Research Projects at the Center for Gait and Movement Analysis (CGMA)

Diversity of CGMA projects is ever-expanding. This appendix describes the subset of research projects conducted by CGMA principle investigators that are related to cerebral palsy. They are categorized into: chapters on gait analysis in the pediatric population; retrospective projects that analyze data from past interventions that help elucidate movement pathology and provide evidence for future clinical decisions; prospective projects that capture subject data that are used to develop clinical evaluation and intervention strategies; and technical projects that develop software, hardware, or quantitative methods that advance data processing or analysis.

**Pediatric Gait Publications**


**RETROSPECTIVE PROJECTS**

04-0552 Effectiveness of Instrumented Gait Analysis in Children with Cerebral Palsy: Comparison of Outcomes
04-0553 Comparison of Surgical Recommendations for Children with Cerebral Palsy and Known Outcomes with and without Comprehensive Gait Analysis

This retrospective study was comparing recommendations following comprehensive gait analysis and recommendations from analysis using clinical data only. This study investigated the therapeutic recommendations for children with cerebral palsy by comparing recommendations of six experienced clinician’s to a multidisciplinary gait lab team. A group of clinicians made surgical recommendations using information typically available during a clinical evaluation. Surgical recommendations from instrumented gait analysis (IGA) were made by a multidisciplinary gait lab team (GLT). This study indicates that data from IGA alters surgical recommendations for children with cerebral palsy.

**Collaborators:** Frank Chang, M.D., Adam Seidl, B.S., James J. Carollo, Ph.D., P.E.

**Paper/Presentations:**

04-1081 Outcome of Rectus Femoris Transfer in Children with Cerebral Palsy: Evaluation of Pre-Operative Indications and Transfer Site
Rectus femoris transfer (RFT) surgery is a treatment option for children with cerebral palsy who exhibit a stiff knee gait pattern. The purpose of this study was to introduce knee flexion angular velocity as a predictor of surgical outcome, as well as to investigate the effect of different transfer sites on the overall success and test the validity of commonly used common preoperative indicators. Thirty-eight patients with cerebral palsy who underwent RFT, and had pre and postoperative instrumented gait analyses, were evaluated. A significant improvement was observed in the angular velocity. The authors recommend RFT in children with cerebral palsy who exhibit a stiff knee gait, regardless of transfer site.

Paper/Presentations:

05-0224 The Effect of Preoperative Baseline Values on Dynamic Hip Function in Children with Cerebral Palsy Following PSOAS Lengthening Surgery
Intramuscular psoas lengthening (IPL) surgery is typically recommended as a treatment for increased dynamic hip flexion in children with CP after review of data from patient history,
physical examination, and kinematics from instrumented gait analysis. This retrospective study was assessing a patient population of children with cerebral palsy who had two or more gait analyses performed and also received a psoas lengthening. The average pre-operative kinematic values were compared to the average post-operative kinematic values to determine if the surgery resulted in a significant change in dynamic hip movements and angles. By retrospectively separating our study group by preoperative kinematic pelvic tilt values, we were able to determine a criterion for iliopsoas lengthening over the pelvic brim surgery.

Collaborators: Muthusamy, Komalam, MRCS, Seidl, Adam J, BS, Friesen, Richard M, BA, Zhaoxing, Pan, Ph.D., Carollo, James J, Ph.D. P.E., Chang, Franklin M, MD.

06-1097  Motor Control Mechanisms Associated with Limited Knee Extension at Terminal Swing during Gait by Children with Cerebral Palsy

Lack of full knee extension during the terminal swing phase of gait (immediately preceding foot contact) is a frequent problem in ambulatory children with cerebral palsy (CP) who have been seen for clinical gait analysis at the Center for Gait and Movement Analysis. This problem is often uncorrectable with existing treatments. This problem has not been systematically addressed in the literature. Impairments in strength, muscle tone, and range of motion characteristic of CP affect the successful attainment of specific critical events in the gait cycle, thereby affecting the stability, efficiency, cosmesis, and overall performance of gait in these children. Limited ability to fully extend the knee at terminal swing shortens the step length and may affect the pattern of foot contact. Children who demonstrate reduced step length increase gait velocity by increasing step frequency, thereby reducing gait efficiency. Atypical foot contact may affect shock absorption and increases stress to the structures of the feet, thereby increasing the likelihood of secondary impairments such as foot pain and deformity. The overall purpose of this retrospective project is to document a) the incidence of limitations in knee extension at the terminal swing phase of gait by children with cerebral palsy (CP), b) the kinematic findings related to these limitations, and c) the relationships of selected measures of strength, range of motion, and muscle tone to knee extension at terminal swing.

