as Lever-Arm Dysfunction, LAD.[15-19] Often these children have excessive hip anteversion, and excessive tibial torsion that require orthopedic surgical correction to address the bony malformation[10,15,20] While correction of these bony deformities is advocated in addition to addressing the soft tissue impairments (in order for the child with CP to achieve optimal ambulation), there is no clear evidence as to best methods by which to accomplish this task.[15,17,18,21]

A specific example of the differing opinions on the selection of specific orthopedic surgical procedures that make up a SEMLS is the intervention to the rectus femoris muscle. Many ambulatory children with CP present with a stiff knee gait which causes them great difficulty when attempting to clear their limb during walking.[22,23] Surgical intervention to the rectus femoris in the form of a transfer of this muscle insertion, known as a Rectus Femoris Transfer, or RFT, has been shown to improve the walking ability of these children.[22-24] However, a new surgical procedure has been proposed to replace this procedure called a distal rectus femoris intramuscular lengthening.[9] It is unclear if this new procedure is as effective as the existing rectus transfer procedure, both in the short term post-operative phase (1 to 2 years after surgery) as well as in the long term post-operative phase (3 to 6 years after surgery). Research needs to be conducted comparing the outcomes of these two differing rectus femoris procedures; however surgical outcomes research is not a simple task in this population.

There are several reasons why investigating surgical outcomes for the ambulatory child with CP is difficult. First, even though these children all have CP, they are an extremely diverse group. The location, amount, and degree of soft tissue and bony impairment vary greatly between each child, even among those children having the same type of CP.[4] Variation in the presentation of impairments can even vary between limbs within the same child.[4] The variability of impairments seen in CP is also dependent upon the child's comorbidities as well as the environment in which they are raised.

Another reason investigating surgical outcomes in children with CP is difficult is due to their complicated gait patterns that often have secondary compensations or substitutive actions.[15,25] A Motion Analysis Laboratory (MAL) can assist with analyzing their gait and help discern primary gait impairments from secondary gait compensations.[15,25] A MAL is also beneficial for measuring changes in their gait after surgery. However, there are few clinical MALs across the United States due to their cost along with the lack or reimbursement for their services. Therefore, most orthopedic pediatric surgeons do not have access to a MAL and the data they provide.

In summary while orthopedic surgical intervention has been shown to help the ambulatory child with CP to walk better, more outcomes research is needed in this area.[26] The aim of this three part dissertation is to add to the literature in the field of pediatric orthopedic surgical intervention for the ambulatory child with CP. Physical therapists should find this information useful for clinical practice; since they often treat these children and advise their parents as to the best interventions to improve their child's walking ability.

CLINICAL RELEVANCE

Shriners Hospitals for Children (SHC) in Houston specializes in orthopedic surgical intervention to improve the gait of children with CP. Their clinical MAL has been analyzing the gait of ambulatory children with CP and presenting gait data to their surgeons for treatment planning for over 30 years. As such, the Houston Shriner's MAL has an extensive amount of surgical outcome information on ambulatory patients with CP who have undergone lower extremity orthopedic surgical procedures. In addition, this clinical MAL has been systematically measuring the surgical outcomes from their lower extremity orthopedic surgeries since 1994. The MAL's post-operative gait studies have been collecting technical and functional outcome measures that can be used to add to the body of knowledge on the surgical outcomes for these patients. However since this laboratory is a clinical MAL, and not solely devoted to research, extensive analysis of these findings has been limited to due patient care needs.

Physical therapy (PT) is an integral part of the treatment of the child with CP after surgical intervention to improve ambulation. And while exact rehabilitation procedures vary depending on the therapist, the facility, and whether bony correction was performed in addition to soft tissue, post-operative physical therapy is included as a part of all SEMLS. In addition since physical therapists (PTs) are frequently consulted by parents of children with CP for recommendations for more invasive procedures to improve their child's walking ability when conservative measures are inadequate, PTs need to be educated as to the evidence based research in this field so they may educate and advise parents appropriately.

METHODS

While the subjects for all three studies were taken from the same subject pool, the SHC Houston MAL, the inclusion criteria for each of the three studies differed. Globally, all subjects were pediatric or adolescent patients of SHC MAL in Houston between the ages of 4 to18 years, with a diagnosis of spastic diplegic (bilateral lower extremity involvement) or hemiplegic CP (one sided involvement). Each subject had received a pre-operative and post-operative gait analysis; and, had undergone orthopedic surgical intervention at SHC in Houston between the years 1994 and 2011. Subjects were also those classified as functioning at a Gross Motor Function Classification (GMFCS) Level I, II or III.[27] While the exclusion criteria also differed slightly between studies, globally the exclusion criteria included the following: incomplete motion lab data; non-adherence to MAL protocols for timing of evaluations; known presence of a comorbidity; a change in the post-operative testing condition; a significant leg length discrepancy equal to or greater than 2 cm; prior neurologic surgery to improve ambulation such as a dorsal rhizotomy or baclofen pump placement.

STUDY ONE: EXPLORATION OF RELATIONSHIPS OF TECHNICAL GAIT MEASURES AND FUNCTIONAL GAIT MEASURES IN PATIENTS WITH CEREBRAL PALSY

Background

One method by which MAL gait measures can be divided for outcome analysis is into "technical" and "functional" outcome measures.[28] Two technical gait outcome measures that are used at the SHC Houston MAL are the Gait Deviation Index (GDI) and Technical Achievement Goals (TAGs). The GDI is a commonly used MAL pathologic gait index. [29-32] TAGs are a system of surgical Technical Achievement Goals developed at the SHC-Houston MAL.[33] When reviewing the surgical outcomes literature for the ambulatory child with CP there exists a wide variety of outcome measures.[13] These outcome measures range from instrumented gait analysis data, summary statistics of gait (such as the GDI), and functional questionnaires (such as the Pediatric Outcomes Data Collection Instrument).[13] However, there is limited literature on how these measures relate to each other and how they may change with differing types of CP at varying ambulatory or functional levels with differing surgical procedures.[13,33-35] In addition, with the GDI growing rapidly as an outcome measure, improved understanding of its meaning and how the GDI relates to other outcome measures would be beneficial.[36-39] While previous research has revealed these two measures (TAGs and GDI) to have a low correlation to each other and thus supported their continued use as a team of technical outcome measures, there has been no literature on how these two technical gait outcome measures relate to functional outcome measures of gait.[33] Examples of functional gait outcome measures include: stride length, walking velocity and the Pediatric Outcome Data Collection Instrument (PODCI). The PODCI is a commonly used and validated functional outcome questionnaire. [40,41] Expanding our knowledge as to how technical gait measures relate to functional gait measures should improve our overall understanding of the surgical outcome analysis for the ambulatory child with CP.

Purpose and Hypothesis

The purpose of this study is to examine the relationships between two technical and four functional gait outcome measures; and, to determine if these relationships change when examining different patient types (Diplegic vs. Hemiplegic) at differing ambulatory levels (GMFCS level I, II, III) and in the presence of prior lower extremity orthopedic surgery. The variables being examined within this dissertation are the following outcome measures: GDI; TAGs; stride length; walking velocity; PODCI-Transfers & Mobility domain; and, PODCI-Sports & Physical Function domain. In addition, examination of the mean differences between the pre-operative and post-operative values will be examined for the GMFCS levels (I vs. II vs. III), diagnostic category (Diplegic vs. Hemiplegic), and for the presence of previous surgery. This is a two part study. Part one will look at the correlational relationships between these measures. Part two will look at the mean differences between the pre-operative and post-operative values of these measures, for the whole group as well as each of the subgroups. There are six scientific hypotheses for this study, they are as follows:

1) There will be significant correlations between the GDI and the functional gait outcome measures of walking velocity, stride length, PODCI Transfers, and PODCI Sports when the group is examined as a whole and by type of involvement (Diplegic and Hemiplegic), functional ambulatory level (GMFCS I, II, III), and by presence of prior surgery.

2) There will be significant correlations between the TAG % and the functional gait outcome measures of walking velocity, stride length, PODCI Transfers, and PODCI Sports when the group is examined as a whole as well as for each of the subgroupings.

3) There will be significant weak to moderate correlations between the post-operative GDI and TAG % for the entire group as well as significantly different correlations between each of the subgroupings.

4) There will be significant negative, moderate correlations between the pre-operative average GDI and the amount of post-operative improvement in the GDI for the entire group as well as for each of the sub-groups.

Part II

5) There will be significant differences between the pre and post-op mean values for the whole group as well as for each of the subgroups for following five measures of gait outcome: walking velocity, stride length, PODCI Transfers, and PODCI Sports.

6) There will be significant differences between the TAG % for each of the subgroups.

STUDY TWO: SHORT-TERM AND LONG-TERM SURGICAL OUTCOMES FOR RECTUS FEMORIS TRANSFERS IN PATIENTS WITH CEREBRAL PALSY

Background

Rectus femoris transfers are believed to improve the gait of children and adolescents with CP by achieving the following three technical surgical goals: 1) improved amount of peak knee flexion during the swing phase of gait; 2) improved timing to achieve peak knee flexion during the swing phase gait; and, 3) improved overall range of knee motion throughout the gait cycle.[22,23,42]

Alternate rectus femoris procedures, such as a mid-rectus lengthening, are being proposed to replace the rectus femoris transfer (RFT).[9] The rationale for the replacement of the RFT procedure appears to be due to a shorter rehabilitative process for the new procedure and the belief that the RFT procedure does not maintain its technical goal achievement in the long term. While a shorter rehabilitative process may be beneficial, if the cost of a shorter rehab is to have a less effective procedure this may not be the better procedure. In addition if the RFT is found to indeed maintain its technical goal achievement long term, this data may help patients and medical staff in decision making as to which procedure to perform.[9]

Purpose and Hypothesis

The purpose of this study is to examine and compare the achievement of the technical surgical goals of the RFT procedure both in the short term post-operative period (1 to 2 years post-surgery) and in the long term post-operative period (3 to 6 years post-surgery). The number of surgical technical achievement goals, or TAGs, for the short post-op period was compared to that of the long-term post-op period to determine the degree of change in the achievement of these TAGs. Each of the subjects in this study underwent bilateral RFTs; therefore each subject had a total of six TAGs (three goals for each limb). The seven scientific hypotheses for this study are as follows:

1) TAGs for the RFT procedure are being achieved in short-term gait analysis and maintained in long-term gait analysis with at least four out of the six TAGs met in short-term and maintained in long-term analysis for the entire groups.

2) TAGs for the RFT procedure are being achieved in short-term gait analysis and maintained in long-term gait analysis with at least four out of the six TAGs met in short-term and maintained in long-term analysis for the GMFCS level II group.

3) TAGs for the RFT procedure are being achieved in short-term gait analysis and maintained in long-term gait analysis with at least four out of the six TAGs met in short-term and maintained in long-term analysis for the GMFCS level III group.

4) There will be a significantly greater number of TAGs met in the GMFCS level II group when compared to the GMFCS level III group for short-term gait analysis.

5) There will be a significantly greater number of TAGs met in the GMFCS level II group when compared to the GMFCS level III group for long-term gait analysis.

6) There will a significant difference between which of the three TAGs are being met in short-term gait analysis for the entire group as well as for the GMFCS sub-groups.

7) There will a significant difference between which of the three TAGs are being met in long-term gait analysis for the entire group as well as for the GMFCS sub-groups.

STUDY THREE: EXAMINATION OF OUTCOMES FOR SOFT TISSUE ONLY AND SOFT TISSUE WITH BONY CORRECTION SEMLS IN PATIENTS WITH CEREBRAL PALSY

Background

Bony malformation in children with CP is common; and is called Lever Arm Dysfunction, LAD.[10,15,20] Correction of these bony deformities concurrently with the soft tissue intervention during one single surgical event is advocated by some pediatric orthopedic surgeons.[10,12] Other surgeons prefer separating the bony and soft tissue procedures into separate surgical encounters, sometimes referred to as “staging”. Staging may be proposed for many reasons, among them are: so a child does not have to undergo such an involved surgical process; to make the post-operative rehabilitation easier for both the child and the parents; and technical surgical limitations.[43] Additional research examining the outcomes of soft tissue only SEMLS and SEMLS that include bony correction concurrently with soft tissue correction should assist parents and medical staff with surgical decision making.

Purpose and Hypothesis

The purpose of this research study was to investigate how gait outcome measures behave for children with CP undergoing both bony and soft tissue correction within their SEMLS versus children who underwent SEMLS with only soft tissue correction. The gait outcome measures examined in this study are: walking velocity; stride length; Gait Deviation Index (GDI); Pediatric Outcomes Data Collection Instrument (PODCI) Transfers & Mobility domain; PODCI Sports & Physical Function domain; and achievement of surgical technical achievement goals (TAGs). This was a retrospective, exploratory study of the pre-operative and short-term post-operative gait studies of patients seen in the MAL at SHC between the years 1994 and 2011.

They are five scientific hypotheses for this study:

1. There will be significant, positive correlations between the pre-operative and post-operative measures of: walking velocity, stride length, GDI, PODCI Transfers & Mobility; and PODCI Sports & Physical Function for both groups.
2. There will be a significant difference in the correlations for each measure between the two groups.
3. There will be significant improvement in the velocity and stride length for both groups.

4. There will be significant improvement in the GDI for both groups.
5. There will be significant improvement in the PODCI Transfers & Mobility and PODCI Sports & Physical Function for both groups.
6. There will be a significant difference in achievement of surgical technical achievement goals between the two groups.

CHAPTER II

LITERATURE REVIEW

THE VARIABILITY WITHIN INDIVIDUALS WITH CEREBRAL PALSY

A review of the literature on the topic of surgical outcomes for the ambulatory child with CP reveals the complexity regarding this topic and the challenges that accompany research in this area. The first challenge, as discussed in the introduction is the complexity involved with Cerebral Palsy. In a 2010 article one author explained the complexities of this diagnosis.[4] The author reports that no publication has yet achieved a precise and clear definition of CP and states that "CP is an umbrella term covering a wide variety of clinical conditions that meet four criteria: presence of a disorder of movement or posture; secondary to cerebral abnormality; arising early in development; and by the time movement exists, the cerebral abnormality is static".[4] The author points out there is no test to confirm the existence of CP; and, "that only motor impairment exists resulting from nonprogressive cerebral pathology acquired early in life".[4]

In this same article the author later goes on to state, what many of the clinicians already working with children with CP are familiar, that each child with CP (even with same type and pattern of involvement) presents with their own unique set of impairments. "Sometimes categorized as bilateral or unilateral or by the number of limbs affected…..It is rare to find spastic hemiplegia with no signs of impairment on the less affected side, bilateral spasticity that is perfectly symmetric, or diplegia that with no signs of impairment in the arms".[4] This lack of uniformity in impairments, differing functional abilities, and differing responses to treatment interventions within each child with CP is further complicated by the fact that each child grows up in a unique environment. A child's environment can vary on multiple factors; among them are the structure, beliefs, attitudes, and financial resources of the family. While an entire dissertation could be devoted to this topic alone, it is mentioned here briefly to point out yet another layer in how these children are unique. While these differences within each child with CP can make for interesting rehabilitation to the physical therapist working to help the child function better, it also creates for heterogeneity among seemingly homogenous groups when attempting outcomes research. Even when researchers attempt to create homogenous groupings by limiting their subject pools to the same CP type and pattern of involvement, multiple other factors need to be considered in order to attempt to create homogeneity among the groupings of research subjects.

Another factor to be considered when designing research groups are the presence of common comorbidities associated with CP such as: cognition; vision; hearing; seizures; scoliosis and significant leg length discrepancy. All these comorbidities have the potential to impact gait and affect outcome measures. Other factors to consider when designing research studies are the patient's past medical history and surgical histories (unknown etiology, familial history of walking impairments, previous orthopedic surgery, and previous neurologic surgeries such as a dorsal rhizotomy or baclofen pump placement). Thus for surgical outcome purposes, creating a homogenous group of children with CP is a challenge and one reason that achieving a large homogenous subject pool is often difficult.

MOTION ANALYSIS LABORATORIES

A motion analysis laboratory (MAL) where instrumented gait analysis (IGA) can occur is considered by some to be the gold standard for pre-operative assessment prior to undergoing a SEML.[15] The data that can be supplied by the motion lab consists of a clinical exam (range of motion, tone, motor control, strength, and anthropometric measures), plantar pressure analysis (pedobarographs), video gait assessment, instrumented gait data (kinematics, kinetics, and spatiotemporal measures), electromyographic information (EMG) and oxygen consumption. The data supplied by the MAL is very useful to the surgeon for surgical decision making as far as which specific procedures should make up a particular child's SEML; and, should be used as part of a "diagnostic matrix" as described by Davids and colleagues.[15,44] The data supplied by the MAL is also useful for outcome measurements when the data is compared pre and post-operatively.