Collaborators: Valvano J, Carollo J.J., Pan X, Chang F,

Paper/Presentations:

09-0972  Changes in Coordination and Functional Outcomes after the Rectus Femoris Transfer Procedure in Children with Spastic Cerebral Palsy
This retrospective study determined that variations in functional gait outcomes after the rectus femoris transfer procedure in children with cerebral palsy gait are influenced by changes in inter-segmental coordination, which reflects selective motor control. This project elucidates the mechanisms of change after the surgical procedure to ameliorate stiff knee gait.

This project applies Dionysis, a software package of nonlinear gait analysis methods developed at CGMA by Kate Worster.

Collaborators: Valvano J, Worster K, Carollo JJ, Davies K, Pan Z

**Paper/Presentations:**

- **Changes in Inter-Segmental Coordination and Gait Performance after the Rectus Femoris Transfer Procedure in Children with Cerebral Palsy.** Carollo JJ, Worster K, Pan Z, Chang F & Valvano J. Accepted for podium presentation. European Society of Movement Analysis for Adults and Children, Vienna, Austria, September 2011.

- **Coordination of Lower Extremity Segments during Gait: A Typical Reference**

  Inter-segmental coordination in a typical reference group was studied to interpret findings in the group with cerebral palsy in the study entitled “Changes in Coordination and Functional Outcomes after the Rectus Femoris Transfer Procedure in Children with Spastic Cerebral Palsy”. Novel methods to quantify inter-segmental coordination of the pelvis, thigh, shank, and foot segments were developed. These methods are coded in the Dionysis software package of nonlinear gait analysis methods that constructs phase portraits (PP) and continuous relative phase diagrams (CRPD).

  Collaborators: Worster K, Valvano J, Carollo JJ

**Presentation:**

- **Essential Segment Coordination Dynamics for Typical Gait: Applications to Pre-Swing.**

**10-0600 Acetabular and Femoral Development after a Varus Derotational Osteotomy in Children with Cerebral Palsy**

- **Hip Surgery for Correction of Hip Dysplasia/Dislocation in Cerebral Palsy**

This retrospective study addresses pathological mechanisms related to a femoral varus derotational osteotomy (VDRO), a definitive treatment for hip dislocation or subluxation in children with cerebral palsy. There are multiple parts to this extensive project. Thousands of x-
rays have been analyzed to identify trends in the typical development of the physeal angle and the acetabular teardrop that can provide a reference for evaluating atypical hip development in children with cerebral palsy.

**Collaborators:** Chang FM, Miller NH, Kolnik A, Carry P, Flynn K, Davis J, Lin W, May A, Faulk LW & Carollo JJ

**Paper/Presentations:**


- **Long-Term Effects of Femoral Varus Derotational Osteotomy in Children with Cerebral Palsy: A 25 Year Follow-Up**

  The goal of this study is to determine at what age to perform a varus derotational osteotomy (VDRO) procedure in children with cerebral palsy and neuromuscular hip dysplasia, what clinical and radiographic factors should be considered and how much correction should be achieved in order to maintain remodeling over longer periods post-operatively. Pre-operative and post-operative radiographs and clinical assessments are analyzed. The evidence gained from this study could influence guidelines for planning this procedure.

  **Collaborators:** Chang FM, Lin W, Davies K, May A

**Presentations:**


**10-0637 Outcomes Comparison of Proximal Tibial Epiphysiodesis with or without Concomitant Proximal Tibial Epiphysiodesis**

The purpose of this retrospective study is to evaluate and compare the relative effects of the proximal tibial epiphysiodesis procedure versus proximal tibial epiphysiodesis with
concomitant proximal fibular epiphysiodesis for the treatment of leg length discrepancy at the proximal and distal fibula and tibial ends. This study could affect the decision making when performing an epiphysiodesis in children with a leg length discrepancy.

Collaborators: Chang FM, Hansen S, Davies K.

10-0694 Results of Patellar Advancement Procedures for the Treatment of Crouch Gait in Patients with Cerebral Palsy (Collaboration with MRC)

This retrospective study aims to describe the population of children who have received the patellar advancement procedures and characterize the outcomes of patellar advancements over the past ten years. Outcome variables include radiographic measurements, physical examination data, and gait analysis data to be collected both pre- and post-operatively.

Collaborators: Chen Q, Hotchkiss M, Rhodes J

Presentations:

10-1084 Inter-Segmental Coordination and Ankle-foot Orthoses during Gait by Children with Spastic Cerebral Palsy

This project uses nonlinear measures to examine changes in coordination at the pelvis, thigh and shank associated with donning a solid ankle foot orthoses during gait by children with cerebral palsy and the equinus (toe-toe) gait pattern. This project is based on preliminary data that relates coordination changes to the capacity for selective motor control to reorganize after the foot position is modified with the orthoses.

Collaborators: Carollo JJ, Valvano, J, Worster K

10-1113 Retrospective Comparison of Allograft versus Bovine Xenograft in Evan’s Calcaneal Osteotomy for Planovalgus Foot Deformity in Cerebral Palsy

This retrospective research project examines the amount of correction achieved, complication rates, and time to incorporation for the bovine xenograft vs. cadaveric allograft in children with cerebral palsy who have received an Evans procedure for correction of flatfoot deformity. This ongoing study will assess radiographs of children who have received an Evans procedure between 2005 and 2010.

Collaborators: Chang FM, Mansour A, Davies K.

Presentations:
10-1563 The Relationship between Hip Disease and Scoliosis in Children with Cerebral Palsy

The purpose of this retrospective review is to ascertain whether long spine fixation in children with spastic cerebral palsy with concomitant scoliosis accelerates the frequency or has no effect on hip subluxation/dislocation, given this cohort’s already preexisting propensity for hip pathology.

Collaborators: Garg S, Chang F, Miller N.

11-0660 Apparent Equinus Gait in Children with Cerebral Palsy, A Quantitative Analysis

This retrospective project is reviewing patients with spastic cerebral palsy and equinus gait who were assessed at the Center for Gait and Movement Analysis. The primary goal of this study is to characterize apparent and true equinus using quantitative gait analysis and kinetic, kinematic, and force elements. This study is hoping to characterize apparent and true equinus using quantitative gait analysis and determine if there are distinct or differentiating features of apparent and true equinus gait patterns.

Collaborators: Halgrimson W, Rhodes J, Davies K, Sinha A
PROSPECTIVE PROJECTS

04-0981 Efficacy of an Anesthetic Continuous-Infusion Device for Pain Management after Minor Surgical Procedures in Children with Cerebral Palsy

This prospective research project, conducted in collaboration with the Department of Anesthesia of TCH and funded by the Research Institute of TCH, examined the effectiveness of a continuous infusion pump used in conjunction with oral analgesics in patients with cerebral palsy after minor surgical procedures. The project has been completed and the final paper was published in 2010.


Paper/Presentations

06-0794 Rhythmic Auditory Stimulation as a Gait Intervention for Children with Cerebral Palsy

This prospective intervention study evaluated the effects of rhythmic auditory stimulation on walking speed and walking patterns in children with cerebral palsy. Rhythmic auditory stimulation involves walking practice while listening to music with an embedded rhythm. This project was funded by the Research Institute of The Children’s Hospital. The training protocol and experimental paradigm have been finalized, and data collection has been completed. Preliminary findings are promising in that they indicate that some children with cerebral palsy increased walking velocity by increasing step length, instead of increasing the number of steps, a difficult achievement for children with cerebral palsy.