Another challenge to surgical outcome analysis in the ambulatory child with CP is the limited number of Motion Analysis Laboratories or MALs. MALs are expensive to run and most insurance companies do not cover the cost; therefore, there are a limited number of these facilities. The gait deviations of children with CP are very complex. They have primary gait deviations as well as secondary compensations that occur during gait; and, it is often not easy to differentiate between them. MAL data can assist with the differentiation of primary gait deviations from secondary compensations. These children often also display asymmetrical pelvic alignment and transverse plan issues which make observational gait analysis difficult. The MAL data can also assist with this assessment as well.

GAIT DEVIATIONS AND SOFT TISSUE SURGICAL INTERVENTIONS

There are several common gait deviations seen in children with CP that present in varying degrees of severity and in varying combinations. One common gait deviation is the crouched gait pattern. During the crouched gait pattern, the child often displays excessive knee and hip flexion throughout the gait cycle. This pattern of walking often creates or further accentuates existing hamstring tightness as well as knee flexion contractures. This gait pattern adversely affects all five prerequisites of ambulation which are: stability in stance, swing limb clearance, prepositioning of the foot for initial contact, adequate step length and energy conservation.[15] Depending on many other factors associated with the child and their gait (which is beyond the scope of this paper), a hamstring lengthening procedure may be indicated to assist in improving this gait deviation. The goals of a hamstring lengthening procedure are to improve knee extension at initial contact as well as throughout the stance phase of gait while at the same time preventing excessive knee extension or recurvatum. Hamstring lengthening procedures will often also decrease the degree of knee flexion contracture, depending of the severity of the contracture, and improve the popliteal fossa measurements.

Another common gait deviation seen in children with CP is the stiff knee gait pattern.[15,25] During this gait pattern, an insufficient amount of knee flexion is displayed during swing thus creating difficulty with swing limb clearance. During a stiff knee gait pattern, the degree and often the timing of peak knee flexion during swing is atypical. This gait deviation also adversely affects at least four out of the five prerequisites of ambulation. This pattern of walking is often associated with rectus femoris over activity.[15,24,42,45] Depending on many other factors associated with the child and their gait, a rectus femoris transfer may be indicated to assist in improving this gait deviation.[15] The surgical goals associated with a rectus femoris transfer are: increased total knee range of motion during gait; increased or maintained (if typical peak knee flexion already exists) peak knee flexion during swing; and, improved timing of peak knee flexion during swing.

Another common gait deviation seen in children with CP is toe walking. During this gait pattern, the talocrural joint is in excessive plantar flexion during stance or throughout the entire gait cycle. This gait deviation can adversely affect all five attributes of ambulation. This pattern of walking is often associated with gastrocsoleus or gastrocnemius shortening. Often a plantar flexion contracture is present when the knee is in a position of extension. Depending on many other factors associated with the child and their gait (which is beyond the scope of this paper), a gastroc lengthening may be indicated. The goals of a gastroc lengthening procedure are to: increase passive ankle dorsiflexion; decrease excessive plantar flexion during gait; and, to avoid excessive dorsiflexion during stance.

Lastly, one more common gait deviation seen in children with CP is a scissoring gait pattern. During this gait pattern excessive hip adduction is apparent. Depending on the severity of the hip adduction, the child's legs may cross during ambulation or be extremely adducted creating a very narrow base of support by which to stand and ambulate. This gait deviation can also adversely affect all five attributes of ambulation as well. This pattern of walking is often associated with adductor tightness either through increased spasticity or a shortening of the adductor muscle or, often times, both. Depending on many other factors associated with the child and their gait, an adductor lengthening may be indicated to improve ambulation. Surgical goals associated with the adductor lengthening procedure are to increase passive hip abduction and decrease adduction during gait.

This brief review of some of the more common gait deviations seen in children with CP, which can occur in isolation or in various combinations, demonstrates the complexity of their gait deviations. When these primary gait deficits are combined with secondary volitional compensations, the complexity of their gait pattern and deviations deepen. Attempting to differentiate between primary and secondary gait deviations can be challenging even with the addition of MAL data.

GAIT DEVIATIONS AND BONY SURGICAL INTERVENTIONS

In-toeing is a common gait deviation in the ambulatory child with CP. It is often due to bony malformation or lever arm dysfunction (LAD). In-toeing can be caused by excessive anteversion of the femur which creates increased internal rotation at the hip. It can also be caused by increased internal tibial torsion. Excessive in-toeing can have a significant adverse impact the prerequisites of ambulation. When bony malformation or LAD is causing significant gait deviations, a bony surgical procedure at the femur or the tibia may be performed to improve the child's gait.

A femoral derotational osteotomy is a surgical procedure that may be performed to address increased anteversion of the hip in the hope of reducing excessive in-toeing. A distal tibial osteotomy is also a surgical procedure that may be performed to address LAD. A distal tibial osteotomy may be performed to address excessive internal or external tibial rotation in the hope of reducing excessive in-toeing or out-toeing. Sometimes only one of these bony surgical interventions is performed to correct the LAD; other times both procedures are needed.

SURGICAL DECISION MAKING

Children with CP often have impairment of the primarily lower extremity two joint muscles needed for ambulation, such as the hamstrings, rectus femoris, adductors and gastrocsoleus. Not all ambulatory children with CP that require surgical intervention need a single event multilevel surgery or SEML to improve their walking. There are some children that continue to need the occasional single joint level surgical procedure. However, careful consideration of multilevel intervention at the time surgical planning is recommended in order to prevent a potential worsening of the child's ambulatory ability and to attempt to decrease the likelihood of future additional surgeries. History has taught pediatric orthopedic surgeons that overall SEMLS have better outcomes than the historic one muscle or muscle group surgery, also known as the “Birthday Surgery” phenomena.[46] Prior to development of the SEMLS approach; a surgical event was often restricted to one muscle group or one joint level, bilaterally if needed, at a time. This approach frequently required repeat or follow-up surgery to either fix a new gait deviation that appeared or to continue to address the same gait issues that were not completely addressed during the first surgery. This type of surgical treatment approach became known as the “Birthday Surgery” due to the fact that the patient needed to undergo repeatedly surgical interventions somewhat yearly for a period of time.[46]

With SEMLS as the new standard of care, the subject pools involved in surgical outcome research typically have undergone multiple soft tissue surgical procedures.[11,12] The most common soft tissue procedures are those involving the hamstrings, adductors, rectus femoris and gastroc muscles.[11] “However widely varying views remain about the appropriate treatments for the ambulatory child with CP”.[11] The exact number and type of surgical procedures a child undergoes can vary with the differing needs of the individual child and family. In addition, differing surgeons bring their own set of surgical intervention beliefs and variations to surgical procedures. The same surgical procedure can vary in technique from one surgeon to another surgeon.

LONG-TERM RECTUS FEMORIS TRANFER RESEARCH

While many studies have examined the short term post-operative effects of the RFT, only a few have examined the long-term post-operative results of the RFT.[45,47,48] In 2003, Saw examined the long term effects of 26 limbs in 18 patients having undergone a RFT between the years 1992 to 1997.[48] The subject pool was a heterogeneous group of patients with CP that included hemiplegic, quadriplegic, and diplegic children with CP that had undergone a RFT for a stiff knee gait. Subjects were excluded if they were nonambulators or had undergone previous surgical procedure to the rectus femoris muscle. The average age of subjects at the time of surgery was 11.7 years. This study measured four kinematic parameters and three temporal parameters using motion analysis. The kinematic parameters were: minimum hip flexion; total knee range of motion; minimum knee flexion in stance and maximum knee flexion in swing. The temporal parameters were: stride length; cadence; and velocity. Analysis of the short-term post-operative gait, approximately one year after surgery, found a significant improvement in maximum knee flexion during swing and in the total knee range of motion. Analysis of the long-term post-operative gait, approximately four and half years after surgery (range 1.7 to 6.7 years), showed the improvement in maximum knee flexion during swing was maintained long-term. However, the increase in total knee range of motion was not found to be maintained in the long-term. It was theorized that the total range of knee motion was not maintained in this group due to a progressive crouching of the gait pattern seen in these patients over time. It was also pointed out that not all subjects in this study received concurrent hamstring lengthenings with the RFT and this may have contributed to the progressive crouch gait and therefore the lack of maintenance of the total knee range of motion.

In another long-term study of the RFT procedure by Moreau in 2004, a comparison of two groups of children with CP undergoing SEMLS was performed.[47] One group had undergone a RFT as part of their SEMLS (RFT group) while the other group underwent SEMLS without a RFT (NonRFT group). Both groups were analyzed approximately one year (10 to 18 months range) post-operatively and then again three years or more (3 to 4.5 years range) after surgery. Forty one subjects with either spastic diplegic or hemiplegic CP were included in the study. The average age at surgery for the RFT group was 10.9 years while the average age at surgery for the non-RFT group was 8.4 years. Subjects were excluded only if they underwent subsequent surgery during the post-operative period. The RFT group had 28 subjects with 50 sides; 21subjects were independent ambulators while 7 used an assistive device. The non-RFT group had 13 subjects with a total of 22 sides; all subjects in this group were independent ambulators without an assistive device except for one. The following measures were analyzed: overall knee flexion during swing; peak knee flexion in swing; terminal knee extension angle; and, time to peak knee flexion in swing. The long-term findings for the nonRFT group showed a decline in peak knee flexion in swing with maintenance of overall knee flexion during swing. The long-term findings of the RFT group showed improved peak knee flexion and improved overall knee flexion during swing. This study concluded that “the non-RFT group followed the natural progression of gait in children with CP …with a decline in the peak knee flexion angle in swing…in contrast to the RFT group who appeared to counteract the natural progression of gait in CP with improvements in the peak knee flexion in swing, and overall knee flexion swing range".[47] This same study also concluded that "the RFT with concomitant multi-level surgical procedures is an effective intervention which counteracts the effects of growth and time at the knee joint, with maintenance or improvement of outcome parameters over time".[47]

In a 2012 study by Dreher, the long-term (9 years) post RFT results for fifty-three ambulatory patients with spastic diplegic CP were analyzed. This study's subject pool had greater homogeneity than the previous long-term studies mentioned and also a longer post-operative phase. The inclusion criteria for this study were as follows: age 6 to 16 years at the time of surgery; a standardized follow up exam one year after surgery; and, a positive pre-operative Duncan-Ely sign. The exclusion criteria for this study were as follows: previous orthopedic surgical intervention in the lower extremities; botulinum toxin injection less than six months prior to the SEML; patients with dyskinetic CP; and, relevant secondary surgery between the short-term and long-term post-operative gait analysis. The fifty-three subjects that qualified for the study were divided into two groups based on pre-operative gait presentations. Those subjects that displayed decreased peak knee flexion during the swing phase of gait and underwent a RFT to correct this gait deviation were placed in a correction group titled "C-DRFT". The C-DRFT group contained 66 limbs in 33 patients. Those subjects that displayed typical or increased peak knee flexion and underwent a RFT were labeled as having a prophylactic procedure and were placed in a prophylactic group titled “P-DRFT”. The P-DRFT group contained 20 patients with 40 limbs. Most patients in this study underwent a transfer of the distal rectus tendon to the gracilis (98 legs in 49 patients). Those subjects that did not have a transfer to the gracilis underwent a transfer of the rectus tendon to the semitendinosus (eight legs in four patients). There were several interesting findings within this study. In terms of increased peak knee flexion, this study found “a significant increase of peak knee flexion in swing for the C-DRFT group, with a significant decrease in the P-DRFT group”. Further, this finding remained true at long-term follow up with the long-term peak knee flexion in swing remaining significantly increased in the C-DRFT group while it remained significantly decreased in the in the P-DRFT group.[45]

In regards to the timing of peak knee flexion, this study also found significant improvement in the C-DRFT group at one year post surgery with maintenance at long-term follow up. No significant changes in timing were found in the P-DRFT group. Finally, the overall swing phase knee flexion was found to be significantly improved for both groups at one year post-operatively. This increase was found to be significantly higher for the C-DRFT group.[45] At long-term follow up this goal was found to be maintained in the C-DRFT group but not in the P-DRFT group.

The authors of this study stated “long-term results showed that the improvements in knee kinematics could be maintained and even enhanced nine years after surgery in the C-DRFT group”.[45] They further stated that “the overall good results nine years after surgery indicate that the RFT carried out as part of a multilevel surgery is an effective approach for the treatment of stiff-knee gait”.[45] The author further stated: “we showed that patients with more involvement have more potential benefit from distal rectus femoris transfer”.[45] This last statement gives direction for future surgical outcomes research for the ambulatory child with CP. Analysis of surgical outcomes measures given specific pre-operative functional levels for patients is increasing and showing interesting results.[39] In order to assist with surgical treatment planning, outcomes research for the ambulatory child with CP is attempting to more accurately define and analyze which subtypes of patients benefit most from specific surgical interventions.

PHYSICAL THERAPY

Post-operative physical therapy (PT) is an essential part of the success of the SEMLS. With multiple orthopedic soft tissue surgical interventions occurring during one single surgical event, and at times bony corrections also occurring during this event, long-term rehabilitation is needed to assist the patient and family with rehabilitation. The post-SEMLS rehabilitation process includes both the initial recovery from the new post-operative impairments as well as PT to maximize the newly gained range of motion and improved biomechanical alignment for an overall improvement in gait and function.[49] Varying institutions, orthopedic surgeons, and surgical procedures have varying post-SEMLS rehabilitation protocols. Unfortunately, "long-term management following SEMLS has received little attention within the PT literature".[49] In a 2010 article on the long-term PT management following SEMLS, a case study is used to examine physical therapy for children post SEMLS.[49] This article gives an overall review of the various orthopedic surgical procedures that may be needed by the child with CP to improve ambulation once conservative measures have proven ineffective. It also provides a review of some of the rehabilitation protocols and treatment techniques used to treat these children. While this article highlights the limited PT literature on this topic, it also exposures several reasons as to why physical therapists need to increase their involvement in this area of research.

First, the article choose to examine the five following outcome measures: Gross Motor Function Measure-66 (GMFM-66), goniometry, manual muscle testing (MMT), numerical pain rating scale (NPRS), and Activity Scale for Kidsperformance38 (ASKp38). The GMFM-66 and the ASKp38 assess patient activity level while the NPRS, goniometry, and MMT quantify impairments of body structures.[49] While the mixture of functional and impairment measures are needed to get an accurate picture of the patient's outcome, there appears to be a lack of specific gait measurements. While a motion analysis laboratory is needed to measure GDI and TAG, other gait measures such as stride length and timed walking distance could be measured in the clinic in order to add a gait specific measure to this research. Investigation into which specific gait measure or measures should be used post-SEMLS intervention would be helpful for the PT working with these children. It would also be beneficial for therapists to know if certain post-SEMLS measures of gait or function have sensitivity issues or could possibly behave differently with differing types of CP patients.

OUTCOME MEASURES

Gross Motor Function Classification System

To help with the task of attempting to analyze outcomes in children with CP, the literature provides several useful measures and scales that assist the researcher. The following is a review of the measures and scales used within these three studies. The first is the Gross Motor Function Classification System (GMFCS). This is a classification system of the gross motor function of children with CP that is widely accepted and used in the literature. The GMFCS was developed in 1997 by Palisano, et al.[27] The GMFCS levels are a classification system designed to classify children with CP according to their mobility level.[27] There are five levels in the GMFCS classification system. Level I represents the most functional level, with the child being able to independently ambulate without an assistive device. Level V represents children with the most limited mobility and refers to those children who use powered mobility. Use of the GMFCS levels with research in children with CP has become common; and, there exists extensive literature on GMFCS levels.[27,50-53] It was revised and expanded in 2007 by providing greater detail for the clinician or researcher to accurately assign the appropriate level.[54] For research purposes, GMFCS levels help to group children with CP based on their functional mobility level. Research has shown that outcomes can differ depending on the functional mobility of the child prior to the intervention. This is an important consideration when designing and analyzing outcomes research. It is standard practice in the Houston SHC MAL to assign a GMFCS level for each patient as part of every gait study, the interrater reliability for assigning GMFCS level was found to be 0.84.[51]

Pediatric Data Collection Instrument

Another tool used in this study and developed for the functional outcomes assessment of children with musculoskeletal heath issues, such as CP, is the Pediatric Outcomes Data Collection Instrument (PODCI).[40] The PODCI is a questionnaire for parents of children or adolescents between the ages 2–18 years. It can also be administered to children between the ages of 11 to 18 years. The entire PODCI questionnaire has 55 items with seven different domains. Two of the domains, Physical Function & Sports and Transfers & Mobility, were used as outcome measures for this study. There are 13 items on the Physical Function & Sports domain, with an internal consistency of .93 and a test-retest reliability of .93. There are 11 items on the Transfers & Mobility domain, with an internal consistency of .95 and a test-retest reliability of .96.[40] The score range is 0 to 100.[40] The PODCI has been found to have internal consistency; interrater and intrarater reliability; and, concurrent, discriminant and evaluative validity.[26] The PODCI was “originally designed to carry out a functional assessment of children and adolescents (including those with cerebral palsy) focusing on musculoskeletal health”.[55] The development of the PODCI was a combined effort of the Pediatric Orthopaedic Society of North American, the American Academy of Orthopaedic Surgeons, the American Academy of Pediatrics, and the Shriners Hospitals for Children. There has been much literature on the PODCI and its use in children with CP.[26,41,56-58] A 2012 article performed a Rasch analysis of the PODCI on 720 patients with CP and found “in summary the PODCI generally performed well in patients with cerebral palsy in terms of fit statistics, scaling and separation”.[55] While there were some recommendations in this article for improvements to the scale, those recommendations were based only on subjects with a GMFCS level I, II or III. Unfortunately, no children functioning at a level IV were included in this study.