Collaborators: Carollo JJ, Thaut M (Colorado State University), Davis J.
06-0815 Measurement of Voluntary Motor Control in the Affected Upper Extremity of the Child with Hemiplegic Cerebral Palsy

This project, completed in 2010, examined motor control in the assisting hand of children with hemiplegic cerebral palsy as they engage in a functional bimanual task. It integrates kinematic measures of coordination with novel grip force measures as the child grips, holds and releases an experimental object. This project was funded by the Research Institute of The Children’s Hospital. Data collection and analysis have been completed. The current focus is on dissemination of findings and application of the findings to clinical evaluation and interventions.

Collaborators: Valvano J, Denniston, N, Davis J, Boulter T, Carollo JJ, Matthews D.

Presentations:


08-0050 Impact of Spinal Fusion Construct with Sacropelvic Fixation on Gait Dynamics

This prospective research project uses complex kinematic methods to evaluate the effects of spine fusion surgery using specialized instrumentation on walking performance in patients with and without neuromuscular scoliosis. In 2008, grant funding for this project ($126,500) was awarded by Medtronic, Minneapolis MN. This is a collaborative effort with the Musculoskeletal Research Center. In 2010, a high number of children were recruited into the study and post-surgery data will be completed in late summer of 2011.

Collaborators: Carollo JJ, Nicklas T, Hotchkiss M, Erikson MA, Miller NH.

08-0304 Anterior Knee Pain in Adolescents

Idiopathic, adolescent, anterior knee pain (AKP) is one of the most common yet poorly understood chief complaints in the pediatric and adolescent sports medicine community. Despite extensive study, the treatment methodology for this frequent disorder remains largely unsubstantiated and controversial. Within the last decade, the AKP literature has described a tendency for hip musculature weakness and abnormal femoral mechanics among females presenting with anterior knee pain. As a result, clinicians have suggested the potential for symptomatic improvement following selective hip and core strengthening.
Although the study investigators have observed positive treatment outcomes following selective hip and core strengthening protocols, little evidence has been published in the literature and moreover, all purported success within this institution is based on anecdotal evidence only. Therefore, the first primary aim of this pilot study is to evaluate the effectiveness of a standardized home-based, hip and core strengthening program in 8 adolescent females that are assumed to be symptomatic due to hip weakness and faulty femoral/pelvic mechanics. It is obvious that, based on this recently proposed theoretical relationship between strength deficiencies, hip/pelvic dysfunction and AKP, the success of any treatment for AKP related to hip/core strengthening is dependent upon the identification of patients with pathological femoral/pelvic mechanics and hip weakness. At this institution, the single limb squat test of functional hip strength is frequently employed by the study investigators as an in-office screening test to identify such patients. In practice, those patients that perform poorly during this test, as indicated by apparent deviations in femoral/pelvic alignment, are assumed to lack appropriate hip strength. However, the clinical assumption that poor performance and abnormal hip mechanics are related to hip weakness has not been formally documented in a symptomatic population nor has satisfactory performance been previously documented in an asymptomatic population. Therefore, the second primary aim of this pilot study is to use three dimensional kinematics and isokinetic strength testing to demonstrate that failures, based on the clinician’s observation, to perform to specified criterion during the SLS test are associated with predictable patterns of hip weakness and faulty pelvic/femoral mechanics. Furthermore, for the purpose of defining acceptable performance, objective measures of hip strength and lower extremity kinematics will also be collected from eight; age matched asymptomatic subjects demonstrating satisfactory performance in each of the specified criterions. The secondary aims of this study will be to test the effects that activity level and compliance have on the outcomes of the proposed intervention. The preliminary findings gained from this pilot study will serve as the basis for a random controlled trial in a much larger and non-gender exclusive adolescent population.


Presentations:

09-0150 Treadmill Training to Improve Gait in Children with Cerebral Palsy
This prospective pilot project evaluated the effects of treadmill training in helping children with moderate to severe cerebral palsy learn to walk. The specialized treadmill in the CGMA training room permits limb unloading which helps children to develop fundamental stepping patterns. A pilot study to document the validity and reliability of the CGMA treadmill apparatus and to develop effective strategies for guiding leg movements during the treadmill training was completed in 2010. This recent work was funded by a pilot grant from the Section on Pediatrics, American Physical Therapy Association.