Gait Deviation Index

The Gait Deviation Index, known as the GDI, is another tool that is used for outcomes research. The GDI is a normative gait index that is designed to represent how typical or atypical a patient walks based on the range of motion of their pelvis and lower extremities during gait. In the 2008 article that introduced the GDI, it was referred to as a “comprehensive quantitative gait index”.[29] The GDI is based on multiple data points from nine motion analysis kinematic plots (3 pelvic, 3 hip, 1 knee and 2 ankle/foot) that are compared to typical range of motion values. A patient’s GDI is designed to indicate the degree of deviation demonstrated in the range of motion of the lower limbs during ambulation. It is calculated by applying advanced mathematical logarithms to these nine kinematic plots which produces a GDI score for each limb, therefore producing a left GDI and right GDI. These two single limb GDI scores are averaged together to produce one single score, referred to the GDI. One author was found to refer to this number as the mean GDI (mGDI), however most authors appear to reference this average as simply the GDI.[37] The range of the GDI score is 0 to 100. A score of 100 presents a typical or “normal” walking pattern based on the range of motion exhibited in the pelvis, hips, knees, ankles and feet during gait. The standard deviation for this measure is 10. The lower the GDI score, the greater the magnitude of gait deviation from typical.[36] The face and construct validity of the GDI as a classification tool has been examined.[29,30,32] The GDI was originally designed as a means to classify the patient in terms of degree of gait pathology. The change in the mGDI (pre-intervention versus post-intervention) is now being used as an outcome measure in a number of patient populations.[31,36-38]

Spatiotemporal Parameters of Gait

The next two outcome measures used within this research are stride length and walking velocity which are also known as spatiotemporal measures (STM). These are two common gait measures that are used often when examining the gait of children with CP. A 2007 article evaluated interventions used to improve gait in CP using a meta-analysis of spatiotemporal measures to evaluate treatment outcome in the CP population.[59] In this article the authors states "the most widely used measures to document changes in gait have been spatiotemporal measures, most typically walking velocity, cadence, and stride length".[59] Various research studies have used velocity as an outcome measure and correlated it to other measures.[60-62]

Surgical Technical Achievement Goals

Finally the last outcome measure used within this outcomes research study are a series of specific surgical technical achievement goals (TAGs) associated with the individual surgical procedures involved in this study. This particular list of procedure specific technical achievement goals (TAGs) was developed at SHC in Houston in 1994 by a team of motion lab physical therapists and orthopedic surgeons. See Appendix C for the complete this of TAGs and their associated criteria to determine if each goal is met. This TAGs list was created by combining common motion analysis and clinical measures used in the literature for outcome assessment. In addition several well-known motion labs and experts in the field of pediatric orthopedics were surveyed during its development. Research studies that are able to use motion analysis gait data or instrumented gait data have the ability to provide a greater amount of detailed information on the walking patterns of each subject. The TAGs assessment is only able to be fully analyzed when motion data is available for review. Examples of the type of motion data that is needed in order to analyze the TAGs associated with the various lower extremity surgical procedures are: exact timing (percentage of swing phase) to peak knee flexion during swing; exact amount of knee flexion at initial contact and at midstance; amount of total knee motion used throughout the gait cycle; and the exact degree of plantar flexion occurring during stance.

Technical achievement goals, or TAGs, also include goals based on clinical exam data in addition to the instrumented gait data. Examples of clinical goals would be improvement of the popliteal angle by 10 degrees, or improvement in hip abduction range by 10 degrees. The use of TAGs has been part of the technical outcome assessment of orthopedic surgical intervention for the ambulatory child with CP at SHC Houston since 1994. The TAG assessment is a standard component of every long and short post-operative gait analysis. In addition, the TAGs assessment serves as part of a yearly surgical outcomes review for the medical executive committee at SHC in Houston. These TAGS are both procedure specific and limb specific. There is a set of descriptive criteria associated with each goal in order to assist the reviewer in determining if the goal was either “met” or “not met.” See Appendix A for a list of TAGs with their associated criteria.

CHAPTER III

STUDY ONE: EXPLORATION OF RELATIONSHIPS OF TECHNICAL GAIT MEASURES AND FUNCTIONAL GAIT MEASURES IN PATIENTS WITH CEREBRAL PALSY

BACKGROUND

One way in which Motion Analysis Laboratories (MAL) present outcome analysis data is by “technical” and “functional” outcome measures.[28] Two technical gait outcome measures that are used at the Shriners Hospitals for Children (SHC) MAL in Houston are the Gait Deviation Index (GDI) and Technical Achievement Goals (TAGs). The GDI is a commonly used MAL pathologic gait index. [29-32] TAGs are a set of surgical Technical Achievement Goals developed at SHC-Houston MAL.[33] TAGs are presented as a percentage of the number of surgical goals achieved divided by the total number surgical goals; this percentage is referred to as the TAG %.

When reviewing surgical outcomes literature for the ambulatory child with CP there is a wide variety of outcome measures.[13] There is also limited literature on how these measures relate to each other and how they may change with differing types of CP at varying ambulatory or functional levels.[33-35,39] In addition with the use of the GDI as an outcome measure growing rapidly in the literature, improved understanding of the GDI and how it relates to other outcome measures would be beneficial.[36-39] For example in a 2011 article, one author found that a moderate inverse relationship between the pre-operative GDI and the amount of improvement in the GDI.[39] This moderate inverse relationship was also found in subsequent research.[33] These findings assist the clinician with interpretation of the post-operative gait analysis results with an enhanced understanding that patients with higher pre-operative GDI values may not show as much improvement in there GDI scores post-treatment as compared to those patients that have lower pre-operative GDI scores. Therefore, this measurement characteristic of the GDI should be considered when using the GDI to measure treatment outcomes.

While previous research has revealed that TAGs and GDI have a low correlation to each other (thus supporting their continued use as a set of technical outcome measures), there appears to be limited literature on how these two technical gait outcome measures relate to other functional outcome measures of gait.[33] Since functional outcome is a critical component of surgical outcomes analysis, examination of how technical outcome measures relate to functional outcome measures is important. The functional outcome measures chosen to be examined in this study are as follows: stride length; walking velocity; transfers and mobility domain of the Pediatric Outcome Data Collection Instrument (PODCI); and, the sports and physical functioning domain of the PODCI. The PODCI is a reliable and validated commonly used functional outcome questionnaire within this population.[40,41]

Expanding our knowledge as to how technical gait measures relate to functional gait measures should help improve our overall understanding of the surgical outcomes analysis for the ambulatory child with CP.

PURPOSE AND HYPOTHESIS

This is a two part study. The purpose of part one is to examine the relationships between two technical gait measures (GDI and TAG %) and four functional gait measure (walking velocity; stride length, PODCI Transfers & Mobility; and, PODCI Sports & Physical Function) used during post-operative outcome analysis. Examination of these relationships will occur for the entire group and then repeated for three subgroups to determine if these relationships change when examined with different patient involvement types (Diplegic vs. Hemiplegic) at differing ambulatory levels (GMFCS levels I, II, III) and in the presence or absence of prior orthopedic lower extremity surgery. While previous research has examined the relationship between the TAGs and GDI, the relationships between these two technical gait measures and functional gait measures have not yet been examined

While the main purpose of part one is to examine the relationships between technical and functional post-operative measures, one pre-operative relationship will be also be examined in this study. The relationship between the pre-operative GDI and the degree in improvement of the post-operative GDI will be examined for the entire group as well as for each of the three subgroups to determine if an inverse moderate relationship exists between these two variables.

The purpose of part two of this study is to examine the mean differences between the outcome measures for the whole group as well as for each of the subgroups. The mean differences between each of the measures, except for the TAG %, will be examined using parametric measures. The mean differences between groups for TAG % will be examined separately because there is no pre-operative TAG value and due to the ordinal nature of this variable. There are six total scientific hypotheses for this study, they are as follows:

Part One

1) There will be significant correlations between the GDI and the functional gait outcome measures of walking velocity, stride length, PODCI Transfers, and PODCI Sports when the group is examined as a whole and by type of involvement (Diplegic and Hemiplegic), functional ambulatory level (GMFCS I, II, III), and by presence of prior surgery.

2) There will be significant correlations between the TAG % and the functional gait outcome measures of walking velocity, stride length, PODCI Transfers, and PODCI Sports when the group is examined as a whole as well as for each of the subgroupings.

3) There will be a significant weak to moderate correlations between the post-operative GDI and TAG % for the entire group as well as significantly different correlations between each of the subgroupings.

4) There will be significant negative, moderate correlations between the pre-operative average GDI and the amount of post-operative improvement in the GDI for the entire group as well as for each of the sub-groups.

Part Two

5) There will be significant differences between the pre and post-operative mean values for the whole group as well as for each of the subgroups for the following five measures of gait outcome: walking velocity, stride length, PODCI Transfers, and PODCI Sports.

6) There will be significant differences between the TAG % for each of the subgroups.

METHODS

Study Design

This study took place at the SHC MAL in Houston, Texas. After an extensive chart review of over 600 subjects, 169 were found to have the complete pre-operative and post-operative data needed for this study. Of those 169 subjects, 100 met all the inclusion and exclusion criteria. The inclusion criteria for this study were as follows: children with hemiplegic or diplegic spastic CP functioning at a GMFCS level I, II or III with a history of undergoing a SEML at SHC in Houston. The exclusion criteria for this study were as follows: history of dorsal rhizotomy or baclofen pump placement; presence of significant comorbidity; classified as asymmetrical diplegic CP; or noted to have unknown etiology of CP. Significant comorbidity for the purposes of this study were defined as any history in the medical record of the following: seizures; ventriculoperitoneal (VP) shunt; cognitive issues; vision issues; atypical post-operative course; atypical or unknown cause of CP; and, a significant leg length discrepancy greater than two centimeters.

Data Collection

The data for this study was collected between January 1994 and October 2011 at the MAL in SHC-Houston using three-dimensional lower extremity kinematic data; all collected and analyzed using the VICON system (VICON, Oxford Metrics, Oxford. U.K.). Since the data collection for this retrospective study spanned 17 years, it incorporated several upgrades in the VICON hardware and software.   A brief history of the hardware and software updates are as follows. In 1994, the MAL was collecting data using the VICON 370 system with Vicon Clinical Manager (VCM) gait analysis software and six infra-red cameras collecting at a sampling rate of 50 hertz. In 2006, the system was upgraded to the VICON 612 and included eight infra-red cameras collecting at a sampling rate of 60 hertz, with continued use of VCM gait analysis software. In 2009, the system upgraded to its current configuration which is the VICON Nexus with Plug in Gait; and, data was collected with an updated eight infra-red camera system at a sampling rate of 120 hertz. Plug in Gait is the next generation of VCM gait analysis software and uses the same modeling principles of three dimensional gait analysis.

While hardware and software updates occurred over the 17 years of data collection, the data for this study was consistently collected over the years with the same marker alignment principles and the same model, the conventional gait model. With each system update, backwards compatibility of gait analysis data was maintained and ensured through dual processing of data for several months to a year prior to making a complete changeover. In addition, the policy of the MAL required pre and post-operative data collection conditions to remain consistent.

During all data collection, trained physical therapists performed the physical exam, patient set up, data collection and data processing. Marker set up included bilateral thigh and tibial wands, which were placed on the lateral aspect of the patient's lower limbs. Wands currently consist of a 14 mm marker placed a distance of 4.5 cm from a plastic base, with a 3 cm width and a 13 cm length. To reduce soft tissue artifact, thigh wands were placed on the distal one-third of the distance between the greater trochanter and lateral femoral epicondyle and between the lateral femoral epicondyle and lateral malleoli. An additional nine reflective markers (currently 14 mm in size) were placed on the pelvis and lower extremities in the following locations: bilateral anterior superior iliac spines; mid distance between the posterior superior iliac spines which is over the second sacral vertebra; bilateral lateral femoral epicondyles; bilateral lateral malleoli; the second metatarsophalangeal joint dorsally; and, calcaneal tuberosity.

Before each data collection the volume of recording space and motion cameras were calibrated allowing for correct three dimensional temporal marker tracking. Protocol for data collection included a static trial of the patient standing still prior to walking to provide joint centers for each subject based on the individual's anthropometric measurements. For data collection, patients were instructed to walk at a self-selected pace over a level ten meter walkway in bare feet with or without their assistive device, depending on patient ability. Three embedded force plates (1000 Hz) were located in the middle of the walkway and time synchronized to the Vicon system through an analog to digital converter. A minimum of three walking trials were collected and processed. Initial foot contact and toe-off were identified by the force plates and estimated throughout the entire walking path. Therapists verified visually foot strikes and toe-offs, processed data and selected one walking trial that was most representative of the subjects' gait pattern. This walking trial was labeled the representative trial and gait data from this representative trial was used for the research data.

Data Analysis

All statistical analysis was performed using SPSS 22.0 for Windows (Chicago, IL). The data was reviewed and screened for outliers and for statistical assumptions such as normality. Pearson r correlations were run on all the measures except for the TAG measure. Since the TAG % does not meet the requirements of a true interval variable, nonparametric tests were utilized to examine this measure. Therefore Spearman r correlations were run for the TAG % measures.

Subject Pool

After reviewing 600 charts, 100 subjects met the criteria for this study and thus made up the study group. For reader convenience and understanding of the processes of this study, the whole group demographics are presented first followed by the subgroup demographics. Table 1 presents the mean age of subjects at the time of the orthopedic surgical intervention as well as the average pre-operative GDI for the entire group. Table 2 presents key demographics for the whole group.

Table 1. Whole Group Age at Surgery (Sx) and Pre-operative GDI

Whole Group N=100	Mean Age	SD	Min	Max
Age at Sx	10.3	3.5	4.5	18.2
Pre-op GDI	61/9	11.5	37.0	94.8

Table 2. Key Demographics for the Whole Group

Ethnicity	Caucasian	32
	African American	19
	Hispanic	46
	Other	3
Gender	Male	63
	Female	37
Pattern of Involvement	Hemiplegic	19
	Diplegic	81
GMFCS Level	Type I	13
	Type II	46
	Type III	41
Previous Surgery	No	65
	Yes	35

Since reporting the number and types of orthopedic surgical procedures that have been experienced by the entire group is helpful in understanding the group demographics, Table 3 lists the number and types of surgeries undergone by the whole group.

Table 3. Number and Types of Surgeries Undergone by the Whole Group

Surgical Procedure N = 100, Limbs = 200	Number Preformed
Hamstring Lengthening	140
Rectus Transfers	133
Tendo-Achilles Lengthening	120
Adductor Tenotomy	90
Femoral DRO	29
Lateral Column Foot Surgery	14
Tibial Osteotomy	13
Psoas Lengthening	11
Medial Column Foot Surgery	8
Anterior Tibialis	10
Posterior Tibialis Lengthening	8
Peroneal Lengthening	2

Since the whole group was subdivided and analyzed by three subgroupings (Level of Involvement, GMFCS Level, and Presence of Prior Surgery), overall demographics are also presented by these three subgroupings in Table 4.

Table 4. Type of Involvement - Age at Surgery and Pre-operative GDI

Diplegic Group N=81	Mean Age	SD	Min	Max
Age at Sx	10.0	3.6	4.5	18.2
Pre-op GDI	59.94	11.0	37.0	86.7
Hemiplegic Group N= 19				
Age at Sx	11.24	3.1	7.3	17
Pre-op GDI	70.4	9.4	60.1	94.7
GMFCS Level I N = 13				
Age at Sx	12.4	3.7	5.7	18.2
Pre-op GDI	70.6	8.4	60.8	87.5
GMFCS Level II N = 46				
Age at Sx	10.8	3.3	5.3	17.8
Pre-op GDI	66.7	9.8	39.0	94.7
GMFCS Level III N = 41				
Age at Sx	9.1	3.1	4.5	16.3
Pre-op GDI	53.7	8.6	37.0	79.8
No Previous Surgery N = 65				
Age at Sx	9.9	3.5	5.4	18.2
Pre-op GDI	61.7	12.5	37.0	94.7
Previous Surgery N = 35				
Age at Sx	11.2	3.4	4.5	17.4
Pre-op GDI	62.3	8.4	49.5	79.8

RESULTS

Part One

The first three scientific hypotheses for this study involve significant correlations between the various measures within this study. The first scientific hypothesis for this study is the presence of significant correlations for the whole group and for each of the subgroups between the GDI and the functional gait measures of: walking velocity; stride length; PODCI Transfers; and PODCI Sports. The results are presented first for the entire group analysis and then for the subgroup analysis. The Pearson r correlations between GDI and velocity, stride length (SL), PODCI Transfers and Mobility (P-T), and PODCI Sports and Physical Function (P-S) are presented below in Table 5. The correlations among the other measures are also included for interest. All correlations between the GDI and the other gait measures were found to be significant for the whole group.

Table 5. Pearson (2-tailed) Correlations for Five Gait Outcome Measures

Whole Group N = 100	GDI	Velocity	SL	P-T	P-S
Velocity	.510***				
Stride Length (SL)	.502***	.829***			
PODCI Transfer (P-T)	.442***	.626***	.642***		
PODCI Sport (P-S)	.394***	.454***	.454***	.705***	

***p <. 001. **p < .01. *p < .05

Next, the same Pearson r correlations were re-run for each of the three subgroups (Type of Involvement, GMFCS Level and Prior Surgery) to determine if the relationships between the GDI and the other variables remained significant when examined by subgroup. The results of these analyses are presented below in Table 6 through 8. For the level of involvement subgroupings, all GDI correlations were significant for the diplegic group. No GDI correlations were found to be significant for the hemiplegic group; however this subgroup only had 19 subjects.

Table 6. Pattern of Involvement - Pearson (2-tailed) Correlations

Involvement		GDI	Velocity	SL	P-T
Diplegic Group N = 81	Velocity	.476***			
	Stride Length (SL)	.457***	.821***		
	PODCI Transfer (P-T)	.404***	.592***	.611**	
	PODCI Sport (P-S)	.287**	.407***	.402**	.678**
Hemiplegic Group N = 19	Velocity	.212			
	Stride Length (SL)	.214	.683**		
	PODCI Transfer (P-T)	.208	.653**	.604**	
	PODCI Sport (P-S)	.408	.412	.339	.729***

***p <. 001. **p < .01. *p < .05

For the GMFCS level subgroupings, the only significant GDI correlation found was with velocity for the Level III group. See Table 7 for details.

Table 7. GMFCS Levels - Pearson (2-tailed) Correlations

GMFCS Level I N = 13	GDI	Velocity	SL	P-T
Velocity	.078			
Stride Length (SL)	-.088	.684*		
PODCI Transfer (P-T)	.361	-.171	.100	
PODCI Sport (P-S)	.332	-.163	.056	.859***
GMFCS Level II N = 46	GDI	Velocity	SL	P-T
Velocity	-.291			
Stride Length (SL)	-.138	.498***		
PODCI Transfer (P-T)	-.196	.312*	.407**	
PODCI Sport (P-S)	.084	.320*	.330*	.504***
GMFCS Level III N = 41	GDI	Velocity	SL	P-T
Velocity	.342*			
Stride Length (SL)	.200	.679***		
PODCI Transfer (P-T)	.134	.261	.290	
PODCI Sport (P-S)	.069	.531	.042	.550***

***p <. 001. **p < .01. *p < .05

For the Previous Surgery subgroupings, all GDI correlations were found to be significant in the No Previous Surgery subgroup. In the Previous Surgery subgroup, the only significant GDI correlations were that between velocity and PODCI Transfers. See Table 8 below.

Table 8. Previous Surgery Group - Pearson (2-tailed) Correlations

No Previous Surgery N = 65	GDI	Velocity	SL	P-T
Velocity	.571***			
Stride Length (SL)	.567***	.814***		
PODCI Transfer (P-T)	.409**	.643***	.683***	
PODCI Sport (P-S)	.419**	.436***	.427***	.676***
Previous Surgery N = 35	GDI	Velocity	SL	P-T
Velocity	.406*			
Stride Length (SL)	.396	.879***		
PODCI Transfer (P-T)	.422*	.617***	.663***	
PODCI Sport (P-S)	.273	.476***	.556***	.700***

***p <. 001. **p < .01. *p < .05

The second scientific hypothesis for this study is the presence of significant correlations for the whole group and for each of the subgroups between the TAG % and the functional gait measures of: walking velocity; stride length; PODCI Transfers and Mobility; and PODCI Sports and Physical Function. Since the TAG % is an ordinal variable, Spearman r correlations were run to examine these relationships, see Tables 9 through 12 for details. This hypothesis was found to be supported for the whole group, diplegic group, and no previous surgery group.

Table 9. Spearman Correlations for TAG % & Post-op Gait Outcome Measures

Whole Group N = 100	TAG %
GDI	.484***
Velocity	.318***
Stride Length (SL)	.259***
PODCI Transfer (P-T)	.285***
PODCI Sport (P-S)	.272***

****p* <. 001. ***p* < .01. **p* < .05

Table 10. Pattern of Involvement – TAG % Spearman Correlations

Diplegic Group N = 81	TAG %
GDI	.424***
Velocity	.307**
Stride Length (SL)	.271*
PODCI Transfer (P-T)	.259*
PODCI Sport (P-S)	.232*
Hemiplegic Group N = 19	TAG %
GDI	.422
Velocity	-.005
Stride Length (SL)	-.288
PODCI Transfer (P-T)	.154
PODCI Sport (P-S)	.184

****p* <. 001. ***p* < .01. **p* < .05

Table 11. GMFCS Levels – TAG % Spearman Correlations

GMFCS Level I N = 13	TAG %
GDI	.323
Velocity	.006
Stride Length (SL)	.006
PODCI Transfer (P-T)	.113
PODCI Sport (P-S)	.357
GMFCS Level II N = 46	TAG %
GDI	.310*
Velocity	.000
Stride Length (SL)	-.236
PODCI Transfer (P-T)	-.053
PODCI Sport (P-S)	.109
GMFCS Level III N = 41	TAG %
GDI	.250
Velocity	-.010
Stride Length (SL)	.121
PODCI Transfer (P-T)	.082
PODCI Sport (P-S)	.070

***p <. 001. **$p < .01$. *$p < .05$

Table 12. Previous Surgery Group – TAG % Spearman Correlations

No Previous Surgery N = 65	TAG %
GDI	.440***
Velocity	.429***
Stride Length (SL)	.283*
PODCI Transfer (P-T)	.301*
PODCI Sport (P-S)	.334**
Previous Surgery N = 35	TAG %
GDI	.543**
Velocity	.096
Stride Length (SL)	.230
PODCI Transfer (P-T)	.056
PODCI Sport (P-S)	.035

***p <. 001. **$p < .01$. *$p < .05$

The third scientific hypothesis for this study is the existence of significant weak to moderate correlations between the post-operative GDI and the TAG %. Spearman r correlations were run between these two variables for the entire group and for each of the subgroupings. The results are presented below in Table 13. This hypothesis was found to be supported for all groups except the GMFCS level I and level III groups, which were weak to moderate but not significant.

Table 13. Post-Operative GDI and TAG %

		TAG %
Whole Group	Post-operative GDI	.484***
Diplegic Group	Post-operative GDI	.424***
Hemiplegic Group	Post-operative GDI	.422***
GMFCS Group I	Post-operative GDI	.323
GMFCS II Group	Post-operative GDI	.310*
GMFCS III Group	Post-operative GDI	.250
Prior Sx Group	Post-operative GDI	.440***
No Prior Sx Group	Post-operative GDI	.543***

***p <. 001. **p < .01. *p < .05

The fourth scientific hypothesis for this study was the existence of significant negative, moderate correlations between the pre-operative GDI and the improvement of the GDI post treatment for the whole group and for each of the subgroupings. This hypothesis was found to supported for all groups; see Table 14 below for details.

Table 14. Pre-operative GDI and Improvement in GDI

		Improvement in GDI
Whole Group	Pre-operative GDI	-.516***
Diplegic Group	Pre-operative GDI	-.534***
Hemiplegic Group	Pre-operative GDI	-.667**
GMFCS I Group	Pre-operative GDI	-.662*
GMFCS II Group	Pre-operative GDI	-.594***
GMFCS III Group	Pre-operative GDI	-.745***
Prior Sx Group	Pre-operative GDI	-.371*
No Prior Sx Group	Pre-operative GDI	-.565***

***p <. 001. **p < .01. *p < .05

Part Two

Part two of this study examined the mean differences between groups. A table of the mean pre and post-operative values with their standard deviations and standard errors is provided below.

Table 15. Whole Group Pre and Post-operative Means

Whole Group N = 100	**Mean**	**SD**	**Std. Error**
GDI			
Pre-op	61.9	11.45	1.1
Post-op GDI	73.3	10.57	1.1
Stride Length			
Pre-op Stride Length	.83	.23	.02
Post-op Stride Length	.86	.21	.02
Velocity			
Pre-op Velocity	.83	.32	.03
Post-op Velocity	.81	.30	.03
PODCI			
Pre-op Transfers & Mobility	77.1	16.6	1.7
Post-op Transfers & Mobility	81.6	13.3	1.3
PODCI			
Pre-op Sports & Phys. Fn.	50.0	20.1	2.0
Post-op Sports & Phys. Fn.	56.0	20.3	2.0

The fifth scientific hypothesis for this study is the existence of significant differences between the pre and post-operative mean values for the whole group as well as for each of the subgroups for the measures of walking velocity, stride length, GDI, PODCI Transfers and PODCI Sports. For the whole group this hypothesis was found to be supported for the GDI, PODCI Transfers and PODCI Sports measures. Paired samples t-tests were run between the pre-operative and post-operative means of each of the five out of the six measures. Paired t-tests were run on the above means and found a significant difference in the GDI score, *t*(99) = -11.5, p<.001, indicating improvement in walking pattern. A significant difference was also found between the pre-operative and post-operative means of the two PODCI measures. The PODCI Transfers & Mobility domain was found to significantly improve, *t*(99)= -3.6, *p*<.001. The PODCI Sports & Physical Functioning domain was also found to significantly improve, *t*(99) = -.4.6, *p*<.001. No significant differences were found for walking velocity or step length.

To test this same hypothesis for the subgroupings (pattern of involvement, GMFCS level and prior surgery), it was decided to examine the differences between the pre and post-operative means using paired t tests with bootstrapping. Bootstrapping was utilized due to the possible normality issues and in order to avoid a type I error. The alpha for the level of involvement group and prior surgery group was set at .025 while the alpha for the GMFCS group was set at .017

The existence of significant differences between the pre and post-operative mean values for GDI were found for all subgroupings with a *p* value of .001. See Table 16 for details.

Table 16. Bootstrap Paired Samples t-tests for GDI

GDI	Mean	Bootstrap[b]		
		Sig. (2-tailed)	95%Confidence Interval	
			Lower	Upper
Hemiplegic Group	-11.43	.001	-15.89	-6.74
Diplegic Group	-11.32	.001	-13.54	-9.21
GMFCS level I	-13.43	.001	-16.85	-9.69
GMFCS level II	-10.62	.001	-13.49	-7.55
GMFCS level III	-11.49	.001	-14.59	-8.65
No Prior Surgery	-13.21	.001	-15.63	-10.61
Prior Surgery	-7.87	.001	-10.15	-5.4

The existence of significant differences between the pre and post-operative mean values for PODCI Transfers and Mobility was found to be significant for the diplegic and no prior surgery group with a *p* value of .001. See Table 17 below for details.

Table 17. Bootstrap Paired Samples t-tests for PODCI-Transfers

PODCI Transfers & Mobility	Mean	Bootstrap[b]		
		Sig. (2-tailed)	95%Confidence Interval	
			Lower	Upper
Diplegic Group	-5.40	.001	-8.28	-2.47
No Prior Surgery	-5.34	.001	-10.28	-3.56

The existence of significant differences between the pre and post-operative mean values for PODCI Sports and Physical Function were found for the hemiplegic group with a p value of .010; and, for the diplegic, GMFCS level II and no prior surgery group with *p* values of .001. See Table 18 for details.

Table 18. Bootstrap Paired Samples t-tests for PODCI-Sports

PODCI Sports & Physical Fn.	Mean	Bootstrap[b]		
		Sig. (2-tailed)	95%Confidence Interval	
			Lower	Upper
Hemiplegic Group	-8.89	.010	-13.84	-3.21
Diplegic Group	-5.36	.001	-8.27	-2.46
GMFCS level II	-7.24	.001	-11.52	-3.09
No Prior Surgery	-6.82	.001	-10.28	-3.56

The existence of significant differences between the pre and post-operative mean values for step length were found for only the GMFCS level II group. See Table 19 below for details.

Table 19. Bootstrap Paired Samples T-tests for Step-Length

Step-Length	Mean	Bootstrap[b]		
		Sig. (2-tailed)	95%Confidence Interval	
			Lower	Upper
GMFCS Level II	-.047	.003	-.073	-.020

No significant differences were found between the pre and post-operative mean values for walking velocity for any of the subgroups.

The sixth hypothesis for this study was the existence of significant differences between the TAG % for each of the subgroups. Since this variable is ordinal in nature, nonparametric testing was used to test the differences between groups. An Independent Samples Mann-Whitney U Test was run on the TAG % across the two levels of involvement, with an alpha set at .025. The mean rank for the

TAG % of the diplegic group (*47.11*) differed significantly from the mean rank for the hemiplegic group (*64.95*), U = 495, z = -2.42, p = .016. The same test was also run across the prior surgery group, again with an alpha set at .025. The mean rank for the no surgery group (56.21) was found to be significantly different from the mean rank of prior surgery group (39.90), U =1,507, z = 2.69, p =.007. Finally for the difference in mean ranks of TAG % across the three GMFCS levels, an Independent Samples Kruskal-Wallis Test was run with an alpha set at .017. The TAG % for the GMFCS level I group was found to be significantly different from that of the GMFCS level III, H(3)= 4.27, p< .001. The p values for the TAG % difference between GMFCS level I and II, and GMFCS level II and III had p values of .023 and .036 respectively. Since the alphas for this test were set at .017, these results were not considered significant. See Table 20 below for Kruskal-Wallis test results for the three GMFCS levels.

Table 20. Kruskal-Wallis Testing for TAG % difference for GMFCS Levels

	Test statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.
GMFCS I and II	22.79	9.08	2.67	.012	.036
GMFCS I and III	39.35	9.21	4.27	.000	.000
GMFCS II and III	16.59	6.21	2.67	.008	.023

DISCUSSION

The inverse, moderate correlations found between the pre-operative GDI and the post-operative improvement in GDI within all eight groups of this study offers strong support for the consistent existence of this relationship. This finding should alert researchers that pre-operative or pre-treatment GDI values should be taken into account when using the GDI measure to evaluate the effectiveness of an intervention. This finding also explains the change in the trend of the correlational relationships found between the GDI and the other interval measures in the higher functioning patients such as those found in the GMFCS level I and II groups.

The consistent significant improvement of the GDI across all group, appears to show strong support for improvement in walking ability of ambulatory children with CP through orthopedic surgical intervention. It also appears to support the sensitivity of this measure in this patient population post orthopedic surgical intervention; and therefore, supports the continued use of this measure in this patient population.

The consistent positive, weak to moderate correlations found between the post-operative GDI and the TAG % in all eight groups of this study is consistent with previous research.[33] Previous research found a positive weak to moderate correlation between these two measures supporting their continued use as a team of technical gait outcome measures. In previous research the TAG % was found to have higher achievement rates with higher functioning children while the GDI was found to have higher improvement rates with lower functioning children. This finding also supported their use as a continued set of technical gait outcome measures.

After the GDI measure, the PODCI Sports and Physical Function measure had the most groups show a significant improvement between pre and post-operative means. Significant improvement in the PODCI Sports and Physical Function measure was found in the following groups: hemiplegic, diplegic, GMFCS level II and no prior surgery groups. The PODCI Transfers and Mobility measure showed significant change in pre and post-operative means for the diplegic and no prior surgery groups. While the stride length measure showed a significant difference only in the GMFCS level II group. Interestingly, the difference in pre and post-op walking velocity means was not shown to change significantly in any groups. This finding leads to the consideration that velocity may not be a sensitive measure of change for this patient population after orthopedic surgical intervention.

The limitations of this study included the small sample sizes for the hemiplegic and GMFCS level I groups. Another limitation was the lack of GMFCS level IV patients. Since these patients have greater ambulatory limitations compared to level I, II and III patients, they are seen less often in a motion analysis laboratory.

Future research should attempt multi-center studies with larger subject pools. The strengths of this study included the large sample size that allowed for both whole group and subgroup analyses. Another strength of this study was the reprocessing of retrospective data to obtain GDI information that previously was unknown.

CONCLUSION

The findings of this study support previous research which showed the GDI and TAG % as a solid set of technical gait outcome measures for ambulatory children with CP having lower extremity orthopedic surgery to improve their ambulation. This study also appears to support the use of the PODCI Transfers and Mobility and the PODCI Sports and Physical Function measures as appropriate outcome measures for this patient population. The findings in this study suggest additional investigation is needed into the measure of walking velocity in this patient population after having orthopedic surgery to improve ambulation. The findings in this study suggest that increased walking velocity may not always be among the gait improvements seen in children with spastic CP after having orthopedic surgery to improve their gait. Therefore increased walking velocity may not always be an appropriate outcome measure for this particular patient population after undergoing orthopedic surgery to improve their gait due to the fact that their gait appears to improve while their walking velocity may not.

CHAPTER IV

STUDY TWO: SHORT-TERM AND LONG-TERM SURGICAL OUTCOMES FOR RECTUS FEMORIS TRANSFERS IN PATIENTS WITH CEREBRAL PALSY

BACKGROUND

One common gait deviation that occurs in children with CP is a stiff knee gait.[22,24] Jacquelin Perry describes a stiff knee gait as "having decreased ROM of the knee throughout the entire gait cycle."[25] She also reports that most problems arising from a stiff knee gait occur during the swing phase of gait and create difficulty with limb clearance and pre-positioning of the foot for the next step.[25] When reviewing motion analysis data, a stiff knee gait pattern typically displays one or all of the following characteristics: an inadequate amount of peak knee flexion during the swing; a decrease in the overall range of knee motion throughout the entire gait cycle; and, a delay in the timing to achieve peak knee flexion during the swing phase of gait. It is believed that the primary cause of these gait deviations, or a stiff-knee gait, is increased spasticity in the rectus femoris muscle.[24,39,42,45,63]

A surgical procedure to this muscle, known as a Rectus Femoris Transfer (RFT), is used to improve these gait deviations and therefore improve the child's walking ability. A brief general description of this procedure includes the following: "the distal rectus tendon is dissected from the underlying vasti, then tenotomized near its insertion to the patella and transferred."[9] The tendon is then transferred most commonly to either the tendons of the medial or lateral hamstrings or to the iliotibial tract.[9,45]

The RFT was proposed by Jacquelin Perry in 1987 as a method of reducing the distal effects of the spastic rectus across the knee during the swing phase of gait while preserving the proximal hip flexion action of the rectus.[22,64] It is believed that by transferring the distal attachment of the rectus femoris, the muscle's ability to act as an inappropriate knee extensor during swing is diminished and thereby reduces the various gait deviations associated with the stiff knee gait pattern.[11] Perry also theorized that with this transfer of the distal insertion of the rectus, the muscle would act as a knee flexor rather than a knee extensor during swing.[9,42] While a few studies have challenged whether this transfer procedure actually creates a knee flexion moment across the knee[65-68], many studies have shown significant improvements in the gait of children with CP after having undergone this procedure.[22-24,39,42]

The RFT is considered "the standard surgical procedure for the treatment of stiff knee gait in children with spastic CP."[45] And is believed to be "the most widely accepted orthopedic surgical treatment to specifically address this stiff knee gait deviation".[9] Multiple studies have purported the beneficial effects of this surgical procedure on the gait of children with CP.[9,22-24,42] Three common technical surgical goals associated with the RFT are: improved overall range of knee motion during gait; improved or maintenance of peak knee flexion; and, improved timing of peak knee flexion during swing. The RFT is often combined with a hamstring lengthening procedure; this combination of surgical procedures is considered successful in the treatment of the stiff knee gait pattern for children with spastic CP.[9] These two procedures have become common components with of a Single Event Multilevel Surgery (SEMLS).[12] SEMLS are the new standard of care in regards to lower extremity orthopedic intervention to improve the ambulation of the child with CP.[11]

While many studies have examined the short term post-operative effects of the RFT, only a few have examined the long-term post-operative results of the RFT.[45,47,48] In 2003, Saw examined the long term effects of 26 limbs in 18 patients having undergone a RFT between the years 1992 to 1997.[48] The subject pool was a heterogeneous group of patients with CP that included hemiplegic, quadriplegic, and diplegic children with CP that had undergone a RFT for a stiff knee gait. This study measured four kinematic parameters and three temporal parameters using motion analysis. The kinematic parameters were: minimum hip flexion; total knee range of motion; minimum knee flexion in stance and maximum knee flexion in swing. The temporal parameters were: stride length, cadence, and walking velocity. Analysis of the short-term post-operative gait, approximately one year after surgery, found a significant improvement in maximum knee flexion during swing and in the total knee range of motion. Analysis of the long-term post-operative gait, approximately four and half years after surgery (range 1.7 to 6.7 years), showed the improvement in maximum knee flexion during swing was maintained long-term.

In another long-term study of the RFT procedure by Moreau in 2004, a comparison of two groups of children with CP undergoing SEMLS was performed.[47] One group had undergone a RFT as part of their SEMLS (RFT group) while the other group underwent SEMLS without a RFT (NonRFT group). Both groups were analyzed approximately one year (10 to 18 months range) post-operatively and then again three years or more (3 to 4.5 years range) after surgery. Forty one subjects with either spastic diplegic or hemiplegic CP were included in the study. The following measures were analyzed: overall knee flexion during swing, peak knee flexion in swing, terminal knee extension angle, and, time to peak knee flexion in swing. The long-term findings of the RFT group showed improved peak knee flexion and improved overall knee flexion during swing. This study concluded that “the non-RFT group followed the natural progression of gait in children with CP …with a decline in the peak knee flexion angle in swing…in contrast to the RFT group who appeared to counteract the natural progression of gait in CP with improvements in the peak knee flexion in swing, and overall knee flexion swing range.”[47]

In a 2012 study by Dreher, the long-term (9 years) post RFT results for fifty-three ambulatory patients with spastic diplegic CP were analyzed. The fifty-three subjects that qualified for the study were divided into two groups based on pre-operative gait presentations. Those subjects that displayed decreased peak knee flexion during the swing phase of gait and underwent a RFT to correct this gait deviation were placed in a correction group titled “C-DRFT”. The C-DRFT group contained 66 limbs in 33 patients. Those subjects that displayed typical or increased peak knee flexion and underwent a RFT were labeled as having a prophylactic procedure and were placed in a prophylactic group titled “P-DRFT”. The P-DRFT group contained 20 patients with 40 limbs. This study found “a significant increase of peak knee flexion in swing for the C-DRFT group, with a significant decrease in the P-DRFT group”. Further, this finding remained true at long-term follow up with the long-term peak knee flexion in swing remaining significantly increased in the C-DRFT group while it remained significantly decreased in the in the P-DRFT group.[45] This study also found significant improvement in timing of peak knee flexion for the C-DRFT group at one year post surgery with maintenance at long-term follow up. No significant changes in timing were found in the P-DRFT group. Overall swing phase knee flexion was also found to be significantly improved for both groups at one year post-operatively; this increase was found to be significantly higher for the C-DRFT group.[45] At long-term follow up this goal was found to be maintained in the C-DRFT group but not in the P-DRFT group.

PURPOSE AND HYPOTHESIS

With current literature proposing to replace the RFT with a new mid-rectus lengthening procedure, two questions arise regarding the RFT procedure that would be beneficial to analyze. The first, do surgical technical achievement goals (TAGs) for the RFT procedure maintain achievement in long-term post-operative gait analysis? The TAGs for a RFT procedure with their matching criteria for determining if each goal is met are listed below in Table 21.

Table 21. TAGs for Rectus Femoris Transfer Procedure

RFT Technical Achievement Goal:	**Criteria for Meeting Goal:**
Increase total knee range of motion in gait	Pre/Post Kinematic Plots: increase total range of knee motion during gait cycle, by >= 10°
Maintain/increase swing knee flexion	Pre/Post Kinematic Plots: peak knee flexion during swing phase is within 5 degrees of pre-op value or within 2 SD of normative value
Improve timing of swing knee flexion	Pre/Post Gait Parameters from Kinematic Plots: improve timing of peak knee flexion during swing phase, by at least 5%

The next question to be examined is whether short-term or long-term achievement of TAGs for the RFT procedure differs when analyzed by GMFCS level. As we saw in the review of the three long-term studies reviewed, the trend in surgical outcomes research is to examine our outcome measures with as homogenous a group as possible. This is often challenging given the small subject pools that are typically found in this area of research. However, blending of subjects with various types of CP with various functional ambulatory levels to increase the subject pool size can blur the outcomes of some of the gait outcome measures being examined. Since certain gait measures have been found to behave differently depending on the functional level of the patient, attempting to create homogenous subgroups for outcome analysis is beneficial and may add to the literature on gait outcome measures in this population.

The six scientific hypotheses for this study are as follows:

1) TAGs for the RFT procedure are being achieved in the short-term gait analysis and maintained in long-term gait analysis with at least four out of the six TAGs met in short-term and maintained in long-term analysis for the entire groups.

2) TAGs for the RFT procedure are being achieved in the short-term gait analysis and maintained in long-term gait analysis with at least four out of the six TAGs met in short-term and maintained in long-term analysis for the GMFCS level II group and level III subgroups .

3) There will be a significantly greater number of TAGs met in the GMFCS level II group when compared to the GMFCS level III group for short-term gait analysis.

4) There will be a significantly greater number of TAGs met in the GMFCS level II group when compared to the GMFCS level III group for long-term gait analysis.

5) There will be no significant different between which of the three TAGs are being met in the short-term gait analysis for the entire group as well as for the GMFCS sub-groups.

6) There will be no significant different between which of the three TAGs are being met in the long-term gait analysis for the entire group as well as for the GMFCS sub-groups.

METHODS

Study Design

This study took place at the SHC MAL in Houston, Texas. After an extensive chart review of long-term gait studies for subjects that underwent a RFT procedure as part of a SEMLS, 27 subjects were found to meet the study criteria. The inclusion criteria for this study were as follows: a child with spastic diplegic CP functioning at a GMFCS level II or III who underwent a RFT as part of a SEMLS and returned for both a short-term and long-term follow up gait study.

Since SEMLS are the new standard of care for the ambulatory child with CP, and isolated RFT procedures without other soft tissue intervention or bony intervention are not commonly performed[11], the subjects in our pool had other soft tissue and/or bony interventions concurrently with their RFT procedure. Any subject who underwent a procedure that is not commonly part of a SEMLS was excluded. For instance, subjects that underwent a bony intervention to the foot or those that only received a single surgical procedure were excluded. Since orthopedic surgical procedures vary greatly and can affect subsequent surgical outcome and gait analyses, the subject pool for this study was limited to only those patients with no history of previous lower extremity orthopedic surgery.

The exclusion criteria for this study were as follows: previous orthopedic lower extremity surgery; history of dorsal rhizotomy or baclofen pump placement; presence of significant comorbidity; presence of an atypical SEMLS procedure; undergoing only one surgical procedure; undergoing a foot procedure, classified as asymmetrical diplegic CP; or, noted to have unknown etiology of CP. Significant comorbidity for the purposes of this study was defined as any history in the medical record of the following: seizures; VP shunt; cognitive issues; vision issues; atypical post-operative course; atypical or unknown cause of CP; and, a significant leg length discrepancy greater than two centimeters.

Data Collection

The data for this study was collected between January 1994 and October 2011 at the MAL in SHC-Houston using three-dimensional lower extremity kinematic data; all collected and analyzed using the VICON system (VICON, Oxford Metrics, Oxford. U.K.). Since the data collection for this retrospective study spanned 17 years, it incorporated several upgrades in the VICON hardware and software.   A brief history of the hardware and software updates is as follows. In 1994, the MAL was collecting data using the VICON 370 system with Vicon Clinical Manager (VCM) gait analysis software and six infra-red cameras collecting at a sampling rate of 50 hertz. In 2006, the system was upgraded to the VICON 612 and included eight infra-red cameras collecting at a sampling rate of 60 hertz, with continued use of VCM gait analysis software. In 2009, the system upgraded to its current configuration which is the VICON Nexus with Plug in Gait; and, data was collected with an updated eight infra-red camera system at a sampling rate of 120 hertz. Plug in Gait is the next generation of VCM gait analysis software and uses the same modeling principles of three dimensional gait analysis.

While hardware and software updates occurred over the 17 years of data collection, the data for this study was consistently collected over the years with the same marker alignment principles and the same model, the conventional gait model. With each system update, backwards compatibility of gait analysis data was maintained and ensured through dual processing of data for several months to a year prior to making a complete changeover. In addition, the policy of the MAL required pre and post-operative data collection conditions to remain consistent.

During all data collection, trained physical therapists performed the physical exam, patient set up, data collection and data processing. Marker set up included bilateral thigh and tibial wands, which were placed on the lateral aspect of the patient's lower limbs. Wands currently consist of a 14 mm marker placed a distance of 4.5 cm from a plastic base, with a 3 cm width and a 13 cm length. To reduce soft tissue artifact, thigh wands were placed on the distal one-third of the distance between the greater trochanter and lateral femoral epicondyle and between the lateral femoral epicondyle and lateral malleoli. An additional nine reflective markers (currently 14 mm in size) were placed on the pelvis and lower extremities in the following locations: bilateral anterior superior iliac spines; mid distance between the posterior superior iliac spines which is over the second sacral vertebra; bilateral lateral femoral epicondyles; bilateral lateral malleoli; and the second metatarsophalangeal joint dorsally, and calcaneal tuberosity.

Before each data collection the volume of recording space and motion cameras were calibrated allowing for correct three dimensional temporal marker tracking. Protocol for data collection included a static trial of the patient standing still prior to walking to provide joint centers for each subject based on the individual's anthropometric measurements. For data collection, patients were instructed to walk at a self-selected pace over a level ten meter walkway in bare feet with or without their assistive device, depending on patient ability. Three embedded force plates(1000 Hz) were located in the middle of the walkway and time synchronized to the Vicon system through an analog to digital converter. A minimum of three walking trials were collected and processed. Initial foot contact and toe-off were identified by the force plates and estimated throughout the entire walking path. Therapists verified visually foot strikes and toe-offs, processed data and selected one walking trial that was most representative of the subjects' gait pattern. This walking trial was labeled the representative trial and gait data from this representative trial was used for the research data.

Data Analysis

All statistical analyses were performed using SPSS 22.0 for Windows (Chicago, IL). The data was reviewed and screened for outliers and for statistical assumptions. The number of TAGs achieved was treated as an ordinal variable and analyzed with nonparametric analyses. Related Samples Wilcoxon Signed-Rank tests were conducted for whole group examination of short-term and long-term TAG achievement. Related Samples Freidman's Two-Way Analysis of Variance by Ranks tests were conducted to examine the individual achievement of each of the three individual goals for the whole group. Independent Samples Mann-Whitney U tests were conducted for sub-group GMFCS level II and GMFCS level III comparisons of TAG short-term and long-term achievement.

Subject Pool

After 600 charts were reviewed, 27 subjects (54 limbs) with spastic diplegic CP were found who had met the criteria for the study and had undergone bilateral RFTs as part of a SEMLS at Shriners Hospitals for Children in Houston, Texas with complete motion analysis data. The distribution of the various types of RFTs underwent by the subjects were as follows: 30 transfers to the sartorius; 14 transfers to the gracilis; 6 transfers to the semimembranosus/semitendinosus;

and, 4 transfers medially. Since all subjects had bilateral RFTs, each subject had a total of six TAGs (three goals for the left procedure and three goals for the right procedure). The average subjects' age at surgery was 7.6 years with a range of 5.3 to 15.9 years. The average time between surgery and short-term gait analysis was 13 months, with a range of 8 to 17 months. The average subject's age at short-term gait analysis was 8.7 years, with a range of 6.2 to 16.9 years. The average time between surgery and long-term gait analysis was 5 years with a range of 3.7 to 9.8 years. The average subjects' age at the time of long-term gait analysis was 13 years with a range of 9.9 to 19.6 years. A snap shot of the overall orthopedic surgical procedures undergone by this group were as follows: 54 hamstring lengthenings (25 medial only, 29 medial and lateral); 45 gastroc tendo-achilles lengthenings or TALS (35 V-TALs, 7 Z-TALs, 3 Baker/Hoke TALS); 32 adductor lengthenings ;13 proximal femoral derotational osteotomies (DROs); 3 psoas lengthenings and 2 posterior tibialis lengthenings. Of note, every subject who underwent a RFT also underwent a hamstring lengthening. The GMFCS distribution of this group was 13 level II and 14 level III subjects. Key demographics for the whole group as well as for the two GMFCS sub-groups are presented in Tables 22 and 23.

Table 22. Entire Group Age at Surgery and Pre-operative GDI

		Whole Group (N = 27)
Mean Age at Sx		7.6 yrs. (±2.3)
Age Range		5.3 to 15.6 yrs.
Gender	Male	18
	Female	9
Ethnicity	Caucasian	11
	Hispanic	12
	African American	3
	Other	1
Median TAGS achieved Short-term		67% or 4 out of 6 goals
Mode TAGS achieved Short-term		67% or 4 out of 6 goals
Median TAGS achieved Long-term		83% or 5 out of 6 goals
Mode TAGS achieved Long-term		100% or 6 out of 6 goals

Table 23. Key Demographics for GMFCS Level II and III Sub-groups

	GMFCS Level II (N = 13)	**GMFCS Level III (N = 14)**
Age at Sx	8.5 yrs. (±2.9 yrs.)	6.8 yrs. (±1.3 yrs.)
Age Range	5.3 to 15.9 yrs.	5.3 to 9.3 yrs.
Gender		
Male	8	10
Female	5	4
Ethnicity		
Caucasian	6	5
Hispanic	4	8
African-American	2	1
Other	1	0
Median TAGS Short-term	100% or 6 out of 6	67% or 4 out of 6
Mode TAGS Short-term	100% or 6 out of 6	67% or 4 out of 6
Median TAGS Long-term	100% or 6 out of 6	67% or 4 out of 6
Mode TAGS Short-term	100% or 6 out of 6	67% or 4 out of 6

RESULTS

The first scientific hypothesis of this study was TAGs for the RFT procedure are being achieved in the short-term gait analysis and maintained in long-term gait analysis with at least four out of six TAGs met in short-term and maintained in long-term analysis for the entire group. This hypothesis was found to be supported. For the entire group, the median number of TAGs achieved for both the short-term goals and the long-term goals achieved was five with a mode of four and six respectively (See Table 19). A related samples Wilcoxon Signed Rank Test was run between the median of the short-term goals and median of the long-term goals with an alpha set at .05. No difference was found in the median ranks between the number of short-term TAGs met versus the number long-term TAGS met (*Z*= *-.203, p*=*.839*).

The second scientific hypotheses of this study looks at TAG achievement by GMFCS level and states TAGs for the RFT procedure are being achieved in the short-term and maintained in long-term gait analysis with at least four out of six TAGs met in short-term and maintained in long-term analysis for the GMFCS level II and level III sub-groups. This hypothesis was found to be supported. The median number of TAGS achieved in GMFCS II and III groups was 6 and 4, respectively with identical modes (See Table 20). There were no significant differences in the number of achieved TAGs between short-term and long-term gait analysis for both the GMFCS II and III groups.

The third scientific hypothesis for this study stated a greater number of TAGs would be met in the GMFCS II group when compared to the GMFCS level III group for short-term gait analysis. This hypothesis was found to be supported with a median number of six and four for short-term TAGs achievement in the GMFCS level II and III groups, respectively. An Independent-Samples Mann-Whitney U test found a significant difference in the mean rank of overall short-term goal achievement for the GMFCS level II subjects (17.50) versus the mean rank of overall short-term goal achievement for the GMFCS level III subjects (10.75).

The fourth scientific hypothesis of this study looked at long-term TAG achievement for the differing GMFCS levels and stated there would be a significantly greater number of TAGs meet in the GMFCS level II group when compared to the GMFCS level III group for long-term analysis. This hypothesis was not found to be supported. Although the long-term median TAG achievement for GMFCS level II and III was six and four respectively, the long-term mean rank of the GMFCS level II group (16.65) was not found to be significantly different in the number of goals achieved from the GMFCS level III long-term mean rank (11.54*)*.

The fifth and sixth scientific hypotheses of this study looked at the achievement of the individual three goals; they stated there would be a difference between which of the three individual RFT TAGs are being met in the short-term and long-term analysis for the entire group as well as for the GMFCS subgroups. Both of these hypotheses were found not to be supported. No differences were found in individual goal achievement for short and long-term analysis for the entire group as well as for the GMFCS sub-groups.

DISCUSSION

This study attempted to examine the long-term achievement of surgical technical goals for the RFT procedure for an entire group of children with spastic diplegic CP as well as for that same group divided into two subgroup groups, GMFCS level II and level III. The findings of this study appear to support the belief that the surgical goals for the RFT procedure are being maintained during long-term gait analysis. This finding offers support for the continued use of this particular procedure.

This study also attempted to examine if the achievement of these TAGS are affected by the GMFCS level of the patient, either in short-term or long-term gait analysis. The findings of this study appear to support that the higher functioning patients, GMFCS level II, may achieve a greater number of surgical goals during short-term analysis but not during long-term analysis. This finding is interesting for several reasons. First it agrees with previous research which also found a higher achievement in short-term TAGs for subjects with higher GMFCS levels. This finding makes sense because higher functioning patients, generally have fewer gait deviations and other impairments that affect the achievement of surgical goals. Next, while this finding showed GMFCS level III subjects achieved less short-term TAGs than the GMFCS level II subjects, the GMFCS level III subjects still met four out of the six goals indicating they do indeed achieve these TAGs just at a slightly lesser rate then the GMFCS level II patients. Finally, the lack of a continued significance difference in the achievement of these TAGs long-term between the two GMFCS levels suggests that the level III patients are meeting more of these TAGs during their long-term gait study and perhaps need a longer time period in which to achieve their maximum number of surgical goals. This finding suggests that GMFCS level III patients continue to make improvements in their gait several years after their initial surgical intervention. This is an interesting finding and in accordance with what is often seen clinically during the long-term gait studies. Given the natural progression of gait in these children is to deteriorate, a finding that suggests continued improvement in their gait over the long term is exciting.

CONCLUSION

Rectus femoris transfers have been shown to improve the gait of children and adolescents with CP by achieving the following three technical surgical goals: 1) improved amount of peak knee flexion during the swing phase of gait; 2) improved timing to achieve peak knee flexion during the swing phase of gait; and, 3) improved overall range of knee motion throughout the gait cycle.[22,23,42] However, an alternate rectus femoris procedure, the mid-rectus lengthening, is being proposed to replace the RFT procedure.[9] Since this is a new procedure short-term and long-term gait analysis data are not yet available to compare the outcomes of these two differing procedures.

The rationale for replacing the current RFT with the mid-rectus lengthening appears to be based on two beliefs. The first belief is that the RFT procedures may not maintain their technical goal achievement in long-term follow up. The second belief is that the rehabilitative process is “easier” for patients undergoing mid-rectus lengthenings versus RFTs. This study attempted to address the question of maintenance of RFT surgical goals, or TAGs, in long-term gait analysis.

The findings of this study offer support that the three surgical technical achievement goals (TAGs) for the RFT procedure used at SHC-Houston and commonly seen in the literature are being met and maintained in long-term follow-up for children with spastic, diplegic CP functioning at a GMFCS level II and III. While subjects at GMFCS level II were found to achieve significantly more TAGs in short-term analysis, the GMFCS III subjects apparently continued to make improvements in their TAG achievement during long-term gait analysis. Given the natural progression of gait in these children is to deteriorate; this is an exciting finding in support of the continued use of the RFT procedure when done as part of a SEMLS which includes a hamstring lengthening.

Two limitations of this research study are the limited sample size and the lack of GMFCS level I and level IV subjects. Small subject size is a common limitation across surgical outcomes research in the ambulatory child with CP. A multi-center study looking at the long-term outcomes of the RFT procedure for GMFCS level I through IV would add to the literature. Also a multi-center study examining the difference in short-term and long-term outcomes by GMFCS level for the RFT procedure versus the mid-rectus lengthening would be beneficial once that data is available to be studied. Gait outcomes for a particular intervention can vary depending on the functional ambulatory ability of patients; therefore, looking at rectus intervention outcomes by GMFCS level is important. A multi-center study producing a larger sample size would hopefully have all the ambulatory GMFCS levels represented in the subject pool with sufficient sample sizes so analysis of rectus outcomes for GMFCS level I through level IV could be performed for each intervention type.

FUTURE RESEARCH

This study did not address the second reason for the newly proposed mid-rectus lengthening, which is the easier rehabilitative process for patients undergoing the mid-rectus lengthening versus those undergoing the RFT. Future research should address this belief. Interviews conducted with physical therapists at SHC-Houston, reveal that these physical therapists do believe the rehabilitative process is “easier” for patients undergoing mid-rectus lengthening versus RFTs. Operational definitions to define “easier” included: less painful muscles spasms; shorter period of time to achieve initial post-operative full knee flexion due to pain in quadriceps; shorter period of time to achieve initial post-operative first steps both with and without knee immobilizers. Overall the clinical impression of these physical therapists was that patients undergoing a RFT procedure take approximately 5 days longer to rehab than those patients who underwent mid-rectus lengthenings due to the painful muscle spasms in the quadriceps that often occur during the first week after a RFT procedure.

Future research should be directed toward investigating the possibility of making the rehabilitative process easier for the child undergoing a RFT procedure. A study of differing pain management techniques employed by physical therapists during the rehab of RFT patients could be examined. Another study of differing muscle spasm reduction techniques could also be examined in these patients. Multiple research studies could be employed to investigate how to reduce these painful muscle spasms and improve the post-operative rehabilitation experience for patients undergoing the RFT procedure.

CHAPTER V

STUDY THREE: EXAMINATION OF OUTCOMES FOR SOFT TISSUE ONLY AND SOFT TISSUE WITH BONY CORRECTION SEMLS IN PATIENTS WITH CEREBRAL PALSY

BACKGROUND

The common bony deviations that often present in ambulatory children with CP are referred to as Lever Arm Dysfunction (LAD). Dr. James Gage, one of the leading pediatric orthopedic surgeons at Gillette Children's Hospital, describes LAD as "the alteration in the leverage relationships necessary for normal gait."[15] Dr. Gage states: "in particular, lever-arm dysfunction describes a set of conditions in which internal and/or external lever arms become distorted because of bony or positional deformities".[15] LAD has many secondary complications associated with it, among which are disturbances in the child's gait pattern. Many articles have discussed the presence of LAD in children with CP and have purported the benefits of surgical intervention to improve the lever arm dysfunction and therefore improve the gait of these children. Two of the most common bony deviations found in children with LAD are excessive anteversion of the femur and excessive internal or external tibial torsion. One common surgical procedure used to correct excessive femoral anteversion is known as a Femoral Derotational Osteotomy (FDRO). The common surgical procedure used to correct excessive internal or external tibial torsion is known as a Tibial Osteotomy (TO). These two surgical procedures are often used to correct the

LAD or rotational deviations of the long bones of the lower extremities; they are therefore commonly performed as part of a SEMLS when bony correction is needed in addition to soft tissue intervention.

Looking at surgical outcomes for children who undergo FDROs or TOs is challenging for many reasons. One reason is due to the lack of homogeneity within the subject pool. Since each child with CP presents with a unique set of impairments, medical histories, and social histories, creating a homogenous group for researching outcomes is difficult. Although challenging, surgical outcome research for the ambulatory child with CP is needed to help families make the best possible surgical decisions for their child. Often times, one of the most difficult decisions for families (when it comes to surgery to improve the gait of their child with CP) is whether to address the common bony deviations that often occur in addition to the soft tissue impairments simultaneously along with the soft tissue correction during a single surgical event versus staging these surgeries into separate events. Families often find this decision difficult because the added surgical intervention to the bone translates to: increased time in surgery; increased post-operative pain; and increased rehabilitation time.

For multiple reasons not all children and families are candidates to simultaneously correct both the bony and soft tissue impairments during a single surgery, and so for these children the surgery is staged into two different surgical events. However if the child and family are candidates to undergo both bony and soft tissue corrections during one single surgical event, this treatment offers the advantages of one surgical event and one rehabilitation period.

Correcting both bony and soft tissue impairments simultaneously, in order to achieve optimal gait improvements, makes biomechanical sense. Much has been written on how the bony impairments in ambulatory children with CP can adversely affect their gait and how correcting these impairments can improve their gait. However, little evidence based research is available comparing the gait outcomes of children who have undergone correction of both bony and soft tissue concurrently versus those children that have only undergone soft tissue corrections. Specific and objective information on the degree of improvements in the gait pattern and behavior of gait outcome measures in those children that undergo both bony and soft tissue correction simultaneously over those that only correct soft tissue impairments appears to be limited in the literature.

PURPOSE AND HYPOTHESIS

The purpose of this research study is to investigate how gait outcome measures behave for children with CP undergoing both bony and soft tissue correction within their SEMLS versus children who underwent SEMLS with only soft tissue correction. The gait outcome measures examined in this study are: walking velocity; stride length; Gait Deviation Index (GDI); Pediatric Outcomes Data Collection Instrument (PODCI) Transfers & Mobility domain; PODCI Sports &

Physical Function domain; and achievement of surgical technical achievement goals (TAGs).

They are six scientific hypotheses for this study:

1. There will be significant, positive correlations between the pre-operative and post-operative measures of: walking velocity, stride length, GDI, PODCI Transfers & Mobility; and PODCI Sports & Physical Function for both groups.
2. There will be a significant difference in the correlations for each measure between the two groups.
3. There will be significant improvement in the velocity and stride length for both groups.
4. There will be a significant improvement in the GDI for both groups.
5. There will be significant improvement in the PODCI Transfers & Mobility and PODCI Sports & Physical Function for both groups
6. There will be a significant difference in achievement of surgical technical achievement goals between the two groups.

METHODS

Study Design

This retrospective study took place at the SHC MAL in Houston, Texas. For the purposes of this study, the presence of LAD at the hip was defined as anteversion greater than 2 SDs (standard deviations) along with a presence of increased passive hip internal rotation with decreased passive hip external rotation. LAD at the tibia was defined as internal rotation of the tibial or external rotation of the tibial greater than 2 SDs as measured by the transmalleolar axis. After an extensive chart review of over 600 subjects, 36 subjects were found to meet the inclusion for this study. Out of the 36 subjects, 18 subjects received intervention to their soft-tissue impairments during their SEMLS (Soft Tissue SEMLS) and 18 subjects received intervention to both their bony and soft tissue impairments during their SEMLS (Bony & Soft SEMLS). During data screening, one of the subjects in the Soft tissue SEMLS group was found to be an outlier and therefore had to be removed for the group; therefore17 subjects were in the Soft Tissue SEMLS group and 18 subjects were in the Bony & Soft SEMLS group.

The inclusion criteria for this study were as follows: a child with spastic diplegic CP functioning at a GMFCS level II or III who presented with LAD on their gait study (as defined above) without any previous lower extremity orthopedic surgery to improve their ambulation. The exclusion criteria for this study were as follows: previous orthopedic lower extremity surgery; history of dorsal rhizotomy or baclofen pump placement; presence of significant comorbidity; presence of an atypical SEMLS procedure; undergoing only one surgical procedure; undergoing a foot procedure, classified as asymmetrical diplegic CP; or, noted to have unknown etiology of CP. Significant comorbidity for the purposes of this study was defined as any history in the medical record of the following: seizures; VP shunt; cognitive issues; vision issues; atypical post-operative course; atypical or unknown cause of CP; and, a significant leg length discrepancy greater than two centimeters.

Data Collection

The data for this study was collected between January 1994 and October 2011 at the MAL in SHC-Houston using three-dimensional lower extremity kinematic data; all collected and analyzed using the VICON system (VICON, Oxford Metrics, Oxford. U.K.). Since the data collection for this retrospective study spanned 17 years, it incorporated several upgrades in the VICON hardware and software. A brief history of the hardware and software updates is as follows. In 1994, the MAL was collecting data using the VICON 370 system with Vicon Clinical Manager (VCM) gait analysis software and six infra-red cameras collecting at a sampling rate of 50 hertz. In 2006, the system was upgraded to the VICON 612 and included eight infra-red cameras collecting at a sampling rate of 60 hertz, with continued use of VCM gait analysis software. In 2009, the system upgraded to its current configuration which is the VICON Nexus with Plug in Gait; and, data was collected with an updated eight infra-red camera system at a sampling rate of 120 hertz. Plug in Gait is the next generation of VCM gait analysis software and uses the same modeling principles of three dimensional gait analysis.

While hardware and software updates occurred over the 17 years of data collection, the data for this study was consistently collected over the years with the same marker alignment principles and the same model, the conventional gait model. With each system update, backwards compatibility of gait analysis data was maintained and ensured through dual processing of data for several months to a year prior to making a complete changeover. In addition, the policy of the MAL required pre and post-operative data collection conditions to remain consistent.

During all data collection, trained physical therapists performed the physical exam, patient set up, data collection and data processing. Marker set up included bilateral thigh and tibial wands, which were placed on the lateral aspect of the patient’s lower limbs. Wands currently consist of a 14 mm marker placed a distance of 4.5 cm from a plastic base, with a 3 cm width and a 13 cm length. To reduce soft tissue artifact, thigh wands were placed on the distal one-third of the distance between the greater trochanter and lateral femoral epicondyle and between the lateral femoral epicondyle and lateral malleoli. An additional nine reflective markers (currently 14 mm in size) were placed on the pelvis and lower extremities in the following locations: bilateral anterior superior iliac spines; mid distance between the posterior superior iliac spines which is over the second sacral vertebra; bilateral lateral femoral epicondyles; bilateral lateral malleoli; and the second metatarsophalangeal joint dorsally, and calcaneal tuberosity.

Before each data collection the volume of recording space and motion cameras were calibrated allowing for correct three dimensional temporal marker tracking. Protocol for data collection included a static trial of the patient standing still prior to walking to provide joint centers for each subject based on the individual's anthropometric measurements. For data collection, patients were instructed to walk at a self-selected pace over a level ten meter walkway in bare feet with or without their assistive device, depending on patient ability. Three embedded force plates(1000 Hz) were located in the middle of the walkway and time synchronized to the Vicon system through an analog to digital converter. A minimum of three walking trials were collected and processed. Initial foot contact and toe-off were identified by the force plates and estimated throughout the entire walking path. Therapists verified visually foot strikes and toe-offs, processed data and selected one walking trial that was most representative of the subjects' gait pattern. This walking trial was labeled the representative trial and gait data from this representative trial was used for the research data.

Data Analysis

All statistical analyses were performed using SPSS 22.0 for Windows (Chicago, IL). The data was reviewed and screened for outliers and for statistical assumptions. One outlier was found in the Soft Tissue SEMLS group, and therefore removed from this group, leaving 17 subjects in the Soft Tissue SEMLS group and 18 subjects in the Bony and Soft Tissue SEMLS group. Although it was attempted to match these 2 groups, due to the unequal sample size and variances between these 2 groups, statistical analysis of the outcomes measure for each of these two groups was done independently of the other group. All measures except for the TAG %, had pre and post-operative values. For each group, Pearson r correlations were run between the pre-operative and post-operative values of each of the five measures which had both pre and post-operative values (velocity, stride length, GDI, PODCI Transfers & Mobility, and PODCI Sports & Physical Function). Next Paired t-tests were run between the differences in mean pre-operative and post-operative values for each of the five measures stated above. Since the sixth outcome measure (TAG %) has only one post-operative value, analysis of the TAG % was done separately. Due to issues with normality, the TAG % variable was analyzed using nonparametrics. An Independent Samples Mann-Whitney U test was performed on the TAG % for both groups to determine if a difference existed between groups in the number of TAGs achieved.

Subject Pool

The subject pool consisted of 35 subjects with spastic diplegic CP and LAD who had undergone a SEMLS at SHC in Houston between the years 1998 to 2011 and were seen at the MAL for an accompanying pre-operative and post-operative gait study. The Soft Tissue SEMLS group contained 17 subjects that underwent soft tissue intervention without bony correction. The Bony and Soft SEMLS group consisted of 18 subjects that underwent soft tissue intervention with bony correction. The key demographics for each of these two groups are seen in Table 24. The distribution of the various types of surgical procedures undergone by these two groups is seen in Table 25.

Table 24. Demographics for the Two SEMLS Groups.

	Soft Tissue SEMLS (N = 17)	**Bony & Soft Tissue SEMLS (N = 18)**
Age at Sx	7.6 yrs. (±2 yrs.)	9.5 yrs. (±2.6 yrs.)
Age Range	5.3 to 15.9 yrs.	5.7 to 14.6 yrs.
Avg Pre-op GDI	57.6 (±12)	56.8 (12.4)
Pre-op GDI range	36.7 to 83.0	39.1 to 76.4
Gender Male	7	10
Female	10	8
GMFCS Level		
GMFCS Level II	8	10
III	9	8
Ethnicity Caucasian	10	8
Hispanic	2	3
African-American	5	6
Other	0	1

Table 25. Number and Types of Surgical (Sx'l) Procedures by Group

	Soft Tissue SEMLS (N=17)	**Bony and Soft SEMLS (N=18)**
Average # of Sx'l Procedures	6.5	8.2
Range of Sx'l Procedures	3 to 8	3 to 11
Average # Sx'l Goals	21.1	20.8
Range of Sx'l Goals	10 to 26	8 to 26
# of Hamstring Lengthenings	33	32
# of Adductor Tentomies	21	16
# of Rectus Transfers	31	32
# of TALS	26	33
Tibial Osteotomy (TO)	0	9
Femoral DRO	0	21
Subjects w. DROs only	0	12
Subjects w/ TOs only	0	4
Subjects w/ DROS and TOs	0	2

RESULTS

The first scientific hypothesis for this study was the existence of significant, positive correlations between the pre-operative and post-operative measures for velocity, stride length, GDI, PODCI Transfers & Mobility; and PODCI Sports & Physical Function for both groups. The relationships of the pre-operative to post-operative values of each of these five outcome measures were examined using Pearson's r correlations. The correlational relationships between these variables for each of the two groups are presented in Table 26. Note, all correlations were found to be significant except for the PODCI-Sports for the Soft Tissue group and the GDI for the Bony and Soft Tissue group.

TABLE 26. Correlations between Pre and Post Measures

Soft Tissue SEMLS N=17	Post-Velocity	Post-Stride	Post-GDI	Post-PODCI Transfer	Post-PODCI-Sports
Pre-operative	.865	.866	.725	.614	.317
Sig	.000*	.000*	.001*	.009*	.215
Bony and Soft SEMLS N=18					
Pre-operative	.836	.796	.456	.714	.614
Sig	.000*	.000*	.057	.001*	.007*

The second scientific hypothesis for this study was the existence of significant differences in the correlations for each measure between the two groups. No significant differences were found between the two groups for the velocity, stride length, GDI, PODCI Transfers, and PODCI Sports correlations.

The third, fourth, and fifth scientific hypotheses for this study was the significant improvement in post-operative mean walking velocity, stride length, GDI, PODCI Transfers, and PODCI Sports compared to the pre-operative means for both groups. The pre and post-operative mean values for each of the outcome variables are presented in Table 27. All post-operative mean values for the Soft Tissue group improved, however this was not the case for the Bony and Soft Tissue group. For the Bony and Soft Tissue group, all means improved except for walking velocity and stride length which showed a slight decline.

Table 27. Mean Pre and Post-operative Values for Outcome Measures

Mean Values	**Soft Tissue SEMLS (N = 17)**	**Bony & Soft Tissue SEMLS (N = 18)**
Pre-op velocity	.693 (±.23)	.892 (±.35)
Post-op velocity	.741 (±.29)	.763 (±.28)
Pre Stride length	.685 (±.19)	.800 (±.17)
Post Stride length	.738 (±.21)	.788 (±.19)
Pre-GDI	57.56 (±12.0)	56.76 (±12.3)
Post-GDI	69.76 (±12.0)	72.19 (±11.0)
Pre PODCI Transfer	67.47 (±16.5)	79.17 (±16.2)
Post PODCI Transfer	78.65 (±10.9)	82.83 (±12.6)
Pre PODCI Sports	45.53 (±15.1)	47.78 (±19.5)
Post PODCI Sports	50.77 (±13.3)	57.11 (±15.7)
TAG %	81.6 (±9.8)	82.8 (±14.6)

Paired samples t-tests, with an alpha set at .01, were run to determine if significant differences existed between the pre-operative and post-operative means for: walking velocity; stride length; GDI; PODCI Transfers & Mobility; and PODCI Sports & Physical Function for each of the two groups. See Table 28 for result details.

Table 28. Paired Samples T-Test

		Paired Differences							
		Mean	SD	St. Error Mean	95 % Confidence Interval				
					Lower	Upper	t	df	Sig. (2-tailed)
Soft Tissue SEMLS	Pair 1. Velocity	-.047	.145	.035	-.122	.028	-1.34	16	.200
	Pair 2. Stride length	-.053	.104	.025	-.106	.000	-2.12	16	.050
	Pair 3. GDI	-12.20	8.92	2.16	-16.78	-7.61	-5.64	16	**.000***
	Pair 4. Transfer	-11.18	13.09	3.17	-17.91	-4.45	-3.52	16	**.003***
	Pair 5. Sports	-5.24	16.72	4.05	-13.83	3.36	-1.29	16	.215

		Paired Differences							
		Mean	SD	St. Error Mean	95 % Confidence Interval				
					Lower	Upper	t	df	Sig. (2-tailed)
Bony & Soft Tissue SEMLS	Pair 1. Velocity	.129	.190	.045	.035	.223	2.88	17	**.010***
	Pair 2. Stride length	.013	.119	.028	-.046	.072	.454	17	.656
	Pair 3. GDI	-15.36	12.22	2.88	-21.43	-9.29	-5.33	17	**.000***
	Pair 4. Transfer	-3.67	11.39	2.69	-9.33	2.0	-1.37	17	.190
	Pair 5. Sports	-9.33	15.85	3.74	-17.21	-1.4	-2.4	17	.023

The third hypothesis, improved velocity and stride length for both groups, was not found to be supported. In fact, for the Bony and Soft Tissue group, a significant decline was noted in the post-operative velocity, t = 2.88, p = .010.

The fourth hypothesis, which stated that the GDI would significantly improve for both groups, was supported. Both for the Soft Tissue only and for the Bony and Soft Tissue groups, a significant improvement was found between the pre-operative and post-operative GDI with a *p* value < .001 and *t* values equal to -5.64 and -5.33, respectively.

The fifth hypothesis, which stated that both PODCI measures would show significant improvement in their post-operative means compared to their pre-operative means was found to be supported in the Soft Tissue group for the Transfers and Mobility domain, *t* = -3.52, *p* = .003.

The sixth hypothesis for this study was the existence of a significant difference in the achievement of TAGS between the soft tissue only SEMLS group and the bony & soft tissue group. The difference in achievement of surgical goals between groups was examined using an Independent Samples Mann-Whitney U test. The Mann-Whitney U test indicated no difference in achievement of TAGS between the Soft Tissue SEMLS group (Mdn = 80.8%) and the Bony and Soft SEMLS group (Mdn = 83.0%), *U* = 178.0, *p* = .41.

DISCUSSION

There were several findings within this study; some findings support previous research while others offer suggestions for future research. The correlational relationships between the pre-operative and post-operative means for each of the measures within each group were found to be significant, moderate to strong relationships with the exception of the PODCI Sports for the Soft Tissue group and GDI for the Bony group. The PODCI Sports and Physical Function measure for the Soft Tissue group had a weak correlation that lacked significance; while the Bony group had a significant, moderate correlation. This difference in trend of improvement for the PODCI Sports measure between these two groups was also seen in the degree of the post-operative improvement. The degree of improvement in the post-operative PODCI Sports mean was 5.24 in the Soft Tissue group and 9.33 in the Bony group. The rationale for the Bony group having a trend for greater improvement in the PODCI Sports and Physical Function measure is unclear. Reviewing the PODCI questionnaire, one possible explanation could be that the higher level activities included in the Sports and Physical Function domain are more difficult to achieve by the continued presence of LAD. This is just one possible explanation; further research is needed in this area.

While most of the pre-post means did not show a significant improvement post-operatively, they all improved with the exception of walking velocity for the Bony group. Interestingly, the walking velocity measure for the Bony group showed a significant decline. The reason for this decline is unclear at this time. One possible explanation is Bony and Soft Tissue SEMLS are more involved than Soft Tissue only SEMLS and perhaps the return to pre-operative velocity takes longer in some subjects. Another explanation is that a decrease in walking velocity could be a reflection of improved motor control for certain children with spastic CP. Further investigation into the behavior of this measure in patients undergoing bony intervention is needed with the addition of long-term gait studies. Further research should also include a larger subject size so that a sub analysis by GMFCS level could also be performed to examine if this decline in velocity seen in the Bony group is affected by GMFCS level.

The post-operative GDI mean was the only variable found to significantly improve for both the bony and soft tissue groups. This improvement in the GDI for both groups makes sense when you consider that the GDI represents range of motion during ambulation and that one of the primary goals of orthopedic surgical intervention for these children is to improve their range of motion during ambulation. This finding also makes sense given both groups started out at very similar pre-operative GDI scores, which were both almost 5 SDs below typical GDI values.

The lack of significant difference in achievement of TAGs between these two groups is also interesting. However since the TAGs are procedure specific, it would make sense that comparison of two groups differing in the type of surgical procedures may not have a significant difference in achievement of their TAGs. Since previous research has shown that higher functioning patients have greater achievement in TAGS as compared to lower functioning patients, further research should be attempted with a larger subject pool that can be subdivided and analyzed by GMFCS level.

CONCLUSION

Both the soft tissue only and bony with soft tissue SEMLS groups help to improve the walking ability of ambulatory children with spastic CP as seen by the improvement in GDI. Whether having bony correction concurrently with soft tissue intervention, for those children that are candidates to have both simultaneously, is better than staged surgery remains a difficult question to answer. More research is needed comparing these two groups with larger subject sizes that are matched by pre-operative GDI and analyzed by GMFCS level. In addition, this research study was limited to diplegic patients. Future research should expand the subject pool to include hemiplegic and quadriplegic patients with a subanalysis of outcomes by pattern of involvement.

CHAPTER VI

CONCLUSIONS

Finding the most effective treatment interventions and the best measures to evaluate those interventions, to improve the gait of ambulatory children with CP is a complex task. While no one study could provide clear answers to these complex questions, this three part dissertation attempted to add to the existing body of knowledge. Since CP is one of the most common neurologic conditions treated by physical therapists and improving the ambulatory ability of these children is a common goal for treatment intervention, physical therapists need to be knowledgeable about the various treatment interventions aimed at improving the ambulation of these children.[1] In addition, since physical therapists are often on the front line in terms of measuring the effectiveness of these interventions, they also need to be knowledgeable about the various gait outcome measures used to judge how well these interventions improve gait.

There are several conclusions from this dissertation that add to or support the current body of knowledge in this field of study. The first finding is that orthopedic surgical intervention used in conjunction with a motion analysis laboratory improves the gait of children with spastic CP. This finding is supported by the consistent improvement in the Gait Deviation Index (GDI) throughout the two studies found within this dissertation that examined GDI.

The second finding, as outlined by Goldberg, states that gait outcome measures need to include a variety of technical and functional measures.[28] In the first study on the exploration of technical to functional gait measures, the changing behavior of the various gait outcome measures with varying patient types is observed and therefore supports the use of multiple gait measures in order to achieve an accurate post-intervention assessment of gait. This changing behavior of the gait outcome measures was also seen in the third study on soft tissue versus bony and soft tissue interventions. The velocity measure was seen to behave differently in those patients that had undergone both bony and soft tissue intervention versus those that had only undergone soft tissue intervention.

The third conclusion is that the following subject characteristics should be taken into account during the outcome analysis of gait in the ambulatory child with CP: GMFCS level, pre-operative GDI value, and pattern of involvement. While other factors (such as the presence of prior surgery and co-morbidity) should also be considered during outcome analysis, the effects of GMFCS level, pre-operative GDI value and pattern of involvement seem to be evident within this dissertation. In study one, the inverse, moderate relationship of the pre-operative GDI to the improvement in GDI was found consistently across several groups. Also in study one, we observed the changes in the measurement correlation values when GMFCS, pattern of involvement and presence of prior surgery were taken into account.

The fourth conclusion is that increased walking velocity does not consistently accompany other improvements in the gait pattern of children with spastic CP; and therefore, may not always be an appropriate outcome measure for this particular population after undergoing orthopedic surgery to improve their gait. For instance in study three of this dissertation, we see that increased walking velocity may not be the best outcome measure to represent post-operative improvement in the gait of children with CP after undergoing bony and soft tissue orthopedic surgery. Consideration should be given to the observed improvements in gait within this study without corresponding increases seen in velocity. Perhaps for some of these children, decreased velocity (rather than increased velocity) may be the result of the improved ambulation that occurs with increased range of motion after undergoing lower extremity orthopedic surgery. For children with spastic CP that have central nervous system damage which remains unchanged by orthopedic surgical intervention, walking velocity may not be the best outcome measure to reflect post intervention improvement in their gait. This finding supports the need for future research in this area, especially given velocity has recently been referred to as the "Sixth Vital Sign".[69]

The fifth finding of this study is support for the use of the GDI along with surgical technical achievement goals, TAGs, as a pair of technical gait outcome measures for ambulatory children with CP having lower extremity orthopedic surgery to improve their ambulation. The weak correlations found between these two measures in the first study, support that these two assessment tools are measuring differing constructs. In addition since the GDI appears to possibly be less effective at measuring change in higher functioning subjects that present with higher pre-operative GDI scores and the TAG % appears to be less effective at measuring change in the lowering functioning children that may have slightly more difficulty meeting technical surgical goals, this pair of technical outcome measures appear to complement each other.

The sixth conclusion of this study is that future multi-center MAL studies using the same motion model, would allow for larger subject pools that would be of great benefit to the study of surgical outcomes for the ambulatory child with CP. Larger subject pools would hopefully lead to increased homogenous groups of subjects with similar GMFCS levels, patterns of involvement and pre-GDI values. This would allow for a more in depth analysis of the outcomes of the various surgical interventions performed on the child with CP to improve their gait. The direction of future research in the area of surgical outcomes for the ambulatory child with CP will hopefully also include the following: an increase in specific inclusion and exclusion criteria to create more homogenous groups; standardized reporting of outcomes for future mega-analysis; improved tracking of upper extremity involvement for enhanced categorization of pattern of involvement; and, standardized reporting of physical therapy and post-operative orthotic intervention so these variables may also be considered in future outcome studies.

The seventh and final conclusion of this dissertation is the need for increased involvement of physical therapists in outcomes research for ambulatory children with CP undergoing orthopedic surgical intervention to improve gait. Physical therapists need to become more involved with this area of research for two reasons. Since gait and the analysis of interventions to improve gait is a specialty of physical therapists, increasing their involvement and knowledge of the various treatment interventions available for improving ambulation should be an area of interest. In addition, since physical therapists are often involved with measuring the effectiveness of various interventions designed to improve gait, they should be knowledgeable about the behavior of the various gait outcome measures used to judge how well these interventions improve gait. Increasing our knowledge regarding how the various gait outcome measures may perform differently with differing patient populations and differing types of interventions should be of importance to the field of physical therapy.

The second reason physical therapists should become more involved with surgical outcomes research for the ambulatory child with CP is the importance of PT and rehabilitation to the success of the surgical intervention. Health care professionals, who work with these children and their families and assist them with surgical decision making, typically will stress the importance of the rehabilitation process in obtaining a successful surgical outcome. Physical therapists, by increasing their interest in the post-operative physical therapy care these children receive, may be able to improve the rehabilitation process for this patient population. For example, future physical therapy research in this area may help with decreasing the painful muscle spasms that these children endure after undergoing a rectus femoris transfer.

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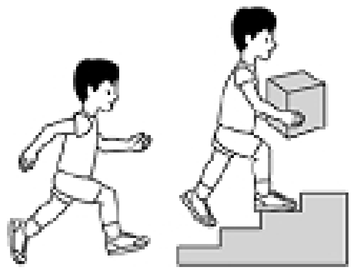
APPENDIX A

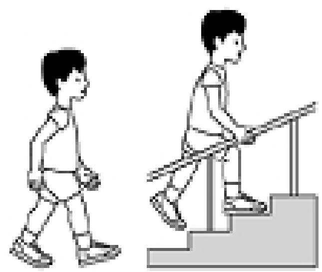
GMFCS LEVELS

GMFCS Levels



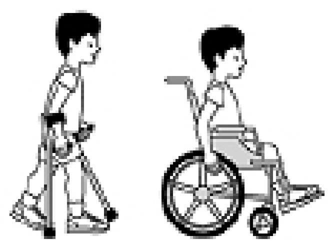
GMFCS Level I

Children walk indoors and outdoors and climb stairs without limitation. Children perform gross motor skills including running and jumping, but speed, balance and co-ordination are impaired.



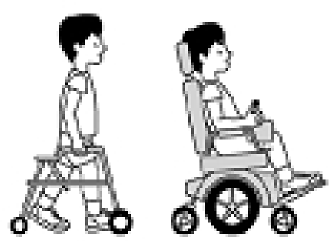
GMFCS Level II

Children walk indoors and outdoors and climb stairs holding onto a railing but experience limitations walking on uneven surfaces and inclines and walking in crowds or confined spaces.



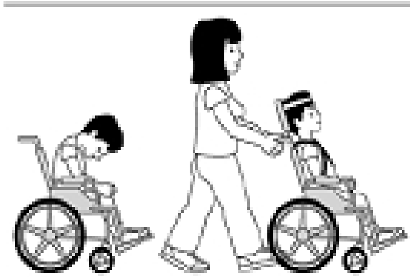
GMFCS Level III

Children walk indoors or outdoors on a level surface with an assistive mobility device. Children may climb stairs holding onto a railing. Children may propel a wheelchair manually or are transported when traveling for long distances or outdoors on uneven terrain.



GMFCS Level IV

Children may continue to walk for short distances on a walker or rely more on wheeled mobility at home and school and in the community.



GMFCS Level V

Physical impairment restricts voluntary control of movement and the ability to maintain antigravity head and trunk postures. All areas of motor function are limited. Children have no means of independent mobility and are transported.

APPENDIX B

Technical Achievement Goals (TAGs)

PROCEDURE	SURGICAL (TECHNICAL) GOAL	CRITERIA
Hamstring lengthening (medial only)	Increase passive hamstring ROM	Pre/Post Clinical Exam: increase in popliteal angle, by >=10°
	Improve knee extension in stance	Pre/Post Kinematic Plots: increase in degree of maximum knee extension during single limb stance by >= 10° (pre-existing excessive knee flexion during stance greater than or equal to 10 degrees needs to be present in order to use this goal)
	Decrease knee flexion at initial contact	Pre/Post Kinematic Plots: decrease in degree of knee flexion at initial contact, by >= 10°
	Resolve fixed knee flexion contractures	Pre/Post Clinical Exam: decrease knee flexion contracture to <= 10° from neutral (pre-existing knee flexion contracture greater than or equal to 10 degrees is defined as a knee flexion contracture)
	Avoid recurvatum	Post-op Kinematic Plots: hyperextension does not occur during stance
Hamstring lengthening (medial & lateral)	Increase passive hamstring ROM	Pre/Post Clinical Exam: increase in popliteal angle, by >=10°
	Improve knee extension in stance	Pre/Post Kinematic Plots: increase in degree of maximum knee extension during single limb stance, by >= 10° (pre-existing excessive knee flexion during stance greater than or equal to 10 degrees needs to be present in order to use this goal)
	Decrease knee flexion at initial contact	Pre/Post Kinematic Plots: decrease in degree of knee flexion at initial contact, by >= 10°
	Resolve fixed knee flexion contractures	Pre/Post Clinical Exam: decrease knee flexion contracture to <= 10° from neutral (pre-existing knee flexion contracture greater than 10 degrees is defined as a knee flexion contracture)
	Avoid recurvatum	Post-op Kinematic Plots: hyperextension does not occur during stance
Distal femoral extension osteotomy (isolated)	Increase passive hamstring ROM	Pre/Post Clinical Exam: increase in popliteal angle, by >=10°
	Improve knee extension in stance	Pre/Post Kinematic Plots: increase in degree of maximum knee extension during single limb stance, by >= 10°

		(pre-existing excessive knee flexion during stance greater than or equal to 10 degrees needs to be present in order to use this goal)
	Decrease knee flexion at initial contact	Pre/Post Kinematic Plots: decrease in degree of knee flexion at initial contact, by >= 10°
	Resolve fixed knee flexion contractures	Pre/Post Clinical Exam: decrease knee flexion contracture to <= 10° from neutral (pre-existing knee flexion contracture greater than 10 degrees is defined as a knee flexion contracture)
	Avoid recurvatum	Pre/Post Kinematic Plots: hyperextension does not occur during stance phase
Distal femoral extension osteotomy (with patella tendon advancement)	Increase passive hamstring ROM	Pre/Post Clinical Exam: increase in popliteal angle, by >=10°
	Improve knee extension in stance	Pre/Post Kinematic Plots: increase in degree of maximum knee extension during single limb stance, by >= 10° (pre-existing excessive knee flexion during stance greater than or equal to 10 degrees needs to be present in order to use this goal)
	Decrease knee flexion at initial contact	Pre/Post Kinematic Plots: decrease in degree of knee flexion at initial contact, by >= 10°
	Resolve fixed knee flexion contractures	Pre/Post Clinical Exam: decrease knee flexion contracture to <= 10° from neutral (pre-existing knee flexion contracture greater than 10 degrees is defined as a knee flexion contracture)
	Avoid recurvatum	Pre/Post Kinematic Plots: hyperextension does not occur during stance
Rectus femoris transfers	Increase total knee range of motion in gait	Pre/Post Kinematic Plots: increase total range of knee motion during gait cycle, by >= 10°
	Maintain *or* increase swing knee flexion	Pre/Post Kinematic Plots: peak knee flexion during swing phase is within 5 degrees of pre-op value or within 2 SD of normative value
	Improve timing of swing knee flexion	Pre/Post Gait Parameters from Kinematic Plots: improve timing of peak knee flexion during swing phase by at least 5%

Rectus femoris lengthening (mid-substance fractional)	Increase total knee range of motion in gait	Pre/Post Kinematic Plots: increase total range of knee motion during gait cycle, by >= 10°
	Maintain/increase swing knee flexion	Pre/Post Kinematic Plots: peak knee flexion during swing phase is within 5 degrees of pre-op value or within 2 SD of normative value
	Improve timing of swing knee flexion	Pre/Post Gait Parameters from Kinematic Plots: improve timing of peak knee flexion during swing phase, by at least 5%
Adductor tenotomy	Increase passive abduction with hip flexion	Pre/Post Clinical Exam: increase in PROM of abduction with hip flexion, by >= 5°
	Decrease adduction during the gait cycle	Pre/Post Kinematic Plots: increase in hip abduction during the gait cycle, by >= 5°
Iliopsoas lengthening	Increase passive hip extension	Pre/Post Clinical Exam: increase in PROM of hip extension, > = 5°
	Increase stance phase hip extension	Pre/Post Kinematic Plots: increase in degree of maximum hip extension during stance phase, by >= 5°
	Maintain hip flexor strength	Pre/Post Clinical Exam: hip flexion strength shows strength grade within 1/2 grade of pre-op value
Zone 1 and/or Zone 2: fractional gastrocnemius lengthening	Increase passive ankle dorsiflexion with knee extension	Pre/Post Clinical Exam: increase in PROM of ankle dorsiflexion with knee extension, by >= 5°
	Decrease excessive plantar flexion (PF) during stance phase of gait Or, Improve mid foot breakdown (Only one goal is chosen from above, see criteria to determine which goal)	Pre/Post Kinematic Plots: Increase peak dorsiflexion during stance phase by >= 5°, *and/or* Increase DF at IC by >= 5° Or, Improvement based on clinical assessment, video, photos, & plantar pressure data (If excessive PF is present on the kinematic plots during stance than the excessive PF goal should be chosen. If excessive PF is not present on the plots due to mid foot breakdown, then the mid foot breakdown goal should be the chosen goal.)
	Avoid excessive dorsiflexion in stance	Pre/Post Kinematic Plots: peak dorsiflexion during single limb stance does not exceed

		2 SD above normative value
Zone 3: tendo-achilles lengthening	Increase passive ankle dorsiflexion with knee extension	Pre/Post Clinical Exam: increase in PROM of ankle dorsiflexion with knee extension, by >= 5°
	Decrease excessive plantar flexion (PF) during stance phase of gait Or, Improve mid foot breakdown (Only one goal is chosen from above, see criteria to determine which goal)	Pre/Post Kinematic Plots: Increase peak dorsiflexion during stance phase by >= 5°, *and/or* Increase DF at IC by >= 5° Or, Improvement based on clinical assessment, video, photos, & plantar pressure data. (If excessive PF is present on the kinematic plots during stance than the excessive PF goal should be chosen. If excessive PF is not present on the plots due to mid foot breakdown, then the mid foot breakdown goal should be the chosen goal.)
	Avoid excessive dorsiflexion in stance	Pre/Post Kinematic Plots: peak dorsiflexion during single limb stance phase does not exceed 2 SD above normative value
Femoral rotational osteotomy	Increase passive external hip rotation	Pre/Post Clinical Exam: increase in PROM into external hip rotation, by >= 10°
	Decrease mean internal hip rotation in gait	Pre/Post Kinematic Plots: a decrease in mean internal hip rotation, by >= 10°
	Improve foot progression angle during stance	Pre/Post Kinematic Plots: improvement in mean foot progression angle during stance phase, by >= 5°
Tibial rotational osteotomy	Improve transmalleolar axis	Pre/Post Clinical Exam: improvement in transmalleolar axis measure by >= 5°
	Improve foot progression angle	Pre/Post Kinematic Plots: improvement in mean foot progression angle during stance phase, by >= 5°
Lateral column lengthening (isolated)	Improve valgus foot posture in gait	Improved foot alignment based on pre/post comparisons of clinical exam, gait, standing video, foot photographs, and plantar pressure data
Medial column stabilization (isolated)	Improve valgus foot posture in gait	Improved foot alignment based on pre/post comparisons of clinical exam,

		gait, standing video, foot photographs, and plantar pressure data
Lateral column lengthening with medial column stabilization	Improve valgus foot posture in gait	Improved foot alignment based on pre/post comparisons of clinical exam, gait, standing video, foot photographs, and plantar pressure data
Lateral column shortening	Improve varus foot posture in gait	Improved foot alignment based on pre/post comparisons of clinical exam, gait, standing video, foot photographs, and plantar pressure data
Posterior tibialis split transfer	Improve passive varus deformity	Pre/Post Clinical Exam: off weight bearing positional foot assessment
	Improve varus foot posture in gait	Improved foot alignment based on pre/post comparisons of clinical exam, gait, standing video, foot photographs, and plantar pressure data
Posterior tibialis lengthening	Improve passive varus deformity	Pre/Post Clinical Exam: off weight bearing positional foot assessment
	Improve varus foot posture in gait	Improved foot alignment based on pre/post comparisons of clinical exam, gait, standing video, foot photographs, and plantar pressure data
Peroneal lengthening	Increase passive inversion	Pre/Post Clinical Exam: improvement in PROM of calcaneal inversion, by >=5°
	Decrease valgus foot posture in gait	Improved foot alignment based on pre/post comparisons of clinical exam, gait, standing video, foot photographs, and plantar pressure data
Anterior tibialis split transfer	Improve passive varus deformity	Pre/Post Clinical Exam: off weight bearing positional foot assessment
	Improve varus foot posture in gait	Improved foot alignment based on pre/post comparisons of clinical exam, gait, standing video, foot photographs, and plantar pressure data

ALL GOALS SHOULD BE USED UNLESS THE DEFORMITY DOES NOT EXIST PRE-OPERATIVELY

APPENDIX C

EXAMPLE OF TAG USAGE

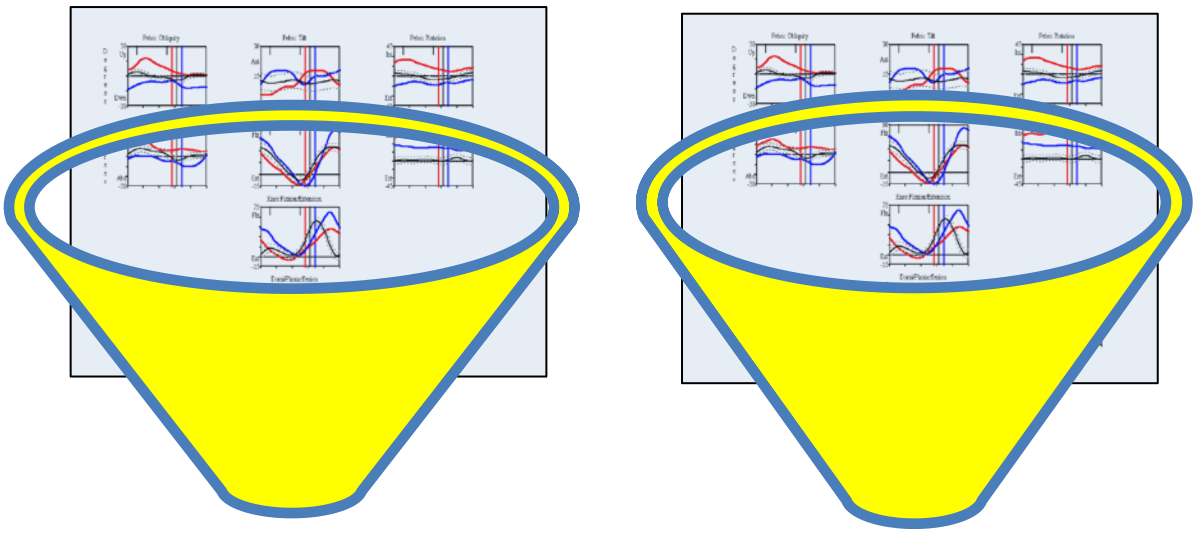
PROCEDURE:	SURGICAL GOAL:	GOAL ACHIEVEMENT:	
		yes	no
HAMSTRING LENGTHENING (medial)	Increase passive hamstring range of motion Improve knee extension in stance Decrease knee flexion at initial contact Resolve knee flexion contractures Avoid recurvatum	2 1 (R) 2 N/A 2	1 (L)
RECTUS TRANSFER	Increase total knee range of motion in gait Maintain/increase swing knee flexion Improve timing of swing knee flexion	2 2	2
ADDUCTOR TENOTOMY	Increase passive abduction Decrease adduction in gait on the right	2 1	
TAL (intramuscular)	Increase passive ankle dorsiflexion Decrease equinus in gait Avoid excessive dorsiflexion in stance	2 2	2
FEMORAL DRO	Increase passive external hip rotation Reduce degree of internal hip rotation in gait Improve foot progression angle	2 2 2	
		24	5
	TECHNICAL GOAL ACHIEVEMENT:	***83%***	

APPENDIX D

Illustration of What GDI Represents

Kinematic Plots - Left

Kinematic Plots - Right



Left GDI

Right GDI

<u>GDI = mean of Left and Right GDI</u>

see Schwartz article for detailed mathematical formulas and procedures[29]