Collaborators: Bodkin A, Carollo JJ.

Presentations:

10-0342 Measurement of Voluntary Motor Control in the Upper Extremity of Children with Down syndrome
This ongoing prospective study integrates kinematic measures of upper body movements with novel measures of grip force production to study upper extremity motor control in children with Down syndrome as they perform a functional task. This project will build on methods established in a pilot study that addressed upper extremity motor control in children with cerebral palsy (described below). A pilot grant ($20,000) was awarded to conduct this research by the Colorado Clinical and Translational Sciences Institute.

Collaborators: Valvano J, Winders P, Rapport MJ & Davis J, Carollo JJ.

10-0531 Comparison of Graft Materials Used in the Evans Calcaneal Lengthening in Children with Cerebral Palsy
A retrospective research project completed in summer 2008 provided the foundation for this prospective study which is in the patient recruitment and data collection phase. This prospective study will examine the outcome of the Evans surgical procedure, which corrects midfoot deformity in children with cerebral palsy, when bovine xenografts are used in comparison to cadaveric allografts. Currently, patients are being recruited and foot pressure measurements, radiographs, clinical evaluations and quality of life surveys are being completed for each subject.

Collaborators: Chang FM, Rhodes J, Miller N, Davies K.

10-0650 K3 Promoter Prosthetic Foot Attachment
The purpose of this prospective clinical study is to determine whether the Tensegrity Prosthetics, Inc. (TPI) K3 Promoter prosthetic foot attachment offers metabolic or stability
advantages over currently available prosthetic feet in individuals with unilateral, transtibial amputations. This prosthetic foot has two compliant joints that enable a smoother and more consistent gait motion. Tensegrity Prosthetics, Inc. provides funding for gait trials performed on the CGMA instrumented treadmill. Contractual arrangements have been finalized and permission to begin data collection has been granted by the Institutional Review Board.

Collaborators: Carollo JJ, Rifkin J & Davis J.

10-1111 Effects of Adapted Skiing and Snowboarding On Quality Of Life of Children With Physical Disabilities

This study is assesses quality of life in children with a physical disability before and after participating in The Children's Hospital Ski/Snowboard Program (HSP). It addresses the child's access to and participation in recreation enjoyed by young people in Colorado. This study will determine the level of child and parent satisfaction in specific aspects of quality of life including: physical activities and health, self-perception, friendships and participation at home and school. This project aims to increase awareness and participation in adaptive physical activities and to improve the health and happiness in the young skiers.

Collaborators: Chang FM, Davies K, Hotchkiss M

11-0041 Impact of VEPTR (Vertical Expandable Prosthetic Titanium Rib) Surgery on Chest Wall Dynamics

This prospective descriptive study involves development of a complex kinematic model for measuring chest wall dynamics during respiration in order to evaluate changes after surgery to improve respiratory function in children with severe spine deformities. Volume changes during different breathing maneuvers can be calculated through computer analysis of movement of reflective markers on the patient’s torso. This project has clinical application to children who undergo spine stabilization procedures that will affect chest expansion for respiration.

Collaborators: Nicklas T, Carollo JJ, Hotchkiss M, Erikson MA, Miller NH

11-1277 Effect of Adapted Skiing and Snowboarding on the Motor Function and Endurance of Children with Physical Disabilities

This study is examining the longitudinal influence of an adaptive skiing/snowboarding program on physical performance and endurance of children with disabilities. All physical and clinical measurements will be taken before and after the ski season over a period of three years with endurance and exertion data collections taking place during the ski season.

Collaborators: Chang F, Davies K, Valvano J, Kanai S, Faulk W, Carollo J.

Walking and its Effect on Health and Function in Individuals with Cerebral Palsy as they Transition to Adulthood: A Health Outcomes Study

Dr. James Carollo and colleagues from the University of Colorado Department Of Physical Medicine & Rehabilitation are proposing to conduct a comprehensive longitudinal study of walking ability and overall health status in young adults with cerebral palsy (CP). This population is particularly at risk since there is now substantial evidence that as people with CP grow into adulthood, they can display a variety of symptoms secondary to their primary condition that are mediated by pain and chronic fatigue, and lead to reduced activity and overall
mobility. We have identified a theoretical mechanism (narrative figure 1) that relates the 
diffuse but interrelated symptoms often reported, and may help explain their propensity for the 
musculoskeletal, metabolic, and cardiovascular conditions that this population is at risk for 
when they reach adulthood. All of these secondary conditions have the effect of decreasing the 
ability of the adult with CP to independently ambulate, which further reduces the overall level 
of activity, continues the downward spiral, and eventually leads to metabolic and cardiovascular 
dysfunction and an increased risk of mortality. Recognition of this mechanism is the reason we 
have placed so much emphasis on measuring gait performance in both children and young 
adults with CP, so that poor walking biomechanics can be identified and corrected before 
independent mobility is lost and overall health status is compromised. Clearly, preventive 
approaches to avoid health decline in individuals with CP are needed and warrant further 
investigation.

Therefore, the purpose of this study is to comprehensively evaluate the physical, 
metabolic, mood, cognition, and quality of life of a cohort of 72 young adults with cerebral 
palsy from Colorado who had previously been tested at the Center for Gait and Movement 
Analysis (CGMA) as children, adolescents, or teenagers. Using the information in our 
comprehensive patient registry created in 1999, we will identify subjects across several levels of 
walking ability, disease severity and greatest risk of decline for inclusion in the current study. 
As all members of the proposed cohort will have had instrumented gait analysis and a physical 
exam at our Center in the past, measures of their walking ability, biomechanics, their GMFCS 
level, and selected measures of strength, range of motion, and spasticity will be compared 
longitudinally. The remaining measures will serve as a cross-sectional sample of young adults 
with CP, focusing on the measures that commonly describe the secondary conditions most 
frequently reported, as well as a detailed physical, cognitive, and quality of life assessment. By 
combining both a longitudinal and cross-sectional study of individuals with CP, we hope to 
better understand the functional basis for the decline in health status often reported. 
Maximizing skills and optimizing rehabilitation care by focusing on the prevention of mobility 
decline in individuals with cerebral palsy will have a positive impact on the quality of life of 
this fragile and neglected population as they reach adulthood.

Collaborators: Carollo JJ, Heyn P
Currently being submitted to the National Institute on Disability and Rehabilitation 
Research for grant program.
TECHNICAL PROJECTS

09-0847 Chest Wall Dynamics Assessment Using Motion Capture

The purpose of this collaborative study with the Musculoskeletal Research Center is to validate optoelectronic plethysmography as a motion capture technique to accurately calculate volume changes in the chest based on the movement of the chest wall. This technique is helpful in pediatric populations where surface area of the chest wall is small and cooperation for complex procedures is limited.

Collaborators: Nicklas T, Benefield E, Hotchkiss M, Carollo J

10-0035 Use of Nonlinear and Conventional Gait Analysis Methods to Model Gait Abnormalities Associated with Spastic Cerebral Palsy

This ongoing retrospective study determined that inter-segmental coordination measures about the knee in children with cerebral palsy are related to conventional gait performance measures and that nonlinear coordination measures can be used to identify one of the four common gait abnormalities in cerebral palsy. Novel insights into the coordination dynamics of atypical gait patterns were gained from using nonlinear measures.

Collaborators: Worster K, Valvano J, Carollo JJ

Presentation:

11-0130 Validation of an Automated Computer Algorithm for Detecting Heel-Off and Foot Positions during Walking

The purpose of this retrospective study, completed in early 2011, was to validate a computer algorithm’s ability to accurately and consistently detect the heel-off gait event and classify the various possible foot positions during the stance period of gait. While deceptively easy to recognize observationally, it is sometimes problematic to detect heel-off automatically because of the variety of foot/floor contact patterns that may exist at initial contact and loading response in subjects with pathologic gait. Providing clinicians with automated tools to detect heel-off can facilitate the clinical gait analysis process and offer insights into how patterns of motion relate to overall gait performance.

Collaborators: Worster K, Carollo JJ

Presentation: