CYCLING AND WALKING BIOMECHANICS IN CHILDREN WITH CEREBRAL PALSY: A NOVEL APPROACH USING ASYMMETRIC CRANK ARMS

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DEDICATION

To my mother, whose unwavering support and encouragement have been my foundation, and to my father, whose memory continues to inspire and guide me every day, this dissertation is dedicated to them and the love they have shown me.

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ABSTRACT

Cerebral palsy (CP) describes a group of persistent disorders affecting movement and posture due to brain injury occurring in the developing fetal or infant brain. It is the most common physical disability in childhood. Children with CP face various biomechanical challenges that significantly impact their movement. The integration of quantitative biomechanical analysis in the study of individuals with CP, with the use of sophisticated data analysis tools like the gait profile score (GPS) and the gait variable score (GVS) for the analysis of evaluation of gait kinematic abnormalities and the walk dynamic motor control index (Walk-DMC) to analyze patterns of coordinated muscle activations, is fundamental for a thorough understanding and effective management of this highly individualized condition.

This series of interconnected studies analyzed biomechanical data to investigate the relationship between walking and cycling kinematics and neuromuscular control in typically developing (TD) individuals and individuals with CP. The first study adapted clinical gait analysis tools, GPS, GVS, and Walk-DMC, for a comparative analysis of walking and cycling at two different speeds in TD individuals. The second study used the adapted tools to examine the effects of asymmetric cycling at two different speeds in TD individuals. The third study applied the concepts from the first two studies to two individuals with CP.

Chapter 4 showed that walking and cycling have distinct movement profiles and there was no strong correlation between any of the kinematic variables between walking and cycling. Additionally, complexity of neuromuscular control decreased in walking

compared to cycling. Chapter 5 found no significant changes in kinematic deviations between different lengths of asymmetric crank. However, complexity of neuromuscular control increased with speed and decreased with shorter crank arm lengths. Chapter 6 showed two individuals with CP have varying changes in cycling deviations, from TD individuals, across different asymmetric crank arm lengths. The complexity of neuromuscular control decreased with speed and increased with shorter crank arms for the two individuals analyzed. Future research should expand on these analyses with a larger and more diverse CP population to validate and expand upon these findings.

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NOMENCLATURE

3D	Three-dimensional
ANOVA	Analysis of Variance
ASIS	Anterior Superior Iliac Spine
BDC	Bottom Dead Center
BMI	Body Mass Index
BW	Body Weight
CP	Cerebral Palsy
CPS	Cycling Profile Score
CVS	Cycling Variable Score
Cycle-DMC	Cycle Dynamic Motor Control
DMC	Dynamic Motor Control
EEG	Electroencephalogram
EMG	Electromyography
FAQ	Gillette Functional Assessment Questionnaire
FMS	Functional Mobility Scale
GAS	Goal Attainment Scaling
GDI	Gait Deviation Index
GPS	Gait Profile Score
GRF	Ground Reaction Force
GMA	General Movements Assessment
GMFCS	Gross Motor Function Classification System
GMFM	Gross Motor Function Measure

GVS	Gait Variable Score
HINE	Hammersmith Infant Neurological Examination
ICF	International Classification of Functioning, Disability and Health
ICF-CY	International Classification of Functioning, Disability and Health, Children and Youth
kg	Kilograms
m	Meter
MG	Medial Gastrocnemius Muscle
MRI	Magnetic Resonance Imaging
N	Newtons
Nm	Newton Meters
NMF	Non-Negative Matrix Factorization
PARQ+	Physical Activity Readiness Questionnaire
PODCI	Pediatric Outcomes Data Collection Instrument
PRF	Pedal Reaction Force
QGA	Quantitative Gait Analysis
RF	Rectus Femoris Muscle
ROM	Range of Motion
RPM	Revolutions per Minute
SCALE	Selective Control Assessment of the Lower Extremity
SENIAM	Surface Electromyography for Non-Invasive Assessment of Muscles
ST	Semitendinosus Muscle

SVD	Singular Value Decomposition
TA	Tibialis Anterior Muscle
TD	Typically Developing
TDC	Top Dead Center
VAF	Variance Accounted For
VL	Vastus Lateralis Muscle
W	Watts
Walk-DMC	Walk Dynamic Motor Control

Chapter 1: Introduction

Background and Rationale

Cerebral palsy (CP) is a broad term used to describe a group of persistent disorders affecting movement and posture, causing activity limitation due to an injury to the brain that occurred in the developing fetal or infant brain (*1-3*). These injuries, or lesions, can arise from a multitude of causes, including prenatal infections, genetic factors, or perinatal complications (*3-5*). CP is the most common physical disability in childhood, and its prevalence is estimated at approximately 2-3.6 per 1,000 live births (*2, 4, 6-9*). The spectrum of presentations of the disorder varies from very mild motor disturbances that are unnoticeable to the untrained individual, to profound motor and intellectual disabilities (*3, 10*). A central aspect of understanding and managing the physical manifestation of CP is quantitative biomechanical analyses.

Children with CP encounter a range of biomechanical challenges that significantly impact their movement and posture, varying notably with the type and severity of the disorder. Gait abnormalities are prevalent (*1, 11*), with common patterns, particularly pronounced in spastic type CP, including one or more of the following; increased knee flexion, hip flexion, and toe walking (*12-14*). Muscle spasticity leads to involuntary muscle contractions and joint contractures, most evident in spastic CP types (*3*). Muscle weakness is a prominent and consistent feature in children with CP, placing them at a disadvantage compared to their typically developing (TD) peers (*1, 15, 16*). In children with CP, poor motor control and coordination are also major challenges that affect

balance, and movement (*3, 17, 18*). Joint and postural instability, crucial factors impacting balance and coordination, are common in CP (*19*).

The severity and type of CP influence the nature of these biomechanical challenges. Spastic CP, characterized by increased muscle tone and reflexes, shows a correlation between the degree of spasticity and the severity of motor control issues (*20*). The Gross Motor Function Classification System (GMFCS) is a useful tool for categorizing the severity of CP, with higher GMFCS levels indicating more severe mobility limitations and correlating with more complex biomechanical challenges (*21*). This comprehensive understanding of the biomechanical challenges in CP, based on the type and severity, is crucial for developing tailored interventions and addressing the diverse needs of children with this condition.

The integration of quantitative biomechanical analysis in the study of CP is fundamental for a thorough understanding and effective management of the condition (*22-25*). This analytical approach provides a detailed and objective assessment of the complex motor dysfunctions associated with CP. Quantitative biomechanical analysis, including sophisticated data analysis tools like the Gait Deviation Index (GDI) (*26*) and the Gait Profile Score (GPS) (*27*) offer a comprehensive evaluation of gait kinematic abnormalities while the Walk Dynamic Motor Control Index (Walk-DMC) and variance accounted for from one synergy (VAF) (*28*) analyzes patterns of coordinated muscle activations. These tools encapsulate the multifaceted nature of gait deviations, crucial for accurately diagnosing, monitoring, and tailoring interventions for individuals with CP (*23, 25*)..

The application of biomechanical analysis extends beyond gait assessment. It encompasses the evaluation of muscle strength, joint range of motion (ROM), and overall motor function (*22, 23, 25, 29*). For example, the Selective Control Assessment of the Lower Extremity (SCALE) is a clinical tool designed to evaluate selective motor control in the lower limbs of children with CP. It assesses the ability to perform isolated movements at different joints (hips, knees, ankles, subtalar, and toes), using a scoring system ranging from 0 (no control) to 2 (normal control) (*30*). By quantitatively measuring these aspects, clinicians and researchers can better understand the specific impairments and functional limitations that children with CP face. This level of analysis is essential in determining the severity and type of CP, which varies widely among individuals. Moreover, quantitative biomechanical analysis plays a pivotal role in the development and assessment of therapeutic interventions (*22*). By providing objective data, it allows for the monitoring of progress over time and the effectiveness of various treatments. This is particularly important in CP, where treatment plans are often highly personalized and need to be adjusted based on the individual's response.

Despite advancements in CP research, significant gaps remain, especially concerning dynamic activities such as cycling and their relationship with more commonly studied functions like walking. An area that lacks in-depth exploration is the comparative biomechanical analysis between walking and cycling. Cycling offers significant benefits to children with CP as the rhythmic and repetitive motion can help reduce muscle spasticity while simultaneously improving their muscle strength, endurance, and joint

mobility (*31, 32*). Cycling not only enhances cardiovascular health but also fosters a sense of independence and boosts self-esteem in children with CP (*33*).

Research predominantly focuses on isolated aspects of CP mobility, often neglecting the interplay between different motor tasks (*1, 34, 35*). This limited perspective hinders a comprehensive understanding of the diverse mobility challenges in CP. Additionally, there's a notable deficiency in studies examining how variations in speed affect walking and cycling biomechanics in CP. Speed-related changes can significantly impact muscle activation patterns and joint kinematics, yet this aspect remains underexplored (*36*). Furthermore, the complexity of neuromuscular control in individuals with CP, particularly in dynamic contexts like the comparison between different activities, has not been addressed in existing literature. This gap is critical as it impedes the development of targeted interventions for specific motor control challenges faced by individuals with CP.

Lastly, the biomechanical effects of assistive technologies, such as asymmetric crank arm lengths in cycling for children with unilateral CP, have not been adequately studied. Relevant research by Millour et al. (*37*) investigated the effects of varying crank arm lengths on cyclists with different limb length discrepancies, and found that shorter crank arms for the shorter limb improved joint kinematics and cycling performance by reducing joint ROM and enhancing comfort and crank power output. Further research confirmed that asymmetric crank arms decrease joint ROM and velocities on the shorter limb side without affecting the unaltered side in TD individuals (*38, 39*). This lack of research on asymmetric crank arm cycling limits our ability to optimize assistive and

therapeutic devices, and their prescriptions, which can significantly enhance mobility and independence for those with CP.

Statement of the Problem

Despite advances in treatment and care for children with CP, significant gaps remain in our understanding of their biomechanical challenges, especially in dynamic activities like cycling. Current research predominantly focuses on isolated aspects of CP mobility, often neglecting how these children manage complex motor tasks in different contexts. This lack of comprehensive insight hinders the development of targeted interventions that effectively address their unique movement challenges. These gaps underscore the need for more holistic research approaches in CP that encompass a range of dynamic activities and their interrelated biomechanical aspects. Addressing these areas is vital for advancing pediatric rehabilitation, fostering the development of comprehensive and effective interventions, and improving the quality of life for individuals with CP.

There is a limited understanding of the relationship between walking and cycling biomechanics in children with CP. Existing literature does not sufficiently explore how deviations in TD movements for individuals with CP correlate between different tasks. Additionally, there is an underrepresentation of research exploring muscle synergy complexity in CP, especially in contrasting movement contexts. This gap in knowledge impedes the creation of holistic rehabilitation programs that can adapt to the changing needs of these children as they engage in different activities. Moreover, there is a lack of specific focus on the biomechanical effects of assistive technology adaptations, such as

asymmetric crank arm lengths in cycling for children with unilateral CP. Understanding how these adaptations affect lower extremity cycling biomechanics is vital for optimizing assistive devices.

The problem this dissertation aimed to address is the insufficient understanding of the interplay between different movement challenges in children with CP. This research gap hinders the development of comprehensive, effective, and personalized interventions. Addressing this problem is crucial not only for enhancing the quality of life for children with CP but also for advancing the field of pediatric rehabilitation as a whole.

Statement of Purpose

This series of interconnected studies utilized experimental designs and 3D motion capture technology to gather and analyze quantitative biomechanical data. The first objective was to adapt established gait analysis tools, GPS, GVS, and VAF, to analyze walking at a fast speed and create a cycling profile score (CPS) and a cycling variable score (CVS) for the biomechanical analysis of walking and cycling at two different speeds for TD individuals to investigate the relationship between walking and cycling kinematics and neuromuscular control in this population. In addition to using the traditional nine kinematic variables to calculate the GVS, this study incorporated trunk segment position relative to the lab across all three planes of movement, expanding the analysis to twelve kinematic variables to generate a more detailed CVS. By examining and correlating walking and cycling deviations, we aim to understand how these activities are interrelated and how they are affected by speed. The second aim was to examine the

effects of cycling with asymmetric crank arms utilizing the adapted gait analysis tools. This will provide insights into the adaptive mechanisms of individuals without CP. The third and crucial aspect of this research focused on the biomechanical effects of using asymmetric crank arms in cycling for children with unilateral CP. This study explored how modifying the crank arm length for the affected limb of individuals with unilateral CP influenced lower extremity cycling biomechanics. It sought to understand whether such adjustments can facilitate movement patterns that are closer to a TD population.

Research Hypotheses

1. Study One: The purpose was to examine the relationship between walking kinematic deviations and cycling kinematic deviations at two different speeds by using a published gait deviation index, GPS and GVS (*27*) and adjusting it for cycling in TD individuals to create a CPS and CVS. Additionally to examine the complexity of neuromuscular control during walking and cycling at two different speeds, using VAF, in TD individuals.
    - First Hypothesis: CPS and CVS scores will decrease, compared to GPS and GVS scores, due to the constrained nature of the movement and scores are expected to increase with speed in both walking and cycling trials .
    - Second Hypothesis: VAF will increase with cycling, indicating a more simplistic movement pattern. This is because walking involves a unique interplay between joints, where one joint may be flexing while another is extending, whereas in cycling, the joints work more in unison to lengthen

or shorten the limb. VAF is also expected to increase with speed due to the overall increased activation of all muscles.

- Third Hypothesis: There will be a strong positive correlation between walking and cycling scores.

2. Study Two: The purpose was to examine the effects of shortened crankarm lengths on CPS and CVS, VAF, and self-selected cadences during asymmetric cycling in TD individuals, compared to cycling with symmetric crank arm lengths.
    - First Hypothesis: CPS and CVS scores will remain constant with asymmetric cycling due to the constrained nature of the movement, However, these scores are expected to increase with speed.
    - Second Hypothesis: Despite changes in joint range of motion, it is anticipated that VAF will remain constant with asymmetric changes to the crank arm length because the overall movement pattern is similar. VAF is also expected to increase with speed due to the overall increased activation of all muscles
    - Third Hypothesis: Self-selected cadence will not significantly differ between symmetric and asymmetric crank arm lengths, as the presence of one shorter crank arm will be counterbalanced by the unchanged length of the other crank arm.
3. Study Three: The purpose was to explore the the relationship between walking kinematic deviations and cycling kinematic deviations are two different speeds in

two individuals with CP. Additionally to examine the complexity of neuromuscular control during walking and cycling at two different speeds. Moreover, we sought to adapt bicycles for individuals with unilateral CP by shortening the crank arm on the side with the affected limb and assess the impact of these modifications on kinematic deviations, complexity of neuromuscular control, and self-selected cadence.

Significance of the Study

The research project holds substantial significance for the CP community due to the focus on the biomechanical challenges of children with CP, particularly in walking and cycling. Firstly, it aims to demonstrate an improved understanding of these biomechanical challenges, which is crucial for better diagnosis and addressing the specific needs of children with CP. This enhanced knowledge base could directly inform the development of more effective rehabilitation strategies, tailoring interventions to individual needs based on a deeper understanding of walking and cycling deviations, and changes in muscle synergy complexity. Furthermore, the potential advancements in assistive technology, particularly from the study on asymmetric crank arm lengths in cycling, could significantly impact the design of assistive and/or adapted devices, leading to innovations that better support the rehabilitation and exercise needs of children with unilateral CP. These findings might not only benefit the CP community but could also be transferable to other contexts where similar physical asymmetric challenges are present, thereby broadening the impact of the research. The research findings may provide valuable contributions to the literature on CP, potentially offering new theories.

Clinically, this could translate into revised assessment and treatment protocols for children with CP. Ultimately, the most profound impact of this research lies in its potential to enhance the quality of life for children with CP. By improving understanding and treatment, the research aims to make daily activities like walking and cycling more manageable and enjoyable, significantly affecting their overall well-being and independence. Thus, this research stands to make a considerable difference in both theoretical knowledge and practical application, with implications for children with CP and related conditions.

Overall, this research aimed to not only enhance theoretical understanding of motor control correlations in different activities for individuals with CP but also to have practical implications. The findings are expected to assist therapists in designing more effective rehabilitation protocols and provide valuable insights for manufacturers of adapted equipment, leading to improved product designs such as adjustable bike components. This research aims to contribute significantly to improving the quality of life and functional capabilities of individuals with CP.

Limitations of the Study

The following limitations were present in the current study:

1. Data from Testing Under Controlled Laboratory Conditions: The outcomes of the research may be influenced by the controlled laboratory settings, which might not replicate real-world conditions.

2. Inaccuracies in Kinematic Data and Inverse Dynamics Calculations: Potential errors in the placement and motion artifacts of retroreflective markers can lead to inaccuracies in kinematic data and subsequent inverse dynamics calculations.
3. Marker Placement on Shoes: Using foot tracking markers on shoes rather than directly on the skin can lead to inaccuracies. This approach may not accurately capture the foot's movement inside the shoe, potentially skewing kinematic data.
4. Self-Selection Bias: The participant recruitment method may lead to self-selection bias. The individuals who respond to flyers might not be representative of the broader population of children with cerebral palsy. This could include factors such as differing levels of motivation, awareness, and accessibility to the doctors' offices where the flyers are placed.
5. Limited Reach: Flyers in doctors' offices might only reach a certain subset of the target population, potentially excluding those who do not regularly visit these specific offices or who have less access to healthcare facilities.
6. Socioeconomic and Geographic Limitations: The socioeconomic and geographic backgrounds of the participants may be limited to those who live in certain areas or have certain healthcare access levels. This could skew the sample towards certain demographics.
7. Health Status Representation: The health status of children who visit doctors' offices may not accurately represent the entire spectrum of cerebral palsy severity. For instance, it might be more likely to attract participants with more severe

conditions who require frequent medical visits, or conversely, those with milder conditions who are more mobile and likely to see such flyers.

8. Influence of Caregivers or Parents: The decision to participate might be influenced more by the caregivers or parents who see the flyers, rather than the children themselves, which could introduce another layer of selection bias.
9. Sample Size and Diversity: The findings may be limited by the size and diversity of the participant group, which might not be representative of the broader CP population.
10. Specificity to CP Types: Variations in CP types and severity levels may limit the applicability of the findings to the entire spectrum of the condition.
11. Compliance and Fatigue in Participants: The ability of children to comply with testing protocols and potential fatigue can influence the outcomes.

Delimitations of the Study

Optimized marker placement is essential in minimizing motion artifacts during 3D motion capture to ensure the most accurate data was collected. Individual retroreflective markers were strategically placed on prominent bony landmarks. This specific placement was critical because bony landmarks provide stable, anatomically correct locations with minimal soft tissue movement, ensuring that the markers remain in a consistent position relative to the underlying bone. Additionally, to track the motion of different body segments during testing, semi-rigid thermoplastic shells equipped with a cluster of four non-collinear retroreflective markers were used. These shells were affixed to the body using neoprene straps, which provide a secure yet flexible attachment. The

non-collinear arrangement of the markers on each shell prevents the markers from aligning in a straight-line during movement, which can cause difficulties in accurately determining their spatial positions. By using clusters on semi-rigid shells, the motion capture system more accurately tracked the 3D movement of each body segment,

The inclusion criteria for participants with CP recruitment were as follows:

- Ages: 10-30
- Diagnosis of unilateral cerebral palsy.
- GMFCS level I and II.
- Male or female.

The exclusion criteria for participants with CP recruitment were as follows:

- For participants aged 18 years or above: A (Body Mass Index) BMI of 30 or greater.
- For participants aged 12 to 17 years: A BMI at or above the 95th percentile for their specific age, as per standardized pediatric BMI charts (Appendix M - Appendix N).
- GMFCS greater than II.
- Less than 12 months post lower extremity orthopedic surgery.
- Currently taking and/or took baclofen in the past 10 weeks.
- Has undergone lower extremity Botox injections within the past 10 weeks.
- Has a neurological or cardiovascular condition that prevents walking or cycling.
- Pregnant or nursing.

The inclusion criteria for TD participant recruitment were as follows:

- Ages: 10-30.
- Male or female.
- Recreationally active, defined as at least 30 minutes of exercise at least two days a week.

The exclusion criteria for TD participant recruitment were as follows:

- For participants aged 18 years or above: A BMI of 30 or greater.
- For participants aged 10 to 17 years: A BMI at or above the 95th percentile for their specific age, as per standardized pediatric BMI charts (Appendix M - Appendix N).
- Lower extremity surgery within the past 12 months.
- Has a neurological or cardiovascular condition that prevents walking or cycling.
- Pregnant or nursing.

Assumptions of the Study

1. Homogeneity within Groups: Assumes that individuals within the CP and TD groups are relatively homogeneous in terms of their motor abilities and general health conditions, aside from their CP status.
2. Age as a non-factor: Presumes that the age range of 10-30 does not significantly impact the motor abilities or biomechanical patterns within each group, i.e., a 10-year-old's gait is comparable to a 30-year-old's gait within the same group (*40*).

3. Consistency in Movement Patterns: Assumes that individuals will exhibit consistent walking and cycling patterns during each trial, meaning their movement does not vary significantly from one trial to another.
4. Effect of CP on Movement: CP affects walking and cycling movements in a specific, measurable way that can be compared to TD individuals.
5. Reliability of Measurement Tools: Assumes that the tools and methods used to measure biomechanical movements are accurate and reliable for both CP and TD individuals.
6. Health and Typical Movement in TD Group: Assumes that individuals in the TD group are in good health and exhibit typical motor and biomechanical patterns for their age group. This means they do not have any conditions or impairments that significantly affect their movement or physical abilities, thereby providing a standard baseline for comparison with the CP group.
7. Environmental Consistency: Assumes that the environment in which the tests are conducted (like surface, footwear, cycle ergonomics) is consistent across all trials and does not differentially affect the performance of the participants.
8. Generalizability of Findings: Assumes that the findings from this study can be generalized to the broader population of individuals with CP and TD individuals in this age range.
9. Non-Influence of External Factors: Assumes that external factors such as medication, previous physical therapy, or other health conditions do not significantly influence the biomechanical patterns observed in the study.

10. Participant Honesty in Self-Reporting: Assumes that participants will offer truthful and accurate answers when responding to screening and health history questions.

Chapter 2: Review of the Literature

Introduction

The purpose of the first study was to examine the relationship between cerebral palsy (CP) walking kinematic deviations and cycling kinematic deviations from a typically developing (TD) and healthy pattern. The purpose of the second study was to examine if muscle synergy complexity changes between walking at two different speeds and cycling at two different speeds in children with CP. The purpose of the third study was to explore how asymmetric crank arm lengths impact the hip, knee, and ankle biomechanics in patients with CP, particularly the effects of a shorter crank arm on the affected limb in children with hemiplegic type CP.

The focus of this chapter is to summarize CP and the effects of the disease musculoskeletal system and movement patterns. This chapter will also review existing literature on biomechanics of cycling in a healthy population and individuals with CP.

Cerebral Palsy

What is Cerebral Palsy?

CP is a broad term used to describe a group of persistent disorders affecting movement and posture, causing activity limitation due to an injury to the brain that occurred in the developing fetal or infant brain (*1-3*). These injuries, or lesions, can arise from a multitude of causes, including prenatal infections, genetic factors, or perinatal complications (*3-5*). CP is the most common physical disability in childhood, its prevalence was estimated at approximately 2-3.6 per 1,000 live births (*2, 4, 6-9*). The spectrum of presentations of the disorder varies from very mild motor disturbances that

are unnoticeable to the untrained individual, to profound motor and intellectual disabilities (*3, 10*). A central aspect of understanding and managing the physical manifestation of CP is quantitative biomechanical analyses. This approach provides clinicians with invaluable insights into the altered movement patterns, muscle imbalances, and joint dynamics in individuals with CP. Such biomechanical insights have long been integrated into therapeutic strategies, driving interventions that are tailored to the unique mechanical and neuromuscular challenges faced by each individual. Interdisciplinary approaches, which combine therapeutic and surgical interventions with in-depth biomechanical understanding, have continually demonstrated positive outcomes in managing CP.

Little's Disease. In the early 1800s, there was a desire to better understand the clinical manifestations of brain lesions with many French publications by pathologists debating the association of hemiplegia of the body with hemiatrophy of the brain identified post-mortem (*6*). In a series of lectures in 1843 entitled, "Deformities of the Human Frame," Dr. Willliam John Little discussed joint contractures and deformities resulting from long-standing spasticity and paralysis. Furthermore, in 1862, Dr. Little published his pivotal work (*41*), which emphasized the impact of "abnormal parturition" on the physical and mental conditions of children, highlighting conditions that resemble what we now understand as cerebral palsy. He indicated that the cause of the spasticity and paralysis was due to damage of the brain and perinatal asphyxia (*1, 6*). Dr. Little's contributions stand out during this period. His series of lectures appears to be one of the early medical discourses that directly linked physical deformities, such as joint

contractures due to spasticity and paralysis, with brain damage. By suggesting perinatal asphyxia as a potential cause, Dr. Little was one of the pioneers in understanding the etiological factors of this condition. Furthermore, the mention of perinatal asphyxia as a causative factor highlights the medical community's recognition of the vulnerability of the infant brain during birth and the potential long-term consequences of complications during this period (*1, 4, 6*).

Dr. William John Little's pioneering work in the mid-19th century laid the foundation for the understanding of a neurological condition that primarily affected movement and posture in children. Due to his significant contributions, the condition was initially termed "Little's disease." However, as medical understanding of the disorder evolved, there was a shift in nomenclature. In 1889, Sir William Osler, a renowned British physician, introduced the term "cerebral palsy" in his publication "The Cerebral Palsies of Children" (*42*). This new term more accurately reflected the condition's origin in the brain (cerebral) and its manifestation as a movement disorder (palsy). Over time, cerebral palsy became the widely accepted term in medical literature, replacing the earlier "Little's disease" (*6*).

Causes of Cerebral Palsy. CP is a complex and multifaceted group of neurological disorders that stem from disturbances in the developing brain. These disturbances can be classified based on when they occurred relative to birth: prenatal, perinatal, and post-natal. Prenatal disturbances occur during fetal development, or before birth, and account for the majority of cases of CP, estimated at 70% to 80% of all diagnoses of CP (*2, 20, 43-47*). Some infections, excluding upper respiratory tract and

gastrointestinal infections, contracted by the mother during pregnancy can significantly interfere with fetal brain development and contribute to the onset of CP (*7, 48*). Additionally, genetic abnormalities that influence the formation and maturation of brain structures can predispose an unborn child to CP (*49*). A recent study performed cohort-based whole exome and whole genome sequencing to identify genetic and copy number variant analyses and identified genetic factors as a major cause of CP (*5*). This genetic understanding is reshaping the diagnostic criteria for CP, underlining that genetic findings complement rather than contradict CP diagnosis, and opens new avenues for targeted, mechanism-based interventions (*5*). Another risk is maternal exposure to harmful substances. For instance, the consumption of alcohol or specific drugs during pregnancy can detrimentally affect the developing brain, leading to structural and functional abnormalities associated with CP (*20, 50*). Furthermore, disruptions or reductions in the oxygen supply to the fetal brain can result in conditions like periventricular leukomalacia, a recognized precursor to CP (*51*). Another prenatal cause of CP is fetal or in utero strokes (cerebrovascular accidents). These are defined as interruptions of blood supply to the developing brain of the fetus. Causes can include blood clots in the placenta or fetal brain, ruptured blood vessels, or other vascular abnormalities (*52*). The resulting brain damage often leads to lesions in the white or gray matter, which can disrupt the development of essential motor pathways. Impairment of these pathways can result in the motor disabilities commonly observed in CP, such as spasticity, muscle weakness, and balance and coordination issues.

Perinatal factors, encompassing events around the time of birth, significantly contribute to the onset of CP. Complications during labor and delivery, such as prolonged or obstructed labor, can lead to a lack of oxygen or physical trauma to the infant's brain, heightening the risk for CP. However, this accounts for only a small proportion of newborn encephalopathy in resource rich healthcare settings (*53, 54*). Additionally, neonatal infections like meningitis or encephalitis can cause inflammation and subsequent damage to the neonate's brain, serving as a potential precursor to CP (*55*). Another perinatal contributor is neonatal asphyxia, a condition where the newborn does not establish regular breathing immediately after birth, leading to reduced oxygen supply to the brain, and consequently, an increased chance of CP (*20*). Premature birth, especially those occurring before 28 weeks of gestation, significantly raises the vulnerability of infants to CP, partly due to the immaturity of the brain and associated risks of intraventricular hemorrhage (*48, 56*).

Postnatal factors occurring after birth also play a crucial role in the development of CP. Infections during infancy have long been recognized as significant contributors to neurological complications, such as CP. For example, bacterial meningitis is a severe and sometimes lethal infection of the membranes covering the brain and spinal cord. Infants with bacterial meningitis often experience inflammation of the brain, leading to possible cerebral damage (*57, 58*). Similarly, viral encephalitis, an inflammation of the brain tissue caused by viruses, can have devastating outcomes. If not diagnosed and treated promptly, it can result in extensive brain damage (*59*). Traumatic brain injuries, whether from accidents or child abuse, can also result in brain lesions that manifest as CP (*60*).

Additionally, complications arising from severe untreated neonatal jaundice can lead to bilirubin-induced brain damage and subsequent CP (*61*). Seizure disorders during early childhood can further pose a risk, as they often carry the potential for lasting consequences. While a single seizure is not necessarily alarming, recurrent seizures, can have profound neurological repercussions (*62, 63*). The brain of young children is especially susceptible given its rapid developmental phase, and repeated or prolonged seizures can interfere with these critical growth processes, resulting in damage to the brain (*64*).

CP is a manifestation of a wide range of disturbances during critical periods of brain development, be they prenatal, perinatal, or postnatal. The etiological factors range from genetic predispositions and maternal infections to birth complications and postnatal injuries or infections. Each stage carries its own unique set of risks, with prenatal factors being the most predominant. Recognizing and mitigating these risk factors, where possible, is vital to preventing CP or minimizing the severity of CP.

Diagnosis and Symptoms of Cerebral Palsy. The diagnosis of CP often revolves around a combination of clinical examination and a detailed history, as there is not one definitive test for CP (*1, 8*). While symptoms generally involve issues with movement and coordination, the expression and severity of these symptoms can vary widely among affected individuals. Just as no two children are the same, the manifestations of CPs are uniquely individualized, with some children experiencing mild motor delays and others having more profound physical and cognitive challenges (*1, 65*). This variability

underscores the importance of personalized care through precision medicine and understanding in the management and support of children with CP (*9*).

Diagnosis of Cerebral Palsy. Diagnosis of CP is multifactorial and begins with an in-depth evaluation of the patient's medical history, focusing on prenatal, perinatal, and postnatal periods. Complications or events during pregnancy, such as infections or premature birth, can be instrumental in suggesting the likelihood of CP (*66*). A comprehensive physical examination, often conducted by a pediatrician or neurologist, includes an evaluation of developmental milestones, movements, muscle tone, and reflexes. Delays or abnormalities in motor developmental milestones in the first 1-2 years of life, like crawling, sitting, or walking often hint at CP (*67*). The General Movements Assessment (GMA) has been shown to be an effective clinical tool for early identification of CP. This non-invasive assessment evaluates spontaneous general movements (characterized by small, gentle, and variable movements of the neck, trunk, and limbs) in young infants, particularly between the ages of 9-20 weeks. Absence or abnormality of these movements can be indicative of CP (*68, 69*). The Hammersmith Infant Neurological Examination (HINE) is another tool that, when combined with GMA, can increase predictive accuracy of a diagnosis of CP (*70*).

For a more conclusive diagnosis, neuroimaging is crucial. Magnetic resonance imaging (MRI) is the most recommended neuroimaging method for diagnosing CP. In high-risk infants, an MRI can detect more than 80% of brain abnormalities related to CP, especially when performed in early infancy (*8*). This is crucial as brain lesions seen in MRI scans can aid in early diagnosis and provide information (*8, 66*). In cases with

accompanying seizures, electroencephalogram (EEG) monitors brain activity, while electromyography (EMG) is pivotal in assessing the electrical activity and health of muscles (*67*). Occasionally, additional laboratory tests, such as blood examinations, are requisitioned to eliminate other conditions manifesting similar symptoms (*67*).

Types of Cerebral Palsy. There are a variety of classification schemes for CPs. CP can be classified according to the main type of movement disorder involved. In this scheme there are four main types of CP: spastic, dyskinetic, ataxic, and mixed. Spastic CP is the most prevalent, accounting for about 70 – 80% of CP (*65*). It is characterized by muscle stiffness and joint contractions. Dyskinetic CP, also known as athetoid, affects 6.5 – 14.4% of individuals with CP (*71*). Individuals with this dyskinesia experience involuntary, fluctuating movements that can be slow and writhing or rapid and jerky. Maintaining posture can be a challenge, often making sitting or walking difficult. Ataxic Cerebral Palsy, which is responsible for 5 – 10% of CP cases, is marked by issues with balance and coordination, often resulting in shaky or imprecise movements (*72*). Fine motor tasks, such as buttoning shirts, can be problematic for those with Ataxic CP (*72*). Lastly, some individuals display symptoms of multiple types of CP and are classified under Mixed Cerebral Palsy with the combination of spastic-dyskinetic as the most common (*73*).

CP can also be classified into the specific regions, or topography of the body that are affected by the disease (*65*). Classifying CP by topography allows clinicians and researchers to delineate which areas of the body exhibit the muscle tone abnormalities and movement challenges characteristic of the condition (*1*). Monoplegia or monoparesis

describes a condition where only one limb, is impacted (*1, 8, 74*). In bilateral (diplegia or diparesis), the primary areas affected are both legs, though arms might also show symptoms to a lesser degree (*74*). Unilateral (hemiplegia or hemiparesis) indicates that one entire side of the body, including both an ipsilateral arm and leg, is affected (*8, 75*). Unilateral is the most prevalent of topography (*65*). When three limbs show symptoms, it's termed triplegia or triparesis, which might manifest as both legs and one arm (*4*). Lastly, Quadriplegia or quadriparesis means all four limbs are affected, and it's not uncommon for individuals with this classification to also experience abnormalities in muscle tone in their trunk, and occasionally, their neck and face (*3*). These topographical designations can be paired with descriptions of the movement disorder type, such as spastic or ataxic, to provide a more detailed diagnosis (*76*).

CP presents a range of mobility challenges, necessitating various classification tools to comprehensively understand and address the movement capabilities of affected individuals. The Selective Control Assessment of the Lower Extremity (SCALE) is a clinical tool designed to evaluate selective motor control in the lower limbs of children with cerebral palsy. It assesses the ability to perform isolated movements at different joints, (hips, knees, ankles, subtalar, and toes) without involuntary movements in other joints. Using a scoring system ranging from 0 (no control) to 2 (normal control), SCALE helps clinicians understand the extent of motor control difficulties (*30*). The Gross Motor Function Classification System (GMFCS) is a developmental trajectory classification scheme and serves as a broad metric, segmenting children with CP into five categories based on their self-initiated movement abilities, particularly focusing on walking, sitting,

and wheeled mobility (*21*). At Level I, children can move around with ease, typically running and jumping independently. While they might display slight coordination challenges and reduced speed, they usually do not need any mobility aids. Level II is characterized by children who walk on their own but might struggle on uneven terrains, inclines, or in crowded areas. Their ability to run or jump is somewhat compromised compared to their peers. Although they can climb stairs, the use of a handrail is necessary. In Level III, children predominantly rely on hand-held mobility devices, like walkers or crutches, to assist with walking. Climbing stairs is possible with a handrail, but assistance or protective measures are often necessary. For greater distances, these children might opt for wheeled mobility options. Children classified under Level IV possess limited self-mobility. They often resort to powered mobility devices or manual wheelchairs in many situations, though some individuals might walk short distances at home with the help of assistive tools. They typically need assistance with transfers and adjusting their position. Finally, Level V represents children with substantial mobility challenges. Their movement is highly restricted, even with the aid of advanced technologies. They require assistance in maintaining an upright posture and are primarily transported using a manual wheelchair, often needing specialized seating for proper support (*21*).

Although the GMFCS provides a widespread application, its general categorization might lack detail in specific mobility contexts. For a more detailed approach, the Gillette Functional Assessment Questionnaire (FAQ) delves deeper into functional mobility, employing a 10-level scale to assess the range and method of

mobility, from proficient walking to complete reliance on wheelchairs (*77*). However, neither GMFCS nor FAQ demarcates mobility based on contextual distance. Addressing this gap, the Functional Mobility Scale (FMS) (*78*) offers a unique approach. Designed explicitly for children with CP, the FMS evaluates mobility over three distinct distances: 5 meters (in-room), 50 meters (within a building), and 500 meters (community-level), providing insights into how a child's mobility transitions across different scenarios. The inclusion of these three tools in clinical assessments ensures a holistic understanding of a child's motor abilities and functional mobility, each offering distinct insights into the challenges and capabilities of children with CP. The combination of SCALE, GMFCS, FAQ, and FMS offers a comprehensive view of mobility in children with cerebral palsy. By integrating the insights from these tools, clinicians can better tailor interventions, promoting improved outcomes and a higher quality of life for affected individuals.

Biomechanics of Children with Cerebral Palsy

Children with CP often present with gait or movement abnormalities, altered muscle mechanics, and joint dysfunctions, which are influenced by muscle tone abnormalities, muscle imbalances, and impaired motor control (*12, 18*). These biomechanical deviations play a pivotal role in the functional limitations observed in these children and can provide insights into optimal therapeutic interventions. Understanding the underlying biomechanics associated with gait disruption and deviations can help clinicians, therapists, and researchers devise strategies that optimize movement, minimize pain, and improve overall quality of life for children with CP (*79*).

Biomechanical Differences in Children with Cerebral Palsy. In children with CP, particularly those with the spastic subtype, a marked increase in muscle tone, termed spasticity, becomes evident. This spasticity, characterized by a velocity-dependent resistance to muscle stretch, often results in joint stiffness, reduced range of movement, and functional limitations (*80, 81*). The persistent spasticity, combined with altered muscle activity patterns in children with CP, leads to significant transformations in their muscular architecture. There is an altered muscle-tendon interaction; the overall length of the muscular-tendon unit is short, the tendons are longer and stiffer, the muscle bellies are decreased in circumference and length, and the myofibrils are stretched, further limiting joint mobility (*16, 82, 83*). This muscle length reduction has been linked to a decreased number of sarcomeres (*83*). The shortening of the muscle bellies is linked with shorter muscle fascicles, leading to a reduced range of motion and diminished force generation capacity (*83, 84*).

Muscle weakness is a prominent and consistent feature in children with CP, placing them at a disadvantage compared to their TD peers. While the primary neural injury undeniably impacts muscle function, the etiology of this weakness is multifaceted (*1*). Beyond the initial neural impairment, secondary muscle changes further compound the weakness. Among these is a notable alteration in the distribution of muscle fiber types. Human muscles contain a mix of slow-twitch Type I and fast twitch Type II fibers; children with CP display an over-representation of Type I fibers, which are endurance-oriented, at the expense of the more forceful Type II fibers (*15*). This shift limits the muscle's capacity for rapid, high-force actions (*15*). The altered muscular composition

coupled with the decreased physiologic cross-sectional area limits the force generating capability of the muscles (*15, 16*).

A joint contracture describes the permanent shortening of muscles, tendons, or ligaments around a joint, resulting in a restricted range of motion and compromised joint function. One primary cause of these contractures is muscle spasticity (*3, 80*). Over extended periods, chronic spasticity can cause muscles to remain in a tightened state, creating anatomical shortening of the muscular-tendon unit (termed a myostatic deformity), leading to joint contractures. Further exacerbating the situation are muscle imbalances frequently seen in individuals with CP, where certain muscles overpower their antagonists due to varying degrees of weakness or spasticity. Such imbalances can draw a joint into an abnormal, persistent position (*3, 85*). Additionally, prolonged immobility, can be a significant contributor (*86*). As children with CP grow, the continuous pull from spastic muscles can adversely affect bone development, leading to joint deformities and furthering the risk of contractures (*18*). The connective tissue in tendons, ligaments, and joint capsules can lose elasticity (*85, 87*). The interplay of muscle spasticity, imbalances, growth dynamics, and changes in connective tissues all contribute to the complex presentation of joint contractures in children with CP.

Selective motor control is the ability to isolate the activation of a particular muscle or muscle group while performing a specific movement, without involuntarily engaging unrelated muscles. This is a pivotal aspect of coordinated movement. In children with CP, this selective control is often compromised. The neuromuscular disruption inherent in CP frequently manifests as difficulty in isolating movements,

leading to a scenario wherein attempts to mobilize certain muscles or joints inadvertently cause the co-activation of additional, unintended muscles (*3, 88*). This lack of selective motor control can be particularly evident in tasks requiring precision and fine motor skills, such as picking up an object or maintaining balance while walking. Increased co-activation not only impedes the execution of the desired movement but can also initiate unwanted, compensatory movements in other parts of the body. For instance, a child trying to extend the knee might simultaneously experience an undesired ankle plantarflexion because of the impaired selective control. This phenomenon not only affects the child's ability to perform specific tasks but also has broader implications for aspects like gait pattern, posture, and overall mobility (*3, 18*). The impaired selective control represents a significant barrier to functional independence in children with CP, affecting their ability to engage in everyday activities and limiting their participation in physical activities.

The coordination and timing of muscle activation during movement often deviate significantly in children with CP (*18*). One primary cause of these altered patterns is the excessive and abnormal co-contraction of agonist and antagonist muscles, limiting the range of motion and resulting in stiffness (*89*). The proper sequencing of muscle contractions, essential for smooth and functional movement, is also disrupted. Children with CP often experience delays in muscle activation, premature activation, or prolonged activation during tasks (*3, 90*). Furthermore, involuntary muscle spasms or reflexive movements can emerge, fueled by the neural disruptions inherent in CP, adding another layer of challenge to intentional movements (*3, 80*). Children might also inadvertently

activate multiple muscles or muscle groups, even when intending to engage only one, due to impaired selective motor control (*3*). This can lead to compensatory strategies, such as over-relying on specific muscle groups to achieve desired movements (*1*). The complex interplay of abnormal muscle activations, spasticity, and impaired selective control profoundly affects the movement capabilities in children with CP.

Gait deviations in children with CP manifest as a direct consequence of the muscular and neuromuscular impairments delineated above. The spasticity altered myo-architecture, muscle weakness, and impaired selective motor control shape their distinctive walking patterns. In a detailed classification by Winters (*12*), gait patterns in children with spastic hemiplegia were systematically classified to enhance clinical understanding. This was expanded by Rodda and Graham (*13, 14*) to include patterns seen in individuals with diplegia.

Hemiplegia gait can be divided into four gait patterns, or types, based on sagittal plane kinematics (Figure 1). Type 1 hemiplegia pattern is characterized by plantarflexion at the ankle during the swing phase of gait due to inability to selectively control the ankle dorsiflexors during this part of the gait cycle. There is no contracture at the ankle, therefore there is adequate dorsiflexion during the stance phase (*11-13*). In Type 2 hemiplegia, there is a static or dynamic contracture of the ankle plantarflexors that results in persistent plantarflexion of the ankle (equinus position) during the stance and swing phase (*11, 12*). Type 2 can be further divided into 2a and 2b. In Type 2a, there is equinus position of the ankle with a neutral knee and extended hip while Type 2b has recurvatum (hyperextension) of the knee (*11, 13*). Type 3 hemiplegia, is characterized with

plantarflexion spasticity or contracture and impaired knee motion due to knee flexor extensor muscle co-contraction that causes a “stiff knee gait” with reduced knee ROM (*11-13*). Type 4 hemiplegia presents similarly to Type 3 hemiplegia, however there are further proximal involvements at the hip. Involvement is unilateral and it causes multiplanar deficits in gait with hip adduction and in the transverse plane there is increased internal rotation of the hip and pelvic retraction (*11-13*).

Diplegia gait is divided into five groups (Figure 2) based on the position of the ankle, followed by the knee, hip, and pelvis (*11, 14*). Group 1 is termed "true equinus." In this group, the ankle adopts an equinus position, while the knee can either extend fully or exhibit a mild recurvatum (knee hyperextension). The hip joint extends fully, and the positioning of the pelvis remains either within the normal range or has a slight anterior tilt (*11, 14*). Group 2 is known as the "jump gait". Here, the ankle is in equinus, especially evident in the late stance phase. Early in the stance phase, both the knee and hip are excessively flexed, but as the phase progresses, they extend to some extent, although never reaching a full extension. Like Group 1, the pelvis in this group may lie within the normal range or be tilted anteriorly (*11, 14*). Group 3 describes the "apparent equinus". In this category, the ankle maintains a normal range of motion. However, the knee and hip joints remain excessively flexed throughout the stance phase. The pelvis either stays in the normal range or inclines anteriorly (*11, 14*). Group 4 is characterized as the "crouch gait". The distinct feature of this group is that the ankle remains excessively dorsiflexed throughout the stance phase. Moreover, both the knee and hip joints are persistently and excessively flexed. The pelvis in this group can either be in the normal

position, tilted anteriorly, or tilted posteriorly (*11, 14*). Lastly, Group 5 represents the "asymmetric gait". This is unique as the gait pattern is asymmetric, meaning each of the lower limbs may belong to separate groups. For instance, an individual's right lower limb might exhibit characteristics of Group 3, apparent equinus, while the left lower limb might correspond to Group 2, jump gait (*11, 14*).

Children with CP face a wide range of biomechanical challenges, from muscle imbalances and joint contractures to impaired selective motor control and coordination. These abnormalities are deeply rooted in both neural disruptions and secondary musculoskeletal changes, each contributing to the unique movement profile observed in these children.

Treatment and Management of Cerebral Palsy. While there have been significant advances in understanding and treating CP, current medical interventions cannot repair the damage to the specific brain areas responsible for muscle coordination and movement. Therefore, the primary focus of treatment for cerebral palsy has focused on managing the resultant physical impairments (*2, 91*). The absence of clinically meaningful interventions for the core brain injury necessitates a comprehensive approach towards managing the symptoms and improving the quality of life for individuals with CP (*91*).

A multi-disciplinary approach is pivotal in managing CP, requiring a cohesive team comprising pediatricians, neurologists, orthopedic surgeons, and various therapists (*9, 87*). Physical therapy, a staple in CP management, offers exercises to enhance balance, muscle strength, and flexibility (*92, 93*). Simultaneously, occupational therapy

aids in refining skills crucial for daily tasks, while speech and language therapy address communication and swallowing challenges (*94*). Some individuals may benefit from orthotic devices like ankle and foot braces, which optimize movement and correct deformities. Medications, including muscle relaxants like baclofen, are often prescribed to control muscle spasms or abnormal movements (*95*). In more severe cases, surgeries like orthopedic surgery or selective dorsal rhizotomy can be necessary to correct deformities or decrease spasticity (*22, 87, 96*). To further aid mobility and communication, assistive devices such as wheelchairs and communication aids (*97*) are indispensable. Beyond conventional therapies, recreational and behavioral therapies offer emotional and physical benefits (*98, 99*). Alternative therapies are occasionally utilized, such as acupuncture (*100*) or horseback riding, sometimes referred to as hippotherapy or equine-assisted therapy (*101*). The comprehensive management of cerebral palsy demands a blend of conventional medical interventions, therapeutic practices, assistive devices, and carefully chosen alternative therapies, all tailored to the individual's needs and carried out under the guidance of a skilled multi-disciplinary team.

Since the late 1980s, there has been the emergence of a new paradigm in orthopedic clinical decision-making for children with CP, emphasizing biomechanics, skeletal alignment, and movement analysis. This paradigm draws from a deeper understanding of normal gait kinematics, kinetics, and dynamic EMG (*22-24*). Modern technology allows precise measurements of gait of TD individuals, leading to age-matched profiles. The identification of typical gait patterns has greatly facilitated the identification of pathological gait deviations in children with CP. Not only has it allowed

for improved treatment in individuals with CP, it has allowed clinicians to differentiate pathologic gait in conditions like cerebral palsy, poliomyelitis, myelodysplasia, and spinal cord injuries so treatment can be customized to the individual (*29, 102*). Investigations into the anatomy and physiology of the muscle-tendon unit show the impact of factors like muscle mass, fiber length, and skeletal alignment on its functioning (*103, 104*). Quantitative gait analysis (QGA), though revolutionary, has faced challenges regarding acceptance in the clinical community due to cost, accuracy, and repeatability concerns (*105*). The process of orthopedic clinical decision-making should integrate clinical history, physical examination, diagnostic imaging, quantitative gait analysis, and examination under anesthesia (*22*). Despite the paradigm's potential, discrepancies in data can arise, underscoring the need for interdisciplinary collaboration to interpret findings accurately and ensure optimal interventions (*26, 105*).

QGA is a comprehensive method utilized to objectively assess and analyze walking patterns. This analysis method provides critical insights into the biomechanical and neuromuscular abnormalities inherent in CP, serving multiple purposes: pinpointing specific gait deviations, steering treatment decisions ranging from physical therapy to surgical interventions, evaluating intervention efficacy, and delivering objective metrics for disease progression or treatment outcomes (*102, 106*). Components of QGA include kinematics, kinetics, dynamic EMG during walking, and pedobarography. Occasionally, oxygen consumption is also evaluated to understand energy expenditure of walking (*23*). QGA plays a pivotal role in clinical applications, notably in planning orthopedic surgeries like bony surgeries, tendon transfers, or muscle lengthening. It is instrumental

in optimizing prescriptions for assistive devices like ankle-foot orthoses and tailoring physical therapy interventions (*107*).

However, the vast volume of data produced by QGA, especially when encompassing modalities like three-dimensional (3D) motion capture and EMG, presents a formidable challenge for interpretation. First and foremost, a comprehensive understanding of typical gait biomechanics is essential (*24*). This foundational knowledge allows clinicians to discern any deviations occurring in pathological gait. Furthermore, children with CP often manifest a range of distinct gait abnormalities (*108*). Recognizing these specific patterns and their biomechanical underpinnings is pivotal for effective therapeutic planning. Equally important is understanding the potential interventions available, ranging from physiotherapy techniques to surgical procedures, which can be tailored based on the identified gait abnormalities (*102*). Yet, amidst the sea of data, clinicians must possess the acumen to sieve through and pinpoint data that is clinically relevant and significant. This process often requires distinguishing critical information from noise (*26*). The process of integrating data from the domains of clinical history, physical examination, diagnostic imaging, and quantitative gait analysis utilizes a process commonly referred to as the diagnostic matrix (*22*). Moreover, the integration of diverse modalities, like merging insights from EMG with motion capture data, demands a holistic approach for a comprehensive understanding of gait abnormalities (*109*). In essence, the intricacies of managing and interpreting the extensive data from QGA necessitate systematic protocols, specialized software tools, and expertly trained personnel to ensure that the insights gleaned are both accurate and clinically actionable.

QGA is a sophisticated process used to identify and quantify deviations in an individual's walking pattern. With the myriad of variables and factors to consider, understanding gait deviations can be overwhelming (*23, 25*). To facilitate the interpretation of gait data and to provide a comprehensive assessment of overall gait kinematics quality, data analysis tools have been developed. The Gait Deviation Index (GDI) (*26*) and the Gait Profile Score (GPS) (*27*) are crucial quantitative tools developed to assess and encapsulate the overall quality of an individual's gait based on kinematics. Their main advantage lies in providing a single score that encapsulates the multifaceted nature of kinematic gait deviations, enhancing the evaluation and communication of gait abnormalities. The GDI's computation stems from analyzing kinematic data from nine pivotal bilateral lower limb joint and segment angles (pelvic tilt, pelvic obliquity, pelvic rotation, hip flexion, hip abduction/adduction, hip rotation, knee flexion, ankle plantarflexion/dorsiflexion, and foot progression angle), per side, during a gait cycle and contrasting this data with a reference dataset. The kinematic data from each gait cycle is extracted and normalized by time. This normalization allows the cycles to be directly comparable. These normalized gait cycles are then arranged into a matrix. Singular Value Decomposition (SVD) is applied to the matrix of gait data to break down the complex, multi-dimensional gait data into simpler, fundamental components. SVD separates the matrix into singular vectors and singular values, which capture the essence of the gait pattern in a reduced number of dimensions. These singular values are indicative of the variance in the gait data, with larger values representing components with greater variance. A reference dataset is constructed using the same process on gait data from

individuals with typical gait patterns. This reference set acts as a baseline for what is considered "normal" gait, providing the context needed for comparison.

The core of the GDI calculation is the comparison between the singular values derived from a patient's gait and those from the reference dataset. This comparison quantifies how much the patient's gait deviates from the typical pattern. Mathematically, it involves squaring the differences in principal components (derived from SVD) between the patient's gait and the normative gait, summing these squared differences, and then calculating the root of this sum. The resulting value is then subtracted from a base score, set at 100, which represents the mean of the reference population's gait pattern. Therefore, the GDI score is calculated as 100 minus the square root of the sum of squared differences in principal components. A score of 100, or above, indicates a gait that is on par with the normative mean, while lower scores point to greater deviation from typical gait patterns. The scale is set so that every 10 points below 100 corresponds to one standard deviation away from the normative mean, providing an intuitive measure of gait abnormality (*26*).

On the other hand, GPS provides an overarching measure of gait quality by calculating the Gait Variable Score (GVS) of the same kinematic variables utilized by GDI. The TD gait data is normalized and then averages are calculated for each of the kinematic variables across the gait cycle. This results in a mean kinematic curve for each variable. To calculate the GVS of each of the kinematic variables, the individual's deviation for each gait variable is calculated by subtracting the normative mean from the individual's gait at each point in the gait cycle and then a root mean square is calculated

for each of the kinematic variables. To arrive at the GPS, the RMS of the individual GVSs. This score consolidates the individual deviations into a single metric, where a higher GPS reflects a greater overall deviation from normal gait (*27*). Both indices give clinicians and researchers an invaluable, consolidated score, that simplifies the comprehension of abnormalities in gait kinematics. The advantage of the GPS score is that abnormalities in specific joints or segments can be identified.

Another data analysis tool has been developed to better understand how the neuromuscular control has been altered due to the brain lesion. Instead of merely focusing on traditional metrics like joint kinematics, the Walk Dynamic Motor Control Index (Walk-DMC) analyzes muscle synergies or patterns of coordinated muscle activations that represent modular neural control strategies (*28*). It has been shown that synergies are simplified during walking for individuals with CP compared with TD children and synergy complexity was correlated with diagnosis, functional impairment, and selective motor control (*28*). During gait surface EMG data from five muscles on each leg (typically the rectus femoris, medial hamstrings, lateral hamstrings, medial gastrocnemius, and anterior tibialis) are collected and processed (*28*). Once the EMG data from the lower limb muscles during gait are processed and prepared, it undergoes a non-negative matrix factorization (NMF), a form of factor analysis that decomposes high-dimensional EMG data into a smaller set of components, known as muscle synergies. These components are constrained to be non-negative, which aligns with the fact that muscles can only generate positive activation. NMF works by breaking down the multivariate EMG signals into two matrices: one that represents the muscle synergies and

another that represents the activation profiles of these synergies over time. The synergies matrix captures the weight or contribution of each muscle to a particular synergy, revealing how muscles are grouped and coordinated during movement. The activation profiles matrix reflects when and how strongly each synergy is activated during the gait cycle. The goal is to find the smallest number of synergies that can accurately reconstruct the original EMG signals, thus explaining the majority of the variability in the muscle activations. This reduces the complexity of the neuromuscular control needed for walking by representing it with fewer, more manageable building blocks.

Following the identification of these synergies, a detailed quantitative analysis ensues, focusing on the computation of specific synergy metrics. These metrics are critical in providing a comprehensive description of the quality and nature of an individual's motor control. Key metrics include the number of distinct synergies that the NMF algorithm identifies as necessary to explain most of the variance in the EMG data, the percentage of the overall variability accounted for by these synergies, and the temporal consistency of the synergy patterns across multiple gait cycles. Collectively, these metrics offer a multidimensional view of motor control, ranging from the complexity of the control strategy to the reliability and efficiency of muscle activations during the act of walking. The culmination of this analytical process is the determination of the Walk-DMC score. A Walk-DMC score of 100 represents an average synergy of a TD individual. Every 10-point divergence from this score signifies one standard deviation from the TD average. A lower Walk-DMC score indicates a greater deviation from normative neuromuscular control, pointing to more pronounced dynamic motor control

impairments during gait (*28, 110*). This detailed perspective provides diagnostic insight, guiding clinical interventions and helping practitioners determine suitable treatment approaches as it has been shown that a better Walk-DMC score is associated with better treatment outcomes (*110*). The Walk-DMC can enhance personalized rehabilitation for individuals with CP by highlighting the specific neuromuscular strategies that the individual employs. An increased understanding of their distinctive muscle activation patterns can tailor therapeutic interventions to the individual by not only focusing on kinematic differences or static deformities, but also incorporating dynamic muscular functions unique to each child.

QGA and other clinical assessments provide invaluable insights into the biomechanics and neuromuscular abnormalities inherent in CP. These tools allow clinicians to develop targeted, effective treatment plans. However, to truly encapsulate the full impact of CP on an individual's life, it is imperative to look beyond the clinical data QGA assessments provide through patient and parent-reported tools. These tools offer a unique perspective, capturing the day-to-day challenges, accomplishments, and overall quality of life as experienced by individuals with CP and their families. A comprehensive approach to managing CP must not only address the physiological and biomechanical dimensions but also embrace the personal narratives and lived experiences of those affected by the condition.

The International Classification of Functioning, Disability and Health (ICF) is a World Health Organization framework that offers a comprehensive view of health, emphasizing the interplay between health conditions and contextual factors (*111*). This

biopsychosocial model focuses on body functions and structures, activities, and participation as key components of health and functioning. The ICF framework shifts the therapeutic focus from solely addressing body function and structure impairments to including goals related to activity and social engagement. For children with CP, interventions are designed not just to treat motor impairments but also to enhance participation in daily activities and improve social interaction. This holistic approach recognizes the importance of integrating therapeutic goals into daily life, making therapy more relevant and engaging for the child and their family. In pediatric rehabilitation, the children and youth version of ICF (ICF-CY) specifically guides the evaluation and treatment program determination for children with CP, outlining impairments and suggesting various therapeutic approaches like neurodevelopmental therapy, goal-directed therapy, and family education (*111-114*). Another tool is the Pediatric Outcomes Data Collection Instrument (PODCI) It is designed to evaluate functional health and well-being in children with orthopedic conditions, including CP. It assesses various aspects of a child's life, including upper extremity function, mobility, physical activities, pain and comfort, and overall happiness. This instrument is crucial for understanding how orthopedic conditions impact a child's daily activities and quality of life, aiding in the development of targeted treatment plans and measuring their effectiveness (*115*).

Goal Attainment Scaling (GAS) and the Gross Motor Function Measure (GMFM) are essential tools in the management and assessment of children with CP. GAS is a technique that enables clinicians and families to set personalized, achievable goals for a child’s treatment and then evaluate the extent to which these goals have been met. This

method is highly individualized, ensuring that the goals are tailored to the child's specific needs and abilities, making it a flexible and valuable tool in treatment planning and assessment (*116*). In contrast, the GMFM is used to assess changes in gross motor function over time in children with CP. It provides a standardized approach to evaluate improvements or changes in motor functions such as sitting, walking, and standing. This tool is crucial for tracking the progress of motor skills in response to interventions, offering an objective measure of physical capabilities (*117*). Together, GAS and GMFM provide a comprehensive approach to setting personalized goals and measuring functional improvements in children with CP.

The treatment and management of CP represents a dynamic and multifaceted challenge that demands a comprehensive approach. While significant advances have been made in understanding and treating CP, the focus remains on managing physical impairments and improving quality of life through a variety of interventions. A multidisciplinary team approach, incorporating physical, occupational, and speech therapies, alongside medical and surgical interventions, forms the backbone of CP management. Innovations in quantitative gait analysis and the development of tools like the GDI, GPS, and Walk-DMC have revolutionized the assessment of motor functions and opened new avenues for personalized treatment plans. Equally important is the integration of patient and family perspectives into the treatment paradigm. Tools like the ICF, PODCI, GAS, and GMFM not only assess physical capabilities but also consider the personal goals and daily life challenges of individuals with CP. This holistic view ensures that treatment plans are not only medically sound but also aligned with the personal

aspirations and life contexts of those affected. Ultimately, the goal of CP management is not just to address the physical manifestations of the condition but to empower individuals with CP to lead fulfilling lives. This is achieved through a blend of cutting-edge medical interventions, empathetic care, and a deep commitment to understanding and meeting the unique needs of each individual.

Physical Activity in Children with Cerebral Palsy

For children with CP, physical activity offers a multitude of benefits, from improved muscle tone and muscular coordination to enhanced emotional well-being (*36*). However, these children face unique barriers when attempting to engage in regular exercise, such as limited mobility or societal perceptions (*10, 87*). Recognizing these challenges, it is paramount to consider specialized guidelines when developing physical activity programs tailored for this demographic to ensure their safety, engagement, and maximization of health benefits (*118*).

Benefits to Exercise. Children with CP often find themselves constrained in their day-to-day activities due to the physical manifestation of their brain lesion. However, the introduction of regular exercise into their routines can usher in a myriad of health benefits (*98*). Many of these children grapple with muscle weakness and spasticity as well as elevated risk of osteoporosis and fractures (*119*). Structured physical activities, notably resistance training, can not only enhance muscle strength but also boost the endurance and improve bone health in individuals with CP. Muscular strength training interventions have yielded substantial improvements in gait function. Strengthening programs have led to improved gait speed, stride length (*120, 121*), and better ankle,

knee, and hip extension during walking, while enhancing self-perception (*122*). The evidence suggests that muscular strengthening, even over short durations, can have beneficial effects on gait and self-image of children with CP (*120-122*). Research has also shown that integrating balance and stability training into physical therapy can lead to marked improvements in gait parameters (*123-125*). When stability training supplements traditional physical therapy, there is a notable enhancement in trunk muscle endurance and gait parameters compared to conventional therapy by itself (*123-125*). Moreover, plyometric and balance exercises have been recognized for their effectiveness in bolstering the isometric strength of essential muscle groups, which contributes to improved stability (*125*). These improvements are instrumental in mitigating muscle atrophy and enhancing stamina, enabling individuals with CP to tackle daily tasks with decreased difficulties and potentially become more active in recreational pursuits (*36, 126*).

Mobility is a significant challenge for children with CP. Techniques such as gait training can refine walking patterns, while holistic exercises like swimming can elevate overall body coordination (*98*). Cycling offers significant benefits to children with CP as the rhythmic and the repetitive motion can help reduce muscle spasticity while simultaneously improving their muscle strength, endurance, and joint mobility. Cycling not only enhances cardiovascular health but also fosters a sense of independence and boosts self-esteem in children with CP (*33*). Adapted bicycles and tricycles often feature supportive seating, stabilizing wheels, and customizable handlebars to cater to the individual physical needs of children with CP. Additionally, modifications like strapped

pedals and easy-to-use brakes enhance safety and accessibility, making cycling a feasible and enjoyable activity for these children (*127*). The inclusion of an adapted bicycle or tricycle can be beneficial because adapted cycling is less dependent on balance than walking (*128*).

Barriers to Exercise. Individuals with CP often encounter a multitude of barriers when attempting to engage in exercise and physical activities. Physical limitations due to the disease itself, such as muscle spasticity, (*1*), and joint contractures, hinder mobility (*98*). Additionally, balance issues inherent to some with CP can make activities that require coordination particularly challenging (*65*). However, beyond the physical, cognitive, and perceptual barriers, there exist additional layers of difficulty. Some individuals may grapple with cognitive impairments, impacting their comprehension or execution of exercises (*74*). Issues concerning proprioception or the sense of body position, can further complicate movement coordination (*129, 130*). Pain and fatigue are commonly reported among individuals with CP and it can be exacerbated by exercise, leading to reluctance in participation (*129*). From an environmental standpoint, many individuals face logistical challenges like the absence of adaptive exercise equipment or inaccessible fitness centers. This is compounded by a notable lack of expertise among fitness instructors or therapists in addressing the unique needs of the CP community (*129*). Individuals with CP face significant challenges in engaging in physical activities, stemming from physical, cognitive, and environmental barriers. Overcoming these requires tailored exercise programs, accessible equipment, and trained fitness professionals. By addressing these issues, we can improve participation and enhance the

well-being of the CP community, promoting a more inclusive and supportive environment for physical activity.

Considerations for Developing Physical Activity Programs for Children with Cerebral Palsy. Physical activity is an important factor in the growth and development of children both physiologically and socially. In children with CP, regular participation in physical activity can also reduce the severity of bone deformation and reduced muscle growth (*35*).

Designing effective physical activity programs for children with CP demands a thorough and individualized approach. The heterogeneity of CP implies a vast array of motor disabilities, highlighting the importance of tailored assessments and program design (*1*). Ensuring safety with both in equipment and environment, is paramount due the various challenges these children might face (*36*). The social dimension of these programs is also an important aspect as group activities have been shown to enhance social and community participation (*131*). Parents play a critical role in the progress of their children with CP, and their involvement has been correlated with more positive outcomes (*132*). Moreover, the dynamic nature of a child's growth necessitates the adaptability of the program, with consistent feedback loops. Integrating fun elements, like aquatic exercises, can provide both motivation and therapeutic benefits (*36*).

In addressing the unique needs of children with CP, physical activity emerges as a crucial component, offering both physiological and emotional benefits (*121*). However, its successful integration demands a holistic approach, combining tailored exercises,

parental involvement, and an environment of encouragement. Through concerted efforts, the quality of life and overall well-being for individuals with CP can be improved.

Cycling

Cycling is recognized not only as an environmentally friendly mode of transportation, but also as a physical activity that has significant potential for improving individual health and wellbeing (*133, 134*). Studies have consistently demonstrated that regular cycling can lead to a range of health benefits including improved cardiovascular fitness, increased muscle strength and flexibility, decreased stress levels, and better mental health (*135-138*).

Cycling Biomechanics

Cycling biomechanics is a specialized field that delves into the study of forces and the resulting motions of the human body while cycling. This discipline combines principles from both biomechanics and cycling science to understand and optimize the movements of a cyclist and interaction between the cyclist and the bicycle. A crucial aspect of this field is its unique nomenclature, which is essential for clear communication and understanding. This terminology not only defines specific movements and positions but also provides standardized language for researchers, clinicians, cyclists, and patients to discuss and assess cycling performance and technique. The following section will discuss literature regarding cycling biomechanics, delving into understanding components of a bike, bike fit methodology, cycling biomechanics, and cycling with individuals with CP.

Components of a Bicycle. The following is a brief overview of basic structures of a cycle. The saddle or seat of a bicycle is where the rider sits on a bicycle, tricycle, or cycle ergometer. The seat has three degrees of freedom to adjust; the seat height, fore-aft position, and seat tilt (*139*). Saddle height is the vertical position of the saddle. The fore-aft position of the saddle refers to the anterior-posterior position of the seat. Saddle tilt describes the inclination of the saddle in the sagittal plane. Adjustments to these three parameters will affect the kinematics and kinetics of the rider at the hip, knee, and ankle (*139-142*). The handlebar is the steering mechanism for bicycles; it is the part the rider holds on to. Changes in position of the hands on the handlebars were related to pelvic tilt and trunk angles (*140*). Pedals are platforms for the feet. The feet can be attached to the pedals with toe clips on the plantar surface of the shoe or with toe cages that go around the top of the foot. The pedals are the point of force application from the rider to the bike to propel the bicycle. During cycling, the riders will experience a reactionary force exerted by the pedals called pedal reaction force (PRF), which can be measured by pedals instrumented with force sensors (*140, 143*). The crankarm is the lever that connects the pedal to the front chainring. Crank arm length is measured from the center of the axis of rotation of the pedal to the center of the axis of the chainring and typical crank arm lengths for bicycles are 170 mm, 172.5 mm, and 175 mm, with 170 mm as the most common length (*144-146*). Crank torque, a key element in cycling mechanics, is the rotational force that the rider applies to the crank arm. This torque is crucial for converting the linear, normal and anterior-posterior, components of PRF exerted by the rider into the rotational motion necessary for cycling (*140*). The Q-factor of a bicycle or

cycle ergometer denotes the horizontal distance between the outermost surface of the crank arms and determines the mediolateral positioning of the feet. Essentially, a larger Q-factor indicates a wider spacing between the pedals (*147, 148*). An increased Q-Factor has been shown to increase internal knee abduction moments (*149-151*).

The Crank Cycle. The crank cycle refers to one complete 360° revolution of the crank arm, initiating with the pedal at top dead center (TDC), or 0°. This cycle can be delineated into two distinct phases. The first known as the downward stroke, or the power phase, spans from 0° to 180° at bottom dead center (BDC) (*152*). During the downward stroke, the muscles around the hip, knee, and ankle are actively producing force to push the pedal down with the greatest internal knee extensor moment and knee power output occurring near the pedal's forward position at 90° (*140, 152-154*). Following the downward stroke is the upward stroke, or recovery phase, which ranges from DBC back to TDC. During the recovery phase, the leg undergoes mass flexion of the hip, knee, and ankle to lift the pedal. During this phase, the hip and knee flexor muscles act to pull the pedal backward and up to assist the contralateral leg through power phase (*140, 152, 153, 155*).

Cadence and Workload. Cadence is the rate at which a cyclist pedals, measured in revolutions per minute (RPM). An optimal cadence range exists where power output balances with energy consumption, promoting greater riding efficiency (*156*). Workrate is a direct measure of the energy, or power output of a cyclist, typically measured in watts (W). Crank power output during cycling is derived from the product of two primary components: pedal torque and crank angular velocity. Pedal torque is calculated by

multiplying the PRF (in Newtons) by the length of the crank arm (in meters). Angular velocity is calculated by converting RPM to radians per second (*140, 156, 157*). The comprehensive power equation is:

$$Power\ (W) = Force\ on\ pedal\ (N) * Length\ of\ crank\ arm\ (m) * Cadence\ (RPM) * \frac{2\pi\ (radians)}{60\ (seconds)} \quad (1)$$

Workload is calculated by integrating the power output over time (*140, 156, 157*).

Cycling exercise intensity is commonly gauged using power output. The specific power output can determine the level of intensity for a cycling workout, though the perceived exertion can differ based on individual factors like fitness level and bodyweight. According to Coggan and Allen (*157, 158*), power outputs can be broadly categorized as follows: Low intensity, typically less than 100 W, is often associated with beginner workouts or warm-up routines. This intensity level is primarily aerobic, characterized by a lower heart rate. Moderate intensity, ranging from 100-200 W, is suitable for steady-state rides or prolonged endurance training. While still aerobic, it involves a slightly elevated heart rate. High intensity, falling between 200-300 W, is indicative of challenging workouts, frequently used in interval training sessions. It approaches the anaerobic threshold. Very high intensity, spanning 300-400 W, is generally seen during short, vigorous bursts, akin to sprints. This zone is primarily anaerobic. Maximum intensity, exceeding 400 W, denotes maximal or near-maximal exertion. Such effort levels are maintained for extremely short durations (*157, 158*).

Cycling Kinematics. Cycling is a complex and dynamic activity that involves intricate biomechanical interactions between the human body and the bicycle. At the heart of this activity are the hip, knee, and ankle joints, which play pivotal roles in

generating the necessary forces and motions to propel the pedals around the crank cycle (*140, 159*). The kinematics of these joints during cycling is a well-researched area and joint motions are similar with differences existing depending on specific manipulations and bike setup, such as seat positions or crank arm length (*140, 141, 152, 160-166*). As the pedal reaches TDC, the hip and knee are in maximum flexion while the ankle is dorsiflexed. There is a combined extension of the hip, knee, and ankle joints in the down stroke until BDC when a combined flexion of these joints begins to occur to initiate the upstroke. Bini and Carpes (*140, 141*) report that ROM of lower extremities vary but are approximately 45° (45-90° of hip flexion angle) for the hip, 75° (25-100° of knee flexion angle) for the knee, and 20° (about ±10° from a neutral ankle position) for the ankle.

Bike Fit

In cycling research, the importance of an accurate bike fit cannot be overstated. It ensures the safety and comfort of participants, while also serving as a linchpin for the validity and repeatability of study outcomes (*167*). Misalignments or inconsistencies in bike fit introduce variables that could potentially skew results, making it essential to prioritize this aspect in experimental setups (*141*). Furthermore, a proper bike fit bridges the gap between biomechanical theory and practical application, enabling researchers to draw more accurate and comparable conclusions about performance and injury prevention (*168*).

Saddle Position. One of the critical concerns while setting saddle position is to ensure that the knee does not undergo undue stress, which can be detrimental, in the long run, to the development of knee injuries. An angle of knee flexion is considered an

effective measure for this purpose (*140*). The saddle height can be measured relative to bicycle components or relative to the cyclist. There have been multiple proposed methods to configure the saddle height using length-based configurations (*162, 163, 169-178*). One common method is the heel method. The heel method is a well-acknowledged technique used by cyclists to set an initial saddle height. In this method, the cyclist sits on the bike, placing one heel on a pedal. The pedals are then rotated until one leg reaches the bottommost position. The seat should be adjusted until the cyclist's leg is fully extended, ensuring the knee is straight but not locked (*169, 176*). Adjusting the seat height to ensure the cyclist's leg is extended without locking the knee is a well-established principle in cycling biomechanics. Burke (*176*) concluded that this slightly flexed leg position allows for optimal power transfer throughout the pedal stroke and minimizes strain on the knee. It engages both the quadriceps and hamstring muscles efficiently. Similarly, a study by Hamley & Thomas (*169*) set the seat to various heights based on inseam length, measured from pubic symphysis to the floor, in 100 different subjects. The saddle height was measured as the distance from the saddle surface to the center of the pedal surface in a straight line (Figure 3a). The study indicated that setting the seat height, with the leg almost fully extended, at 109% of inseam length correlates with improved oxygen consumption rates, signifying an efficient cycling posture. Incorrect seat heights can lead to increased oxygen consumption, suggesting inefficiency, and potential discomfort or injuries in the long run (*169*).

Another common method is the Greg Lemond method. The Greg LeMond method, named after the renowned three-time Tour de France champion Greg LeMond,

offers a systematic approach to determining the optimal bicycle saddle height. This method begins by measuring the cyclist's inseam while the cyclist stands barefoot with their feet 20 cm apart. An inseam measurement is taken from floor to pubic symphysis and then multiplied by 0.883. The resulting value indicates the recommended distance from the center of the bike's bottom bracket where the pedal cranks attach to the top of the saddle, aligned along the seat tube (Figure 3b) (*176, 179*). While this method is similar to the method developed by Hamley and Thomas (Figure 3a), it does not account for the length of the crank arm, another adjustable component of the bike (*143*). A 2005 study (*180*) compared the Hamely and Thomas method (*169*) with the Greg Lemond method (*179*). No significant difference was reported between the two methods and both methods did not ensure that the knee angle was between 25-30° for minimizing joint load (*141*).

Over the years, researchers and cyclists have developed other methods to try and optimize and standardize bike fit. One method utilized a percentage of trochanteric length measured from floor to bony prominence of the greater trochanter (*159, 163, 172, 181-184*). Another method is a percentage of the distance measured from the ischial tuberosity to the floor (*160-162*). Nordeen-Snyder (*163*) noted that 100% of trochanteric length minimized oxygen consumption compared to 95% and 105% of trochanteric length and knee and ankle ROM increased while the hip remained unchanged. This was further demonstrated by Price and Donne (*181*) when they showed decreased efficiency at 104% of trochanteric length with an optimal range for decreased oxygen consumption between 96% and 100%. Changes in the seat height also influence muscle activation. Higher

quadriceps and hamstring activation has been noted at a saddle height of 95% of trochanteric length compared with 100% (*159*). However, Desipres (*171*) saw no significant effects of saddle height on quadriceps and hamstring activation with a saddle height between 95% and 105% of inseam leg length. Gastrocnemius and soleus activation has been shown to increase with an increase in saddle height of 107% compared to 102% and 92% (*182*). Ericson et al. (*160*) found increased activation of the gluteus medius, semimembranosus, soleus, and gastrocnemius medialis muscles when saddle height was 120% of ischial tuberosity to the floor compared with 102% and 113%.

However, there is concern that these saddle height adjustment methods may not result in similar joint kinematics between participants because it does not take into account individual variations in the femur, tibia, and foot length (*141, 185*). Therefore, using the knee joint angle when the crank is at bottom dead center may be the most reliable method (*140, 141, 145, 177*). The most common method, and current recommendation based on cycling literature is to position the saddle so that knee flexion angle is between 25-35° with the pedal at bottom dead center (*140, 141, 145, 149, 150, 176, 177, 186-189*). When compared to Hamley and Thomas' recommendation of 109% of inseam length (*169*), it has been reported that a 25° angle of the knee at BDC produced a significantly higher power output (*190*) with a significantly reduced oxygen consumption (*185, 191*).

The anterior-posterior position of the saddle should also be adjusted so that the vertical projection of the anterior aspect of the knee should intersect with the pedal axis when the crank is in the forward most position of 90° (*140, 149, 150, 186, 187, 192*).

Saddle positioning plays a quintessential role in optimizing cycling performance, ensuring comfort, preventing potential long-term injuries, and standardization of cycling research. Through extensive research and varied methodologies, it is evident that there is not a one-size-fits-all approach. Factors such as individual anatomy, cycling style, and specific objectives dictate the optimal saddle height and position. While methods like the heel and Greg LeMond techniques offered starting points for standardization, contemporary research emphasizes the significance of knee flexion angle, especially ensuring it remains between 25-35° with the pedal at bottom dead center.

Handlebars. In cycling biomechanics, while saddle position is crucial, handlebar orientation is equally vital in determining a cyclist's posture, weight distribution, and upper body joint angles. The placement, relative height to the saddle, and distance of handlebars from the saddle can significantly influence force transmission through the pedals and the musculoskeletal system's kinematics. For instance, a lowered handlebar position results in an increased anterior pelvic tilt and a decreased trunk angle, impacting mechanical effectiveness. This altered posture leads to increased hip flexion and a more dorsiflexed ankle position (*193*). Diaz et al. (*194*) noted that an upright trunk cycling position increased maximal oxygen consumption compared to a lowered trunk position. While oxygen consumption was similar at submaximal workloads in both positions, the relative consumption was slightly higher in the low sitting position. This suggests that an upright posture might be more biomechanically optimal (*194, 195*).

Crank Arm Length, Crank arm length is a simple component of a bicycle's anatomy yet holds profound implications for cycling biomechanics. As the lever that

connects the cyclist's effort to the bicycle's drivetrain, the length of the crank arm can influence pedaling dynamics, force application, and the overall kinematics of the cycling motion (*196*). Variations in this length can lead to subtle yet consequential shifts in joint angles, muscle activation patterns, and energy expenditure (*140, 196*). Adjustments can play a crucial role in optimizing performance and dictate comfort (*140*). Understanding the biomechanical implications of crank arm length offers insights into optimizing performance, personalizing bike fits, and enhancing our understanding of the intricate relationship between the cyclist and the machine (*197*).

Although not inherently adjustable, crank arms can be swapped out to fit different lengths (*140*). This length plays a pivotal role in cycling dynamics. For instance, a longer crank arm offers riders the ability to maintain their work rate with reduced force, thanks to the increased leverage due to increased torque of the created by the extended crank arm (*198, 199*). However, it also means the rider's lower leg undergoes a broader range of motion (*38, 199*) and increased joint angular velocities (*39*) which may have implications, especially in individuals with CP who have compromised joint mobility due to contractures and spasticity.

Various studies have researched crank arm length and its effects on cycling (*196, 198-202*). Inbar et al. (*200*) studied the effect of crank arm length on crank power output with crank arm lengths of 125 – 225 mm. This study highlighted a crank arm length of about 165mm as the length that produces the greatest crank power output. It also emphasized a correlation between optimal crank arm length with leg length. When the crank length is adjusted within a range of ±5 cm from the optimal length, the mean power

and peak power output vary only minimally, by less than 0.77% and 1.24% respectively. For a group of similar body size, a standard crank length is nearly optimal for power production. However, for diverse groups with varying body sizes, not customizing the crank length to fit individual anthropometric measurements can lead to significantly reduced short-term cycling power performance (*200*). However, this study (*200*) did not account for pedaling rate, which may diminish the correlation between crank arm length and power output (*196*). In a 2011 study, Barratt and colleagues (*199*) investigated the influence of crank length on joint-specific power during maximal cycling. Using varying crank lengths (150, 165, 170, 175, and 190 mm), they found that crank length does not significantly impact joint-specific power when pedal speed (the mathematical product of crank length and crank angular velocity) and pedaling rate (cadence) are controlled. Thus, crank length is not a crucial determinant of maximum cycling power production. In a study investigating the effects of crank length on cycling biomechanics, trained cyclists performed maximal cycling trials using various crank lengths, from 150 mm to 190 mm, at a constant pedaling rate of 120 rpm. The study supports previous findings that overall maximal cycling power is not significantly affected by crank length once the effects of pedal speed and pedaling rate are accounted for. However, it revealed that shorter cranks (150 mm) increased knee power due to a reduced ROM, necessitating more force from the knee. In contrast, these shorter cranks decreased hip power, suggesting less engagement or mechanical advantage at the hip joint (*199*). In 2016, (*198*) researchers investigated how changes in pedal speed and crank length affect pedaling mechanics during submaximal cycling. The study involved fifteen trained cyclists performing trials

at pedal speeds of 1.41 to 1.61 m/s and crank lengths of 150 mm, 165 mm, 170 mm, 175 mm, and 190 mm. The results indicated significant increases in knee and hip angular excursions and joint velocities with increased pedal speed and crank length, while ankle kinematics remained relatively unchanged. Additionally, knee extensor moments and powers decreased, whereas hip extensor power increased with longer crank lengths. These findings suggest a neural strategy to minimize muscle stress and have implications for athletic training and clinical practices (*198*). A 2010 study (*203*) evaluated the impact of three crank lengths (170, 172.5, and 175 mm) on performance in female cross-country mountain bikers. The 170 mm crank length allowed athletes to achieve peak crank power 27.8% quicker than the 175 mm length. However, crank length did not significantly affect other performance metrics, suggesting shorter cranks, 170 mm compared to the 175 mm, might offer race advantages (i.e., achieving peak power quicker) without compromising overall performance.

While a myriad of research has explored the effects of crank arm length, they primarily focused on symmetric crank arm lengths. However, a recent study examined the impact of crank arm length on cyclists with limb length discrepancies (*37*). It involved three male cyclists with limb length differences of 28 mm, 14 mm, and 10 mm. They underwent three test sessions with different crank arm lengths for the shorter limb (160 mm, 165 mm, 170 mm), including an 8-minute pedaling exercise, sprints, and a Wingate test. The study measured crank power output, physiological and biomechanical variables, and perceived exertion and comfort. Results indicated that shorter crank arms for the shorter limb reduced knee and ankle extension, and hip and knee range of motion,

while enhancing maximal crank power output, comfort, and reducing exertion. This suggests that asymmetric crank arms can compensate for limb length discrepancy, improving joint kinematics and cycling performance (*37*). This study sheds light on the impact of asymmetric crank arms for cyclists with limb discrepancies. However, it also underscores a crucial research gap: the effects of systematic variations in crank arm lengths on lower limb biomechanics, particularly joint moments and joint power, in cyclists with lower limb asymmetries. Future research should focus on how different crank arm lengths influence joint kinetics in these cyclists. This would not only enhance our understanding of cycling biomechanics for individuals with limb discrepancies but also aid in optimizing cycling performance and reducing injury risks.

Cycling can be an excellent exercise modality for those with CP due to its low-impact nature and potential for enhancing muscular coordination (*204*). However, despite its benefits, there has been a notable absence of research exploring the use of asymmetric crank arms in cycling for individuals with CP. This gap highlights a critical need for targeted studies that investigate how variations in crank arm length might impact cycling biomechanics and efficiency in the CP population. The relevance of crank arm length in cycling becomes even more critical for those with CP Existing research suggests that using a shorter crank arm does not require more muscular power, and importantly, it reduces the ROM necessary to complete the crank cycle (*38, 198, 199*). This reduction in ROM is particularly beneficial for individuals with CP, who may have compromised joint mobility or muscle strength. The concept of using asymmetric crank arm lengths for the sound leg versus the impaired leg in individuals with unilateral CP

presents a unique approach to customizing cycling for individuals with CP. The asymmetric nature of CP means that the impaired leg might be better suited to a shorter crank arm, accommodating limitations in joint mobility by reducing the necessary ROM during the crank cycle. This customization may improve comfort, lessen muscle strain, and boost cycling efficiency. By tailoring crank arm lengths in this manner, each leg is allowed to operate within its optimal biomechanical range, potentially reducing the risk of strain or injury and improving muscle coordination. This approach emphasizes the importance of personalized assessments and the potential need for adaptive cycling equipment, underscoring the value of considering individual biomechanical needs. Thus, for individuals with CP, adjusting the crank arm length is not just a matter of enhancing cycling performance; it is a crucial step towards ensuring a comfortable, efficient, and beneficial cycling experience that may be a potential exercise and rehabilitation tool.

Effects of Cadence on Cycling Biomechanics. Pedaling cadence has a significant impact on the biomechanics of cycling, influencing various aspects such as ROM, joint velocities, joint moments, and joint powers. Higher pedaling cadences typically lead to a reduction in the ROM for knee and hip joints, resulting in a more compact motion. This more constrained motion can potentially lower the risk of overuse injuries by minimizing excessive joint movement (*139*).

Increased cadences also demand higher joint velocities, particularly at the ankle joint, as the cyclist needs to adapt to faster pedaling speeds. This results in increased ankle joint angles, suggesting that quicker motions are necessary to accommodate the elevated cadence (*139*). Additionally, variations in crank torque profiles with different

cadences indicate that joint moments are affected. Studies have shown that at higher cadences, the peak torque exerted on the crank decreases, while the overall distribution of torque becomes smoother. This results in a relative increase in knee joint moments and a decrease in hip joint moments. Consequently, the power generated by the knee joint increases, while that generated by the hip joint decreases (*139, 205*). The relationship between cadence, joint mechanics, and power generation efficiency is complex because it involves not only the mechanical properties of the joints but also the neuromuscular control of the cyclist. Efficient power generation at higher cadences often requires a balance between maintaining high crank torque and minimizing unnecessary joint movement, which can reduce energy expenditure and the risk of injury.

Muscle Coordination. Muscle coordination during cycling is a sophisticated interplay of various muscle groups working in tandem to ensure efficient pedaling (*206*). The quadriceps, especially the vastus lateralis and rectus femoris, are pivotal during the power phase, driving knee extension and pushing the pedal downward (*207*). In contrast, the recovery phase sees the hamstrings, particularly the biceps femoris , assisting in knee flexion and lifting the pedal (*153, 159*). The gluteus maximus contributes significantly to hip extension during the power phase. Its activation is vital for generating the necessary force (*208*). Just before the bottom dead center of the pedal stroke, the calf muscles (the gastrocnemius and soleus) peak in their activity, adding an extra push to the pedal stroke (*161*). The tibialis anterior muscle becomes active near BDC and remains active throughout the upward stroke, assisting with the recovery phase and ensuring the foot's correct positioning at the onset of the downward stroke (*140, 209*). For a cyclist to

achieve optimal performance, the synchronized activation of these muscles is paramount. As one muscle group contracts, another relaxes, creating a harmonious pedal stroke (*206*).

For individuals with CP, this intricate coordination may be disrupted. As a result, the harmonious interplay observed in typical muscle coordination during cycling can be compromised for individuals with CP. Challenges may arise in synchronizing muscle contractions and relaxations, which are crucial for a smooth pedal stroke (*18*). While cycling demands a symphony of muscle groups working harmoniously in most individuals, those with CP face unique challenges that may disrupt this natural rhythm, underscoring the importance of continued research.

Cycling and Cerebral Palsy

Children with CP face a myriad of challenges that impede their ability to engage in physical activities typically performed by their peers. These challenges stem from the disorder's impact on the brain's development, leading to impairments in selective motor control, muscle tone, and coordination (*108*). When these challenges are combined with joint contractures, such as an equinus position of the foot, it becomes particularly difficult for individuals to perform exercises where their bodyweight is supported by their own volition (*210-212*). Given these constraints, cycling, particularly when adapted to meet the needs of these children, provides a promising avenue for physical activity that can be both beneficial and enjoyable (*31, 32, 128, 211, 213-216*).

Bike Fit and Cerebral Palsy. As previously discussed, bike fit and setup plays a crucial role in the biomechanics of the rider. It has been heavily researched and

documented in a healthy and TD population. However, bike fit for children with CP is not well documented in the literature as most research studies did not elaborate on their methodology on bike fit. One study that involved two participants with diplegic CP, set the distance between the saddle and the crank to 85% of the distance from the greater trochanter to the base of the heel (*217*). Another study, involving fourteen children with various forms of spastic CP, set the saddle height so that the right knee was flexed to an angle of 75° and the left knee was flexed to an angle of 155°, with the right crank at top dead center (*35*). To achieve this joint position, the length of the crank arm was set to approximately 20% of the leg length of the participant (right greater trochanter to the floor). The handlebars were adjusted such that the trunk angle was 60° from the horizontal plane (*35*). While specific guidelines for bike fit for children with CP remain scarce, these studies provide a foundational understanding that can be combined with established guidelines for a healthy population to guide appropriate bike setup for research.

Cycling Biomechanics in Children with Cerebral Palsy. In a 2016 study (*35*), researchers examined how children with different types of CP (hemiplegic, diplegic, and quadriplegic) cycle in comparison to their TD peers. It was reported that children with CP were able to cycle at a lower resistance and reduced cadence compared to TD individuals, indicating reduced adaptability to changes in movement speed. Furthermore, when compared to their TD peers, children with CP exhibited variations in kinematics and kinetics across all three planes of motion. These findings indicate that children with CP tend to cycle with lower efficiency than their TD counterparts (*35*). The study presented

information on individual participants by comparing an individual with hemiplegic type CP to a group of TD peers. It has been noted that in the affected leg, there is increased ankle plantarflexion. It was hypothesized that the ankle position was the primary driver in altering knee and hip kinematics when compared to their TD peers (*35*). It was also noted that there was an increase in knee extension torque during the power phase of the affected limb and all joint torques in the frontal and transverse planes were all greater than their TD peers (*35*).

A study by Kaplan (*218*) quantified pedaling smoothness and EMG patterns in children with spastic diplegic CP compared to TD children. Video analysis revealed that while the TD group maintained consistent pedaling rhythm, the CP group exhibited irregular timing, with more time spent at the bottom of the pedaling cycle. Children with CP exhibit altered muscle activation patterns. There is typically earlier onset and prolonged duration of muscle activity, suggesting a lack of selective muscle control and more frequent agonist-antagonist co-contractions. These patterns contribute to the decreased cycling efficiency observed in children with CP compared to typically developing peers (*218-222*).

Research on cycling biomechanics in children with CP is scarce compared to studies on gait analysis. Further, the prevalence of specific gait abnormalities in children with CP varies with distribution of involvement (hemiplegia, diplegia, or quadriplegia), GMFCS, and changes with age and orthopedic surgery (*19*). This suggests that the type of CP a child has can significantly influence their gait patterns, and thus could greatly impact their cycling patterns.

Despite the known benefits of cycling and the adaptations made for children with CP, there is still a lack of comprehensive research on how to best modify cycling equipment to suit individual needs. A case study conducted in 2008 (*223*) examined the impact of a shank guide on the cycling biomechanics of a 13-year-old with spastic diplegic CP. The study's objective was to analyze 3D lower-extremity joint kinematics and muscle activity during cycling with and without the use of a shank guide. They found that with the guide, the participant could cycle significantly faster (40.1 rpm) compared to without the guide (13.7 rpm), showing less variability in kinematic curves and suggesting increased motor control and cycling efficiency. The study concluded that a shank guide could potentially help people with CP cycle faster and improve joint kinematics. Asymmetric crank arm lengths have also been suggested as beneficial for individuals with lower limb discrepancies, potentially leading to reduced exertion and increased comfort and power output (*37, 224*). However, these findings are preliminary and warrant further investigation, particularly in children with CP.

Children with CP navigate through numerous hurdles to participate in physical activities common among their peers. The neuromuscular impairments characteristic of CP markedly hinder their movement and exercise capabilities. Cycling emerges as a viable and enjoyable form of physical activity for these children, especially when the bicycles are tailored to their unique requirements. However, there remains a significant gap in research regarding optimal bike fit and adjustment for this demographic, with studies offering only preliminary insights into the appropriate modifications needed.

Chapter 3: Methods

The overarching purpose of these interconnected studies is to deepen our understanding of the biomechanical challenges faced by children with cerebral palsy (CP) in various movement contexts, specifically focusing on walking and cycling. In the first study, the aim is to examine the relationship between walking kinematic deviations and cycling kinematic deviations, utilizing gait and cycling deviation indices, and to explore complexity of neuromuscular control in walking and cycling at different speeds in typically developing (TD) individuals. The second study focuses on the biomechanical effects of asymmetric crank arm lengths in cycling for TD individuals. The study aimed to explore how adjusting the crankarm length on one limb influences the lower extremity cycling biomechanics. The third study looked to apply an analysis of kinematic deviations and complexity of neuromuscular control to individuals with unilateral CP to examine the relationship between walking and cycling in this population and to understand how shortening the crankarm length for the affected limb in individuals with unilateral CP influences their lower extremity cycling biomechanics. Collectively, these studies aim to provide a comprehensive analysis of commonly utilized gait analysis tools applied to alternative forms of movement and to explore movement dynamics in children with CP across walking and cycling, offering insights that could inform more effective rehabilitation strategies and assistive device designs.

Participants

This study focused on two groups between the ages of 10-30 years, a TD group with 13 participants (11 female and 2 male, 18.0 ± 3.5 years, 1.68 ± 0.06 m, 62.4 ± 12.3

kg, 22.0 ± 4.0 kg/m^2, Table 1) and two individuals with unilateral CP (Table 2). This study was approved by the Institutional Review Board at the University of Tennessee (UTK IRB-23-07900-FB, Appendix C), ensuring adherence to ethical guidelines and protocols. Prior to participation, all participants were provided with detailed information about the study and their informed consent was obtained (Appendix D -Appendix G). We targeted individuals with a confirmed diagnosis of unilateral CP. Our efforts combined direct engagement within the local community, through recruitment emails, and indirect methods such as word of mouth and strategically placed informational flyers (Appendix J**Error! Reference source not found.**) in local pediatric medical offices. Potential participants were encouraged to self-identify and initiate contact with the research team. Participants were required to meet a set of inclusion and exclusion criteria (Table 3).

For the recruitment of the TD group, flyers (Appendix I) were prominently displayed on community bulletin boards and around various locations on the university campus. Additionally, we collaborated with a local youth soccer club to send out recruitment emails. Interested individuals were encouraged to self-identify and reach out to the research team. Participants were required to meet a set of inclusion and exclusion criteria (Table 4).

Experimental Protocol

Participants took part in one testing session. During the test session, participants completed an informed consent (Appendix D -Appendix G), assent form if under the age of 18 (Appendix H), and a physical activity readiness questionnaire (PAR-Q+, Appendix L).

The testing session began with a three-minute walking warm up on a treadmill, paced at the participant's discretion. Anatomical and tracking retro reflective markers were affixed with double-sided tape and neoprene straps to specific locations to monitor the motion of body segments. EMG sensors were attached bilaterally over the rectus femoris, vastus lateralis, semitendinosus, medial gastrocnemius, and tibialis anterior muscles, according to SENIAM guidelines (*225*).

The participants performed the cycling conditions first to streamline the data collection process. The cycle ergometer was adjusted to standardize the participants' biomechanics and ensure accurate measurements. The saddle height was adjusted to achieve a knee flexion angle of 25° to 30° with the crank arms at a standard length of 170mm when the pedal was positioned at the bottom dead center. This measurement was taken with a hand-held goniometer. The fore-aft position of the saddle was adjusted so that the participants' knee aligned vertically with the pedal spindle when the crank was in the forward horizontal position. A plumb bob hung from the most anterior aspect of the knee was used to validate this position. The handlebar position was set to create a 90° angle between the trunk and thigh using the hand-held goniometer with the crank in the forward horizontal position. The participants cycled in six conditions: at two different cadences of a self-selected comfortable revolution per minute (RPM) condition and a self-selected maximum RPM, in each of the three different lengths of the crank arms: 130mm, 150mm, and 170mm (170mm being the length of a typical crank arm). The resistance was set at 70 Watts. The crank arm length was kept at 170mm on one limb and adjusted on the other. In the CP group, the limb with greater deficits had its crank arm

length altered for the conditions. In the TD group, the crank arm of their dominant limb, determined by preferred kicking leg, was adjusted throughout. Participants performed two minutes of cycling in each self-selected slow condition to acclimate to the cycling condition. Data were captured during the final ten seconds of each two-minute period. Following the self-selected slow condition, participants were asked to cycle as fast as they could for thirty seconds while data was captured during the final ten seconds of this thirty second period. After each condition, participants stated their rating of perceived exertion (RPE) on a scale of 6-20 (6 would be equivalent to sitting comfortably and 20 is maximum effort exercise) to monitor their physical effort. A minimum of two-minute rest period was given between conditions.

Following cycling tests, participants performed five walking trials in each of two conditions. Participants walked over three force platforms in a straight line at a self-selected typical walking speed and a self-selected fast speed. For typical speed trials, participants were instructed to walk straight, emulating their regular community walking pattern. For fast speed trials, they were asked to walk as fast as safely possible without running. Upon completing the cycling and walking conditions, the CP group underwent additional assessments to measure passive ROM, selective voluntary motor control with SCALE, and manual muscle strength of bilateral hips, knees, and ankles. During this assessment, participants were initially positioned supine on the exam table. In this position, hip flexion/extension and abduction/adduction, knee flexion/extension, hamstring length measured based on popliteal angle, and ankle plantarflexion/dorsiflexion ROM of the lower limbs were measured using a goniometer.

The participants were then placed in a side-lying position. In this position the strength of hip abduction and adduction, along with the hip SCALE assessment, were conducted. For the SCALE assessment, participants were asked to voluntarily move the joint through its entire range of available motion. The participants were then moved into a prone position to assess hip internal/external rotation ROM and knee flexion strength. The participants then sat on the edge of the exam table to measure knee extension strength, ankle dorsiflexion strength, and SCALE assessments were performed for the knee, ankle, subtalar joint, and toes. Finally, ankle plantarflexion strength was assessed in the standing position.

Instrumentation

A thirteen-camera motion capture system (240 Hz, Vicon Motion Analysis Inc., UK) was used to collect three-dimensional (3D) kinematics data collection during the testing session. For each participant retro reflective markers were placed on the following anatomic landmarks: acromion processes, sternal notch, C7 vertebrae, anterior superior iliac spines (ASIS), posterior superior iliac spines (PSIS), iliac crests, greater trochanters, medial and lateral epicondyles, medial and lateral malleoli, the head of 1st and 5th metatarsals, and the distal phalanx of the second toe. To track segment motions during testing, semi rigid thermoplastic shells with a cluster of four non-collinear retro reflective markers were affixed with neoprene straps to the thighs and shanks. One cluster of four markers was attached to the posterolateral aspect of the heel counter of each shoe with double sided tape.

A sixteen-channel wireless EMG system (1200 Hz, Delsys Trigno Wireless EMG., Delsys, Natick, MA, USA) was used to record muscle activity during gait and cycling trials. The sensors were placed on the following bilateral muscles: rectus femoris (RF), vastus lateralis (VL), semitendinosus (ST), medial gastrocnemius (MG), and tibialis anterior (TA). The skin of the participant was shaved to remove hair and cleaned with alcohol swabs prior to electrode placement. Electrode placement on each muscle followed the surface EMG for non-invasive assessment of muscles (SENIAM) guidelines (*225, 226*). Sensors were affixed with double sided adhesive tape and anchored with athletic pre-wrap.

Participants performed cycling exercises on an electromagnetically braked stationary ergometer (Excalibur, Lode B.V., Groningen, Netherlands) equipped with a pair of custom crank arms with adjustable length, allowing the crank arm length to be altered from 130mm to 170mm in 10mm increments. To define and track the motion of the pedals, three markers were rigidly attached to the lateral side of each pedal and two additional markers were placed on the anterior surface of the pedal. One reflective marker was placed on each crank arm axle, and three additional markers were placed on the front of the bike, which provided reference points for tracking the motion of the crank axel markers. A custom jig was constructed to secure the bike to a floor mounted force platform to ensure the ergometer was aligned with the laboratory coordinate system.

Three force platforms (1200 Hz, BP600600, American Mechanical Technology Inc., Watertown, MA, USA) were used to measure the ground reaction forces (GRF) and the moments of forces during the walking trials. 3D kinematics, GRFs and EMG data

were simultaneously collected during the gait trials using Vicon Nexus (Version 16.0, Vicon Motion Analysis Inc., UK).

Data Analysis

Kinematic Data

The collected data were exported from Vicon system and imported into Visual3D software (Version v2022 11.3, C-Motion Inc., Germantown, MD, USA) for the computation of 3D kinematic variables. For cycling data, raw kinematic marker data were filtered using a fourth-order zero-lag Butterworth lowpass filter, with a cutoff frequency set at 6 Hz (*188*). For walking trials, raw marker data were filtered using a fourth-order zero-lag lowpass Butterworth filter at cutoff frequency of 6 Hz. The anatomic markers on the acromion processes, sternal notch, and C7 vertebrae were used to track the motion of the trunk. After a static trial, all other anatomic markers were removed for dynamic trials. Hip joint centers were calculated with the Bell method (*227, 228*). Angular kinematics were calculated using the joint coordinate system (*229*) and a Cardan rotational sequence of X-Y-Z with conventions expressed using the right-hand rule. 3D kinematic variables related to the ankle, knee, and hip joints as well as kinematics of foot and pelvis segments were computed and extracted for further analyses.

Kinematic Movement Deviation Calculations

The gait profile score (GPS) was calculated to provide a comprehensive measure of gait quality and then adapted for cycling to create a cycling profile score (CPS). This process involved using analyzing kinematic data from nine critical bilateral lower limb joint and segment angles during a gait cycle. These angles included pelvic tilt, pelvic

obliquity, pelvic rotation, hip flexion, hip abduction/adduction, hip internal/external rotation, knee flexion, ankle plantarflexion/dorsiflexion, and foot progression angle. In addition to employing the traditional nine kinematic variables, trunk segment position, across all three planes of movement (trunk tilt, lateral bend, and rotation), has been incorporated (for a total of twelve kinematic variables) to provide a more detailed analysis. The TD gait data were normalized with linear interpolation to 101 datapoints and averages were computed for each kinematic variable across the gait cycle, resulting in a mean kinematic curve of 101 datapoints for each variable. To calculate the individual gait variable scores (GVS) and individual cycling variable scores (CVS) for each of the twelve kinematic variables, we determined each participant with and without CP's deviation at every point in the gait cycle by subtracting the TD mean from their gait data. A root mean square was then calculated for each kinematic variable (Eq. 2).

$$GVS_i = \sqrt{\frac{\sum_{n=1}^{101}(x_{i,n} - \bar{x}_{i,n})^2}{100}} \quad (2)$$

- GVS_i: The gait variable score for the *i*-th variable
- $X_{i,n}$: The *n*-th observation of the *i*-th variable
- $\bar{x}_i$: The mean value for the *n*-th observation of the *i*-th variable for the TD group

The GPS and CPS were obtained by calculating the average of these individual GVSs and CVSs, effectively consolidating the deviations into a single metric. This process was also conducted on the fast-walking data to calculate a fast GPS and on the fast-cycling data to calculate a fast CPS. One revolution of the crank starting at TDC and ending at TDC was used as one cycle for the cycling conditions.

Muscular Synergy Calculations

The dynamic motor control (DMC) was calculated to provide an analysis of muscle synergies during each movement task. EMG data went through an initial embedded hardware bandpass 20-450 Hz. Then it went through a high-pass filter at 40Hz, rectified, and then low-pass filtered at 10Hz. To facilitate comparisons between participants, EMG data from each muscle during the walking condition was normalized to its peak value from all walking trials while the EMG data from the cycling conditions were normalized to its peak value that occurred during all of the cycling trials. These time series were then time normalized to 101 data points. Following normalization, the processed signals from all the muscles for each subject were concatenated into one comprehensive dataset. The next step involved applying non-negative matrix factorization to this concatenated EMG data to decompose the high-dimensional data into simpler components, commonly referred to as muscle synergies. Initially, the EMG data was represented as a $m \times t$ matrix, where m is the number of muscles (5 muscles), and t is the number of time points (101 across the normalized gait and cycling conditions). The EMG matrix was then factorized into two non-negative matrices, W, representing the muscle synergies, and C, representing the relative activation of those synergies. W is an $m \times n$ matrix and C is a $n \times t$ matrix, with n the specified number of muscle synergies (1 in this study). This factorization was constrained by the requirement that all elements of W and C be non-negative, aligning with the physiological reality that muscle activation levels cannot be negative. The decomposition was achieved through an iterative optimization process using the following parameters: 50 replicates, 1,000 maximum

iterations, and a 1×10^{-6} threshold for completion. The optimization was aimed at minimizing the discrepancy between the EMG matrix and the product $W \times C$. The resultant muscle synergies, represented by the columns of *W*, and their temporal activations, depicted by the rows of *C*, were subsequently analyzed. The key metric for the DMC calculation, the variance accounted for (VAF) by a single synergy, was then calculated from this processed data. The total VAF by n (1 for this study) synergies were calculated by comparing W × C and the EMG data for both the CP and TD groups. The DMC score was then determined from one synergy (*28*) using an equation (Eq. 3) that incorporated these VAF values.

$$DMC = 100 + 10\left[\frac{(VAF_{Ave} - VAF)}{VAF_{SD}}\right] \quad (3)$$

- VAF_{Ave}: The average of the VAF for 1 synergy derived from the TD group.
- VAF: The VAF calculated from the participant's EMG data.
- VAF_{SD}: The standard deviation of the VAF from the TD group.

The average DMC score for the TD group is 100, and each 10-point deviation represents one standard deviation from the TD controls. For example, a DMC of 80 indicates that an individual's VAF during the movement is two standard deviations above the TD group, suggesting simplified control. Note that a higher VAF results in a lower DMC score as a higher VAF means that the synergies used in the model explain most of the variance in the muscle activity data. For example, if the VAF is 0.90 or 90%, it indicates that 90% of the variance in the muscle activity can be explained by the synergies. A higher VAF indicates a decrease in the complexity of neuromuscular control. This is because fewer synergies are needed to account for the majority of the variance, suggesting a more simplified control strategy. In other words, the

neuromuscular system is using fewer, more generalized patterns of muscle activation rather than many specific and distinct patterns. This process was also conducted on the walking data to calculate a DMC for gait (Walk-DMC), on fast-walking data to calculate a fast Walk-DMC, the cycling data to calculate a cycling DMC (Cycle-DMC), and on the fast-cycling data to calculate a fast Cycle-DMC. One stride from heel-strike to ipsilateral heel-strike was used as one gait cycle and one revolution of the crank starting at TDC and ending at TDC was used as one cycle for the cycling conditions.

Statistical Analysis

A comprehensive statistical analysis was conducted, using IBM SPSS Statistics (version 27), to test various hypotheses and relationships in the data, with the alpha level of 0.05 set *a priori*. The assumption of normality was assessed using a Shapiro-Wilk test. To account for potential violations of the assumption of sphericity, a Greenhouse-Geisser correction was applied whenever necessary. Post-hoc comparisons were conducted with Bonferroni adjustments to account for multiple comparisons. Partial eta squared (η^2) was used to evaluate effect size using the following benchmarks: small ($\eta^2 = 0.01$), medium ($\eta^2 = 0.06$), and large ($\eta^2 = 0.14$) (*230*).

Study One:

A profile analysis was performed to analyze the GVS values. The profile analysis comprised three main tests: a test of parallelism (test of interaction), a test of flatness (within-subjects main effect), and a test of levels (between-subjects main effect) (*231*). The test of parallelism assessed whether the shape of the profile (i.e., the relative differences between GVS/CVS values across conditions) was consistent across groups.

The test of flatness evaluated whether the profile across each condition was significantly different from flat, indicating variability in the GVS/CVS values across the conditions. Lastly, the test of levels determined if there were overall differences in the profiles' height across conditions, suggesting average differences in overall movement quality. For the GVS/CVS values, the analysis examined whether the profiles were parallel across different conditions, assessed overall differences in the levels of GVS/CVS values between conditions, and evaluated significant differences among the GVS/CVS values within each condition. Post-hoc comparisons using Bonferroni corrections were conducted to identify specific differences between conditions. differences between conditions. Given that there were 6 pairwise comparisons, the original alpha level of 0.05 was divided by 6, resulting in an adjusted p value of 0.0083.

Two two-way repeated measures analysis of variances (ANOVA) were conducted to explore the effects of movement type (walking vs. cycling) and speed (slow vs. fast) on GPS/CPS and VAF for one synergy. This analysis included examining the main effects of movement type and speed, as well as their interaction effect, to determine if the GPS/CPS scores and VAF varied significantly across different conditions and speeds.

Additionally, a Pearson correlation analysis was conducted to examine the relationships between GPS/GVS values for the different conditions of Slow Walking, Fast Walking, Slow Cycling, and Fast Cycling.

Study Two:

A profile analysis was performed to analyze the CVS values of the limb of the adjusted crank arm length. The test of parallelism assessed whether the shape of the

profile (i.e., the relative differences between CVS values across conditions) was consistent across groups. The test of flatness evaluated whether the profile across each condition was significantly different from flat, indicating variability in the CVS values across the conditions. Lastly, the test of levels determined if there were overall differences in the profiles' height across conditions, suggesting average differences in overall movement quality. For the CVS values, the analysis examined whether the profiles were parallel across different conditions, assessed overall differences in the levels of CVS values between conditions, and evaluated significant differences among the CVS values within each condition. Post-hoc comparisons using Bonferroni corrections were conducted to identify specific differences between conditions. differences between conditions. Given that there were 6 pairwise comparisons, the original alpha level of 0.05 was divided by 6, resulting in an adjusted p value of 0.0083.

Multiple two-way repeated ANOVAs were conducted to explore the effects of crank length (170 vs. 150 vs 130) and cadence (slow vs. fast) on CPS, self-selected cadence and VAF Post-hoc comparisons using Bonferroni corrections were conducted to identify specific differences between crank length and cadence conditions. Given that there were 6 pairwise comparisons, the original alpha level of 0.05 was divided by 3, resulting in an adjusted p-value of 0.0167.

Chapter 4: Comparative Biomechanical Analysis of Walking and Cycling in Typically Developing Individuals: Adaptation of Gait Analysis Tools

Abstract

Cerebral palsy (CP) is the most common physical disability in childhood that affects movement and posture. This study aimed to adapt common clinical gait analysis tools, Gait Profile Score (GPS) and variance accounted for (VAF) from one synergy of walk dynamic motor control (Walk-DMC), to create cycling profile score (CPS) and cycling variable score (CVS) for analyzing walking and cycling biomechanics in typically developing (TD) individuals. Thirteen participants engaged in walking and cycling at self-selected slow and fast speeds. Results showed significant differences in kinematic variability between walking and cycling, with higher variability in trunk and pelvis motions during cycling. CPS and CVS did not decrease with cycling but remained consistent across speeds, while VAF was higher during walking. Correlations between walking and cycling deviations ranged from -0.37 to 0.64, indicating distinct biomechanical profiles for each activity. These findings suggest that while adapted gait analysis tools can effectively capture biomechanical differences between walking and cycling, movement type rather than speed is crucial for distinguishing the gait and cycling movement patterns. This study highlights the potential for incorporating cycling into rehabilitation programs for individuals with CP, providing a broader understanding of motor function and enhancing clinical outcomes through tailored interventions that consider both walking and cycling biomechanics.

Introduction

Cerebral palsy (CP) is a broad term used to describe a group of persistent disorders that affect movement and posture that can cause activity limitations due to an injury to the brain that occurred in the developing fetal or infant brain (*1-3*). These injuries can have a multitude of causes, including prenatal infections, genetic factors, or perinatal complications (*3-5*). CP is the most common physical disability in childhood, and its prevalence is estimated at approximately 2-3.6 per 1,000 live births (*2, 4, 6-9*). The spectrum of presentations of the disorder varies from very mild motor disturbances that are unnoticeable to the untrained individual, to profound motor and intellectual disabilities (*3, 10*). Quantitative biomechanical analyses are central to understanding and managing physical manifestations of CP.

The integration of quantitative biomechanical analysis in CP research and clinical care is fundamental for a thorough understanding and effective management of the condition (*22-25*). This analytical approach provides a detailed and objective assessment of the complex motor dysfunctions associated with CP. Data analysis tools like the gait profile score (GPS) and gait variable score (GVS) offer a comprehensive evaluation of gait kinematic abnormalities (*27*), while the walk dynamic motor control index (Walk-DMC) and the variance accounted for (VAF) by synergies analyzes patterns of coordinated muscle activations (*28*). These tools encapsulate the multifaceted nature of gait deviations, crucial for accurately diagnosing, monitoring, and tailoring interventions for individuals with CP (*23, 25*).

Despite advancements in CP research, significant gaps remain, especially concerning dynamic activities such as cycling and their relationship with more commonly studied functions like walking. Cycling offers significant benefits to individuals with CP as the rhythmic and repetitive motion can help reduce muscle spasticity while simultaneously improving their muscle strength, endurance, and joint mobility (*31, 32*). However, the comparative biomechanical analysis between walking and cycling remains underexplored. Research predominantly focuses on isolated aspects of CP mobility, often neglecting the interplay between different motor tasks (*1, 34, 35*).

Understanding how different activities influence each other is crucial, as this interplay can provide deeper insights into the overall motor function in individuals with CP. For instance, speed-related changes can significantly impact muscle activation patterns and joint kinematics, yet this aspect is insufficiently studied (*36*). Furthermore, the complexity of muscle synergy in CP, particularly in dynamic contexts like comparison between different activities, has not been addressed in existing literature. This gap impedes the development of targeted interventions for specific motor control challenges faced by individuals with CP.

Walking and cycling share several biomechanical and motor control characteristics, making them both valuable activities for individuals with CP (*32*). Both activities involve coordinated muscle activations, joint movements, and balance control (*31, 32*). However, there are distinct differences in the mechanics and muscle engagement between the two activities. Walking typically involves a more complex balance and weight-bearing component, while cycling provides a more controlled and

rhythmic motion, often reducing the impact on joints and allowing for a different pattern of muscle activation. These similarities and differences justify the adaptation of gait analysis tools for cycling. By understanding how the movement variability and muscle coordination of typically developing (TD) individuals changes between activities, we can develop more comprehensive analyses to understand the motor abilities and challenges of individuals with CP, leading to more effective interventions.

The primary purpose of this study was to adapt established gait analysis tools—GPS and VAF from one synergy of Walk-DMC—to analyze walking at a fast speed and create a cycling profile score (CPS) and a cycling variable score (CVS) for the biomechanical analysis of walking and cycling at two different speeds for TD individuals. It was hypothesized that the CPS and CVS scores will decrease, compared to GPS and GVS scores, due to the constrained nature of the movement and scores are expected to increase with speed in both walking and cycling trials. Additionally, it is anticipated that VAF will increase with cycling, indicating a more simplistic movement pattern. This is because walking involves a unique interplay between joints, where one joint may be flexing while another is extending, whereas in cycling, the joints work more in unison to lengthen or shorten the limb. VAF is also expected to increase with speed due to the overall increased activation of all muscles. Furthermore, it is predicted that there will be a strong positive correlation between walking and cycling scores.

Methods

Participants

Thirteen TD individuals (11 female and 2 male, 18.0 ± 3.5 years, 1.68 ± 0.06 m, 62.4 ± 12.3 kg, 22.0 ± 4.0 kg/m^2) were recruited from the local community to participate in this research study. The inclusion criteria were males and females between the ages of 10-30 years who were recreationally active (defined as at least 30 minutes of exercise at least two days a week). Individuals were excluded if participants aged 18 years or above had a body mass index (BMI) of 30 or greater. Individuals aged 10 to 17 years were excluded if they had a BMI at or above the 95th percentile for their specific age, as per standardized pediatric BMI charts (Appendix M -Appendix N). Individuals were excluded from the study if they had lower extremity surgery within the past 12 months, were pregnant or nursing, or had a neurological or a cardiovascular condition that prevented walking or cycling. Prior to data collection, experimental procedures received ethical approval from the university's Institutional Review Board.

Instrumentation

A thirteen-camera motion capture system (240 Hz, Vicon Motion Analysis Inc., UK) was utilized to collect three-dimensional (3D) kinematic data during the testing sessions. For each participant retro reflective markers were placed on the following anatomic landmarks: acromion processes, sternal notch, C7 vertebrae, anterior superior iliac spines (ASIS), posterior superior iliac spines (PSIS), iliac crests, greater trochanters, medial and lateral epicondyles, medial and lateral malleoli, the head of 1st and 5th metatarsals, and the distal phalanx of the second toe. To track segment motions during

testing, semi-rigid thermoplastic shells with a cluster of four non-co-planar retro-reflective markers were affixed with neoprene straps to the thighs and shanks. One cluster of four markers was attached to the posterolateral aspect of the heel counter of each shoe with double sided tape.

A sixteen-channel wireless EMG system (1200 Hz, Trigno^{TM} Wireless EMG, Delsys Inc., Natick, MA, USA) recorded muscle activity during gait and cycling trials. EMG sensors were attached bilaterally over the rectus femoris, vastus lateralis, semitendinosus, medial gastrocnemius, and tibialis anterior muscles (*225*). Participants performed cycling exercises on an electromagnetically braked stationary ergometer (Excalibur, Lode B.V., Groningen, Netherlands). 3D kinematics and EMG data were simultaneously collected during the cycling and gait trials using Vicon Nexus (Version 16.0, Vicon Motion Analysis Inc., UK).

Experimental Protocol

Participants took part in one testing session that included cycling and walking conditions. Following the completion of an informed consent (Appendix D -Appendix G), assent form if under the age of 18 (Appendix H), and a physical activity readiness questionnaire (PAR-Q+, Appendix L), the testing session began with adjusting the cycle ergometer to the participant. The saddle height was adjusted to achieve a knee flexion angle of 25° to 30° when the pedal was positioned at the bottom dead center. The fore-aft position of the saddle was adjusted so that the participants' knee aligned vertically with the pedal spindle when the crank was in the forward horizontal position. The handlebar position was set to create a 90° angle between the trunk and thigh with the crank in the

forward horizontal position. This was followed with a three-minute walking warm up at a self-selected speed on a treadmill.

Data Analysis

The collected data were exported from Vicon system and imported into Visual3D software (Version v2022 11.3, C-Motion Inc., Germantown, MD, USA) for the computation of 3D kinematics and processing of EMG signals. For walking and cycling data, raw kinematic marker data were filtered using a fourth order zero lag Butterworth lowpass filter, with a cutoff frequency set at 6 Hz (*188*). Angular kinematics were calculated using the joint coordinate system (*229*) and a Cardan rotational sequence of X-Y-Z with conventions expressed using the right-hand rule.

The GPS is a measure of overall gait pathology, representing the root mean square (RMS) difference between an individual's gait data and the average data from a reference population. The GVS, on the other hand, quantifies the RMS difference for individual kinematic variables within the gait cycle. The GPS summarizes these deviations into a single comprehensive score. This approach allows for a clearer interpretation and assessment of gait abnormalities. The GPS (*27*) was calculated for the walking trials and then adapted for cycling to create CPS. This process involved using the same nine bilateral kinematic variables as the traditional GPS (*27*). In addition to using the traditional nine kinematic variables to calculate nine GVS, trunk segment position relative to lab, across all three planes of movement (trunk tilt, lateral bend, and rotation), has been incorporated (for a total of twelve kinematic variables) to provide a more detailed analysis to generate the CVS. This process was also conducted on the

fast-walking data to calculate a fast GPS and on the fast-cycling data to calculate a fast CPS.

The VAF was calculated to provide an analysis of muscle activation complexity during each movement task (*28*). EMG data from each muscle during the walking condition was normalized to its peak value from all walking trials while the EMG data from the cycling conditions were normalized to its peak value that occurred during all the cycling trials and time normalized to 101 data points. This data was used to calculate VAF from one synergy using non-negative factorization, the key metric for the Walk-DMC calculation (*28*). A higher VAF means that the synergies used in the model explain most of the variance in the muscle activity data. For example, if the VAF is 0.90 or 90%, it indicates that 90% of the variance in the muscle activity can be explained by the synergies. A higher VAF indicates a decrease in the complexity of neuromuscular control. This is because fewer synergies are needed to account for the majority of the variance, suggesting a more simplified control strategy. In other words, the neuromuscular system is using fewer, more generalized patterns of muscle activation rather than many specific and distinct patterns.

Statistical Analysis

A comprehensive statistical analysis was conducted, using IBM SPSS Statistics (version 27), to test various hypotheses and relationships in the data, with the alpha level set a priori at .05 for all tests to determine statistical significance. Partial eta squared (η^2) was used to evaluate effect size using the following benchmarks: small ($\eta^2 = 0.01$), medium ($\eta^2 = 0.06$), and large ($\eta^2 = 0.14$) (*230*). A profile analysis was performed to

analyze the GVS values. The profile analysis comprised three main tests: a test of parallelism (test of interaction), a test of flatness (within-subjects main effect), and a test of levels (between-subjects main effect) (*231*). The test of parallelism assessed whether the shape of the profile (i.e., the relative differences between GVS/CVS values across conditions) was consistent across groups. The test of flatness evaluated whether the profile across each condition was significantly different from flat, indicating variability in the GVS/CVS values across the conditions. Lastly, the test of levels determined if there were overall differences in the profiles' height across conditions, suggesting average differences in overall movement quality. For the GVS/CVS values, the analysis examined whether the profiles were parallel across different conditions, assessed overall differences in the levels of GVS/CVS values between conditions, and evaluated significant differences among the GVS/CVS values within each condition. Post-hoc comparisons using Bonferroni corrections were conducted to identify specific differences between conditions. differences between conditions. Given that there were 6 pairwise comparisons, the original alpha level of 0.05 was divided by 6, resulting in an adjusted p-value of 0.0083.

Two two-way repeated measures analysis of variances (ANOVA) were conducted to explore the effects of movement type (walking vs. cycling) and speed (slow vs. fast) on GPS/CPS and VAF for one synergy. This analysis included examining the main effects of movement type and speed, as well as their interaction effect, to determine if the GPS/CPS scores and VAF varied significantly across different conditions and speeds.

Additionally, a Pearson correlation analysis was conducted to examine the relationships between GPS/GVS values for the different conditions of slow walking, fast walking, slow cycling, and fast cycling. In this analysis, we interpret the strength of the Pearson correlation coefficients as values between 0.1 and 0.3 are considered weak, values between 0.3 and 0.5 are considered moderate, and values above 0.5 are considered strong (*232*).

Results

A profile analysis was conducted with the mean GVS/CVS scores (Table 5). The analysis for parallelism revealed a significant interaction between condition (walking and cycling, both slow and fast) and GVS/CVS values ($F(33, 112.66) = 2.202$, $p < 0.001$) indicating that the profiles were not parallel (Figure 4). This suggests that the pattern of GVS/CVS values across conditions differed. For the level analysis, the main effect of the condition was significant, ($F(3, 48) = 8.438$, $p < 0.001$), indicating that there were overall differences in the GVS/CVS scores between the conditions. The test of flatness showed that the main effect of the GVS/CVS variables was significant, ($F(11, 38) = 23.301$, $p < 0.001$), indicating significant differences among the GVS/CVS scores within each condition (Slow Walk -Figure 5, Fast Walk -Figure 6, Slow Cycle -Figure 7, Fast Cycle -Figure 8).

Post-hoc comparisons revealed significant differences between various conditions after applying Bonferroni corrections (adjusted p-value = 0.0083). When comparing cycle slow vs. walk slow, significant differences were found in pelvis tilt ($p = 0.004$) and ankle dorsiflexion ($p < 0.001$), with cycle slow having higher mean values. In the comparison

of cycle fast vs. walk fast, significantly higher values in trunk tilt, pelvis tilt, and ankle dorsiflexion (all $p < 0.001$) were observed for cycle fast. For walk fast vs. walk slow, no significant differences were found (all $p > 0.0083$). Finally, for cycle fast vs. cycle slow, a significantly higher trunk tilt ($p < 0.001$) was found for cycle fast compared with cycle slow.

The ANOVA tests of GPS/CPS indicated a significant main effect of movement type, ($F(1, 12) = 6.390$, $p = 0.027$, partial $\eta^2 = 0.347$), suggesting that GPS differed from CPS (Table 6). However, the main effect of speed was not significant, ($F(1, 12) = 2.713$, $p = 0.125$, partial $\eta^2 = 0.184$), indicating that GPS/CPS did not significantly differ between slow and fast speeds. Additionally, the interaction effect between movement type and speed was not significant, ($F(1, 12) = 2.701$, $p = 0.126$, partial $\eta^2 = 0.184$), suggesting that the effect of speed on GPS did not depend on the type of movement.

The ANOVA tests of VAF indicated a significant main effect of movement type, ($F(1, 11) = 4.860$, $p < 0.050$, partial $\eta^2 = 0.306$), suggesting that VAF differed between walking and cycling (Table 7). However, the main effect of speed was not significant, ($F(1, 11) = 0.615$, $p = 0.450$, partial $\eta^2 = 0.053$), indicating that VAF did not significantly differ between slow and fast speeds. Additionally, the interaction effect between movement type and speed was not significant, ($F(1, 11) = 3.031$, $p = 0.110$, partial $\eta^2 = 0.216$), suggesting that the effect of speed on VAF did not depend on the type of movement.

The correlation coefficients between Slow Walking and Fast Walking ranged from 0.34 to 0.96, with significant positive correlations observed for trunk lateral bend, pelvic tilt, hip abduction, hip rotation, ankle plantarflexion, and foot progression (

Table 8, Figure 9 -Figure 21). Between slow walking with slow cycling, the correlation coefficients ranged from -0.37 to 0.56, with a significant positive correlation found for trunk lateral bend. For slow walking vs. fast cycling, the correlation coefficients ranged from -0.42 to 0.61, with significant correlations found for trunk lateral bend and hip rotation. For fast walking vs. slow cycling, the correlation coefficients ranged from -0.23 to 0.64, with significant positive correlations observed for trunk lateral bend, trunk rotation, pelvic tilt, and hip abduction. Between fast walking with fast cycling, the correlation coefficients ranged from -0.23 to 0.6, with a significant positive correlation found for hip abduction. For slow cycling vs. fast cycling, the correlation coefficients ranged from 0.15 to 0.95, with significant positive correlations observed for GPS, trunk tilt, and ankle plantarflexion.

Discussion

The present study aimed to investigate the effects of movement type (walking vs. cycling) and speed (slow vs. fast) on kinematic variability as measured by GPS/GVS in a TD population. The hypothesis that GPS and GVS scores would decrease with cycling was not supported, in fact, the opposite change was observed. The ANOVA results reveal a significant main effect of movement type on the GPS/CPS values, and the post hoc results showed a significant increase from 3.7 for GPS-slow and 4.2 for GPS-fast to 5.0 for CPS fast and slow. When comparing these data to published data by Baker et al. (*27*), our GPS scores are lower than their GPS score of 5.2. A possible explanation for this difference in average age of test participants. The average age of their cohort was 11 ± 3 years, while we had an average age of 18 ± 3.5 years.

However, the main effect of speed was not significant, indicating that changes in speed, whether slow or fast, did not impact the GPS/CPS values. Additionally, the interaction effect between movement type and speed was not significant, suggesting that the influence of speed on the GPS/CPS values remains consistent regardless of the type of movement. These findings imply that while the type of movement is a crucial factor in differentiating GPS and CPS, the speed at which these movements are performed does not substantially alter the GPS/CPS outcomes. This could have implications for the design of interventions or assessments, where focusing on movement type rather than speed might be more critical for capturing meaningful biomechanical differences.

In regard to the profile analysis of the kinematic variables that make up the GVS/CVS scores, there was a significant interaction effect observed that suggest the patterns of GVS/CVS values differ across conditions, indicating distinct biomechanical profiles for walking and cycling. These tools can effectively capture the biomechanical differences between walking and cycling.

Post-hoc comparisons reveal specific biomechanical differences between walking and cycling. For instance, higher CVS scores for trunk tilt, pelvis tilt, and ankle dorsiflexion in cycling, especially at faster speeds, indicate greater upper body variability between and ankle motion variability between individuals compared to walking. These differences could be attributed to the fixed position, supported upper body through contact with the handlebars, and continuous rotational movement in cycling, contrasting with the dynamic movement patterns in walking. In cycling, the bodyweight is supported by the seat, so the trunk does not have to be positioned to maintain balance of the total

body. This support allows for more variability in pelvic tilt and trunk tilt during cycling compared to walking. Additionally, the increased variability at the ankle could stem from the pedals' ability to freely rotate, unlike the fixed ground position during walking. Contrary to the hypothesis, the speed did not significantly affect GVS/CVS scores, suggesting that while the constrained nature of cycling influences biomechanical profiles, speed alone does not significantly alter the scores. This might be due to the fundamentally different mechanics and constraints of walking and cycling, which do not amplify with increased speed in a straightforward manner.

The ability to utilize GPS and GVS for cycling kinematics introduces new opportunities for assessing and monitoring motor control in clinical populations. Patients with movement disorders could benefit from tailored interventions that consider both walking and cycling biomechanics, enhancing rehabilitation strategies by incorporating cycling as a therapeutic exercise. This comprehensive approach provides a broader understanding of a patient's motor capabilities, potentially improving clinical outcomes. The findings of this study offer significant insights into the adaptation of GPS and GVS tools for analyzing cycling biomechanics in TD individuals. The adaptation of these established gait analysis tools has demonstrated their efficacy in distinguishing between different conditions and speeds in cycling, highlighting the versatility and applicability of these tools beyond traditional walking analyses.

The present study also aimed to investigate the effects of movement type (walking vs. cycling) and speed (slow vs. fast) on the VAF by one synergy. Contrary to our hypothesis that anticipated an increase in VAF during cycling due to the more unified

movement pattern of the joints, the results indicated that VAF was actually higher during walking compared to cycling. One synergy accounted for 68.0% (95% confidence interval [CI] 60.6–75.4%) of the variance in muscle activity during gait at the slow speed, compared to 65.8% (58.9–72.8%) for the slow-cycling condition, and 68.7% (62.7–74.6%) for the fast-walking condition compared with 63.6% (59.6–67.5%) for the fast-cycling condition. This finding suggests that walking, despite its more complex interplay between joints, may have a decreased complexity of control compared to cycling. When comparing the results of this study to published data, literature has documented that one synergy accounted for 74.6% (73.1–76.1%) of the variance in muscle activity during gait at free speed (*28*). However, there is a large difference in the age of the participants with Steele et al.'s study (*28*) having an average age of 10.3 years and a range from 4.3–18 years. It is also worth noting that all but one of the participants did not partake in cycling as a regular activity, which may have influenced the muscle activations due to the unfamiliarity of the task compared to walking, a daily activity. This unfamiliarity may have created atypical muscle activity during the cycling trials compared with a trained cyclist.

Our hypothesis also suggested that VAF would increase with speed due to the overall increased activation of all muscles. However, the results showed that the main effect of speed was not significant, indicating that VAF did not differ significantly between slow and fast speeds within each movement type. This suggests that the neuromuscular control employed during both walking and cycling is relatively consistent across different speeds, indicating a robust neuromuscular control mechanism that is not

significantly altered by speed variations. It should be noted that Steele et al. (*28*) found a moderate relationship between walking speed and walk-DMC among unimpaired individuals, where walk-DMC increased with increasing walking speed. Again, age difference between this study and Steele et al. (*28*) may explain the difference. Additionally, the interaction effect between movement type and speed was not significant. This indicates that the effect of speed on VAF does not depend on whether the movement is walking or cycling. This finding further supports the idea that the complexity of control underlying these movements are distinct yet consistent across speeds.

The present study also aimed to investigate the relationship between walking and cycling deviations as measured by GPS/GVS. The hypothesis that there would be a strong positive correlation between walking and cycling scores was not supported. The results show varying degrees of correlation between the movement deviation scores GPS/GVS and CPS/CVS across different conditions, with few significant positive correlations. When comparing slow walking to slow cycling, there was only one significant correlation of 0.56 for trunk lateral bend. The results of this correlation analysis indicate that GPS/GVS cannot be estimated from CPS/CVS. Consequently, cycling deviations should not be used to predict walking deviations in non-ambulatory populations.

Several limitations must be acknowledged. The relatively small sample size of 13 participants may limit the generalizability of the findings to a broader population and the disproportionate distribution of sex, with 11 female and 2 male participants, may

introduce a sex bias in the results, further affecting the generalizability of the findings. Additionally, the age range of the participants may not fully represent the variability in biomechanics across all age groups. However, the selected age range was chosen to ensure that the participants were in a developmental stage characterized by fully matured gait and cycling biomechanics, minimizing the variability associated with growth and developmental changes. This age group is also representative of a physically active population, which aligns with the study's focus on analyzing walking and cycling at different speeds. By selecting individuals within this age range, we aimed to standardize the biomechanical assessments and reduce the potential confounding effects of age-related biomechanical differences. Differences in physical activity levels and familiarity with cycling among participants could have influenced the results, especially in the muscle activation patterns observed. Furthermore, the fixed resistance of 70 Watts for all participants may not be appropriate for all fitness levels, potentially affecting the biomechanical data collected during cycling. The adaptation of gait analysis tools (GPS and VAF) to cycling may not fully capture the unique biomechanical aspects of cycling, potentially affecting the validity of CPS and CVS. The self-selected speeds for walking and cycling may introduce variability that is not controlled for, impacting the comparability of the data across participants. However, this approach also adds to the strength of the results, as participants moved at a speed typical to their own pace, providing a more realistic representation of their natural movement patterns.

Conclusion

This study successfully adapted the GPS/GVS and VAF tools to the biomechanical analysis of cycling in typically developing individuals. The results indicate that these tools can be modified to work with alternate activities and speeds. The differences in trunk and pelvis GVS scores between walking and cycling and differences in muscle control complexity underscore the distinct kinematic variation involved in these activities. Future research should explore the application of these tools in clinical populations and investigate the potential benefits of incorporating speed training and cycling into rehabilitation programs. This study contributes to the growing body of knowledge on movement analysis, highlighting the versatility and applicability of established gait analysis tools in new contexts.

Chapter 5: Adapting Clinical Gait Analysis Tools for Cycling: Evaluating the Impact of Asymmetric Crank Arm Lengths on Lower Limb Biomechanics

Abstract

Cerebral palsy (CP) is a common childhood disability affecting movement and posture. Cycling offers therapeutic benefits, but the impact of asymmetric crank arm lengths on lower limb biomechanics in CP is underexplored. This study aimed to use adapted gait analysis tools, Gait Profile Score (GPS) and variance accounted for (VAF) from one synergy of walk dynamic motor control (Walk-DMC), to create cycling profile score (CPS) and cycling variable score (CVS) for evaluating asymmetric crank arm lengths in typically developing (TD) individuals. Thirteen participants cycled at slow and fast cadences with asymmetric crank arms of 170mm, 150mm, and 130mm on a stationary ergometer. Results showed consistent CPS and CVS across crank lengths and speeds, however there were inconsistent CVS across kinematic variables. VAF was higher at slower speeds, indicating simplified muscle activation, while cadence increased with shorter crank arms at slower speeds but remained constant at faster speeds. These findings suggest that asymmetric crank arm adjustments do not significantly alter overall movement variability, though they influence specific kinematic and muscle activation patterns. This study highlights the potential of adapting gait analysis tools for cycling, providing new insights into optimizing cycling mechanics for individuals with movement disorders such as CP. Future research should explore these adaptations in clinical populations to enhance mobility and independence for those with CP.

Introduction

Cerebral palsy (CP) is a general term for a group of chronic disorders affecting movement and posture, caused by an injury to the brain during the development of the fetal or infant brain (*1-3*). CP, with an estimated prevalence of 2 to 3.6 cases per 1,000 live births, is the most common physical disability in childhood (*2, 4, 6-9*). Children with CP encounter a range of biomechanical challenges that significantly impact their movement and posture (*1, 11*), with common patterns, including one or more of the following; increased knee flexion, hip flexion, and toe walking (*12-14*). Muscle spasticity leads to involuntary muscle contractions and joint contractures (*3*). Cycling offers significant benefits to children with CP as the rhythmic and repetitive motion can help reduce muscle spasticity while simultaneously improving their muscle strength, endurance, and joint mobility (*31, 32*). Cycling not only enhances cardiovascular health but also fosters a sense of independence and boosts self-esteem in children with CP (*33*).

Crank arm length is one component of a bicycle that may hold implications for cycling biomechanics. As the lever that connects the cyclist's effort to the bicycle's drivetrain, the length of the crank arm can influence pedaling dynamics, force application, and the overall kinematics of the cycling motion (*196*). Variations in this length can lead to subtle yet consequential shifts in joint angles, muscle activation patterns, and energy expenditure (*140, 196*). Various studies have researched crank arm length and its effects on cycling biomechanics and noted that shorter crank arms leads to decreased hip, knee, and ankle angular range of motion (ROM) and joint velocities (*196, 198-202*).

While a myriad of research has explored the effects of crank arm length, they primarily focused on symmetric crank arm lengths. An area that lacks in-depth exploration is the biomechanical analysis of adaptive cycling, such as asymmetric crank arm lengths in cycling for children with unilateral CP. Millour et al. (*37*) investigated the effects of varying crank arm lengths on cyclists with different limb length discrepancies, and found that shorter crank arms for the shorter limb improved joint kinematics and cycling performance by reducing knee and ankle joint extension and reduced the hip and knee ROM. These alterations on the shortened limb side increased the riders perceived comfort and increased maximal power output. Further research confirmed that asymmetric crank arms decrease joint ROM and velocities on the shorter limb side without affecting the unaltered side in TD individuals (*38, 39*). Further research on asymmetric crank arm cycling is needed to optimize assistive and therapeutic devices, and their prescriptions, which can significantly enhance mobility and independence for those with CP.

Incorporating quantitative biomechanical analysis into CP research and clinical care is essential for a comprehensive understanding and effective management of the condition (*22-25*). This approach enables a precise and objective evaluation of the complex motor dysfunctions associated with CP. The previous chapter demonstrated that tools like the gait profile score (GPS) and gait variable score (GVS) (*27*) can be successfully adapted from walking to cycling, to create a cycling profile score (CPS) and a cycling variable score (CVS), to assess kinematic deviations in TD individuals. This adaptation has proven effective in capturing the intricacies of movement patterns in

cycling, providing a robust framework for evaluating dynamic activities beyond traditional gait analysis. Additionally, metrics such as the walk dynamic motor control index (Walk-DMC) and the variance accounted for (VAF) (*28*) have shown promise in analyzing patterns of coordinated muscle activations, extending their utility to cycling biomechanics.

Despite these advancements, substantial gaps still exist, particularly regarding the analysis of adapted cycling. While cycling offers significant benefits for individuals with CP, including the reduction of muscle spasticity and an increase of muscle strength, endurance, and joint mobility (*31, 32*), the application of these adapted tools to cycling remains underexplored. Research has predominantly focused on walking, often neglecting cycling and other adaptive motor tasks (*1, 34, 35*).

The primary purpose of this study was to assess the impact of asymmetric crank arms on cycling biomechanics by utilizing the CPS and CVS and VAF. This analysis aims to provide insights into the adaptive mechanisms of TD individuals when exposed to shortened crank arm lengths during asymmetric cycling. It is hypothesized that the CPS and CVS scores will remain constant with asymmetric cycling, however these scores are expected to increase with speed. Despite changes in joint ROM, it is anticipated that VAF will remain constant with asymmetric changes to the crank arm length because the overall movement pattern is similar. However, VAF is expected to increase with increased cadence due to the overall increased activation of all muscles. Furthermore, it is predicted that cadence will not change between crank arm lengths as the presence of one

shorter crank arm will be counterbalanced by the unchanged length of the other crank arm.

Methods

Participants

Thirteen TD individuals (11 female and 2 male, 18.0 ± 3.5 years, 1.68 ± 0.06 m, 62.4 ± 12.3 kg, 22.0 ± 4.0 kg/m^2) were recruited from the local community to participate in this research study. The inclusion criteria were males and females between the ages of 10-30 years who were recreationally active (defined as at least 30 minutes of exercise at least two days a week). Individuals were excluded if participants aged 18 years or above had a body mass index (BMI) of 30 or greater. Individuals aged 10 to 17 years were excluded if they had a BMI at or above the 95th percentile for their specific age, as per standardized pediatric BMI charts (Appendix M -Appendix N). Individuals were excluded from the study if they had lower extremity surgery within the past 12 months, a neurological or a cardiovascular condition that prevented cycling, or were pregnant/nursing. Prior to data collection, experimental procedures received ethical approval from the university's Institutional Review Board.

Instrumentation

A thirteen-camera motion capture system (240 Hz, Vicon Motion Analysis Inc., UK) was utilized to collect three-dimensional (3D) kinematic data during the testing sessions. For each participant retro reflective markers were placed on the following anatomic landmarks: acromion processes, sternal notch, C7 vertebrae, anterior superior iliac spines, posterior superior iliac spines, iliac crests, greater trochanters, medial and

lateral epicondyles, medial and lateral malleoli, the head of 1st and 5th metatarsals, and the distal phalanx of the second toe. To track segment motions during testing, semi-rigid thermoplastic shells with a cluster of four non-co-planar retro-reflective markers were affixed with neoprene straps to the thighs and shanks. One cluster of four markers was attached to the posterolateral aspect of the heel counter of each shoe with double sided tape.

A sixteen-channel wireless EMG system (1200 Hz, Trigno™ Wireless EMG, Delsys Inc., Natick, MA, USA) recorded muscle activity during gait and cycling trials. EMG sensors were attached bilaterally over the rectus femoris, vastus lateralis, semitendinosus, medial gastrocnemius, and tibialis anterior muscles (*225*). Participants performed cycling exercises on an electromagnetically braked stationary ergometer (Excalibur, Lode B.V., Groningen, Netherlands). 3D kinematics and EMG data were simultaneously collected during the cycling and gait trials using Vicon Nexus (Version 16.0, Vicon Motion Analysis Inc., UK).

Experimental Protocol

Participants took part in one testing session that included cycling with one crank arm of the bike adjusted to three different lengths. The first condition consisted of a symmetric condition with both crank arms at a length of 170mm Following the completion of an informed consent (Appendix D -Appendix G), assent form if under the age of 18 (Appendix H), and a physical activity readiness questionnaire (PAR-Q+, Appendix L), the testing session began with adjusting the cycle ergometer to the participant. The saddle height was adjusted to achieve a knee flexion angle of 25° to 30°

with the crank arms at a standard length of 170mm when the pedal was positioned at the bottom dead center. The fore-aft position of the saddle was adjusted so that the participants' knee aligned vertically with the pedal spindle when the crank was in the forward horizontal position. The handlebar position was set to create a 90° angle between the trunk and thigh with the crank in the forward horizontal position. This was followed by a three-minute walking warm up at a self-selected speed on a treadmill.

The participants cycled in six conditions: at two different cadences of a self-selected revolution per minute (RPM) condition and a self-selected maximum RPM, in each of the three different lengths of the crank arms: 130mm, 150mm, and 170mm (170mm being the length of a typical crank arm) (*144-146*). The self-selected cadence was chosen to provide a more realistic representation of their natural movement patterns. The crank arm length was adjusted on the participants' dominant limb, defined as preferred leg to kick a ball, and kept at 170mm on the other. The resistance was set at 70 Watts. Participants performed two minutes of cycling in each slow condition to acclimate to the cycling condition. Data were captured during the final ten seconds of each two-minute period. Following the self-selected slow condition, participants were asked to cycle as fast as they could for thirty seconds while data was captured during the final ten seconds of this thirty second period. A minimum of a two-minute rest period was given between conditions.

Data Analysis

The collected data were exported from Vicon system and imported into Visual3D software (Version v2022 11.3, C-Motion Inc., Germantown, MD, USA) for the

computation of 3D kinematic and EMG. Raw kinematic marker data were filtered using a fourth order zero lag Butterworth lowpass filter, with a cutoff frequency set at 6 Hz (*188*). Angular kinematics were calculated using the joint coordinate system (*229*) and a Cardan rotational sequence of X-Y-Z with conventions expressed using the right-hand rule.

The GPS (*27*) was adapted for cycling to create a cycling profile score (CPS). The GPS is a measure of overall gait pathology, representing the root mean square (RMS) difference between an individual's gait data and the average data from a reference population. The GVS, on the other hand, quantifies the RMS difference for individual kinematic variables within the gait cycle. The GPS summarizes these deviations into a single comprehensive score. This process involved using the same nine bilateral kinematic variables as the traditional GPS (*27*). In addition to using the traditional nine kinematic variables used to calculate nine gait variable scores (GVS), trunk segment position relative to lab, across all three planes of movement (trunk tilt, lateral bend, and rotation), has been incorporated (for a total of twelve kinematic variables) to provide a more detailed analysis and generate the cycling variable scores (CVS). This process was also conducted on fast-cycling data to calculate a fast CVS.

The VAF was calculated to provide an analysis of muscle activation complexity during each movement task (*28*). EMG data from each muscle during the cycling conditions were normalized to its peak value that occurred during all the cycling trials and time normalized to 101 data points. This data was used to calculate VAF from one synergy using non-negative factorization, the key metric for the Walk-DMC calculation

(*28*). A higher VAF means that the synergies used in the model explain most of the variance in the muscle activity data. For example, if the VAF is 0.90 or 90%, it indicates that 90% of the variance in the muscle activity can be explained by the synergies. A higher VAF indicates a decrease in the complexity of neuromuscular control. This is because fewer synergies are needed to account for the majority of the variance, suggesting a more simplified control strategy. In other words, the neuromuscular system is using fewer, more generalized patterns of muscle activation rather than many specific and distinct patterns. One revolution of the crank starting at top dead center (TDC) and ending at the following TDC was used as one cycle.

Statistical Analysis

A comprehensive statistical analysis was conducted, using IBM SPSS Statistics (version 27), to test various hypotheses and relationships in the data, with the alpha level set a priori at .05 for all tests to determine statistical significance. Partial eta squared (η^2) was used to evaluate effect size using the following benchmarks: small ($\eta^2 = 0.01$), medium ($\eta^2 = 0.06$), and large ($\eta^2 = 0.14$) (*230*). A profile analysis was performed to analyze the CVS values of the limb of the adjusted crank arm length. The profile analysis comprised three main tests: a test of parallelism (interaction), a test of flatness (within-subjects main effect), and a test of levels (between-subjects main effect). The test of parallelism assessed whether the shape of the profile (i.e., the relative differences between CVS values across conditions) was consistent across groups. The test of flatness evaluated whether the profile across each condition was significantly different from flat, indicating variability in the CVS values across the conditions. Lastly, the test of levels

determined if there were overall differences in the profiles' height across conditions, suggesting average differences in overall movement quality. For the CVS values, the analysis examined whether the profiles were parallel across different conditions, assessed overall differences in the levels of CVS values between conditions, and evaluated significant differences among the CVS values within each condition. Post-hoc comparisons using Bonferroni corrections were conducted to identify specific differences between conditions. differences between conditions. Given that there were 6 pairwise comparisons, the original alpha level of 0.05 was divided by 6, resulting in an adjusted p-value of 0.0083.

Multiple two-way repeated measures analysis of variances (ANOVA) were conducted to explore the effects of crank length (170 vs. 150 vs 130) and cadence (slow vs. fast) on CPS, self-selected cadence, and VAF Post-hoc comparisons using Bonferroni corrections were conducted to identify specific differences between crank length and cadence conditions. Given that there were 3 pairwise comparisons, the original alpha level of 0.05 was divided by 6, resulting in an adjusted p-value of 0.0167.

Results

A profile analysis was conducted to test the hypotheses of parallelism, level, and flatness across the CVS values (Figure 22). The analysis for parallelism revealed no significant interaction between condition and CVS values, ($F(55, 330) = 0.621$, $p = 0.983$), indicating that the profiles were parallel (Table 9). For the level analysis, the main effect of condition was not significant, ($F(5, 72) = 0.274$, $p = 0.926$), indicating no overall differences in CVS scores between conditions. The test of flatness showed that the main

effect of the CVS was significant, ($F(11, 62) = 54.969$, $p < 0.001$), indicating significant differences among the scores within each condition (Figure 23 -Figure 28).

For the CPS score, the ANOVA tests showed no significant main effect of speed ($F(1, 12) = 1.156$, $p = 0.304$, partial $\eta^2 = 0.088$), indicating that there was no significant difference in CPS between the slow and fast speeds. The main effect of crank length was also not significant ($F(2, 24) = 0.740$, $p = 0.400$, partial $\eta^2 = 0.058$), indicating that CPS did not vary significantly across the different crank lengths (Table 10). Similarly, the interaction effect between crank length and speed was not significant ($F(2, 24) = 1.024$, $p = 0.374$, partial $\eta^2 = 0.079$).

The results of the multivariate tests of VAF showed a non-significant interaction effect between crank length and speed, ($F(2, 22) = 1.017$, $p = 0.378$, partial $\eta^2 = 0.085$) (Table 11). This suggests that the effect of speed on VAF does not depend on the crank length. However, there was a significant main effect of speed, ($F(1, 11) = 5.939$, $p = 0.033$, partial $\eta^2 = 0.351$), indicating that VAF was significantly higher for the slow speed compared to the fast speed with a mean difference of 0.031. The main effect of crank length was also significant, ($F(2, 22) = 3.943$, $p = 0.034$, partial $\eta^2 = 0.264$), indicating that VAF varied significantly across the different crank lengths. However, pairwise comparisons for crank length did not reveal any significant differences between specific lengths after applying Bonferroni correction. To further explore the significant main effect of speed, pairwise comparisons were conducted between the two speeds (slow and fast) for each crank length. At the 170 mm crank length, the mean difference in VAF between slow and fast speeds was 0.02, which was not statistically significant ($p = 0.155$). At the 150 mm

crank length, the mean difference was 0.05, which was statistically significant ($p = 0.033$). At the 130 mm crank length, the mean difference was 0.03, which was not statistically significant ($p = 0.129$). These results indicate that the significant main effect of speed is primarily driven by the difference at the 150 mm crank length.

The results of the multivariate tests of self-selected cadence showed that the interaction effect between crank length and speed was significant, ($F(2, 24) = 12.464$, $p < 0.001$, partial $\eta^2 = 0.509$) (Table 12). There was also a significant main effect of speed, ($F(1, 12) = 145.495$, $p < 0.001$, partial $\eta^2 = 0.924$), with the fast speed showing a significantly higher mean cadence. The pairwise comparisons revealed significant differences in cadence between the slow and fast speeds at all crank lengths. At all crank lengths, the mean cadence was significantly lower at the slow speed compared to the fast speed (all $p < 0.001$). The mean differences were -39.892 at 170mm, -34.146 at 150mm, and -31.469 at 130mm. The main effect of crank length was not significant. ($F(2, 24) = 2.885$, $p = 0.075$, partial $\eta^2 = 0.194$), indicating that cadence did not vary significantly across the different crank lengths.

Discussion

This study aimed to explore the impact of asymmetric changes of crank arm lengths (170mm, 150mm, and 130mm) and cadence (slow vs. fast) on kinematic variability as measured by CPS and CVS in a TD population. The hypothesis that CPS and CVS scores would remain constant with asymmetric cycling and increase with cadence was partially supported. The profile analysis indicated that the CVS profiles were parallel, with no significant interaction between cycling conditions, suggesting that the overall pattern of

kinematic variability remained consistent across different crank arm lengths and cadences. The lack of significant differences in the CVS scores between conditions also aligns with the hypothesis that asymmetric crank arm lengths would not substantially alter overall movement variability. However, significant differences were observed within the CVS scores, highlighting specific kinematic deviations in each condition.

These findings suggest that while overall movement variability, as measured by CVS, remains consistent across different crank arm lengths and cadences, specific kinematic deviations do occur. For instance, higher CVS scores for trunk tilt, pelvis tilt, and ankle dorsiflexion in cycling indicate greater upper body variability between and ankle motion variability between individuals compared to walking. Comparatively, Baker et al. (*27*) reported relatively similar GVS scores across kinematic variables, indicating a more uniform movement variability pattern. The visual analysis of their plots, showing GVS values between 2 and 6, supports the idea that while cycling introduces specific variability, the overall variability pattern in kinematic variables remains consistent. These differences could be attributed to the fixed position, supported upper body through contact with the handlebars, and continuous rotational movement in cycling, contrasting with the dynamic movement patterns in walking. In cycling, the bodyweight is supported by the seat, so the trunk does not have to be positioned to maintain balance of the total body. This support allows for more variability in pelvic tilt and trunk tilt during cycling compared to walking. Additionally, the increased variability at the ankle could stem from the pedals' ability to freely rotate, unlike the fixed ground position during walking. This underscores the importance of considering specific kinematic factors when analyzing movement patterns

and designing interventions for cycling biomechanics, particularly in contexts where precise control of movement variability is critical.

The CPS analysis revealed no significant main effects of speed or crank arm length, and no interaction between the two main effects. This suggests that CPS remained relatively stable across different speeds and crank arm lengths, contradicting the hypothesis that CPS scores would increase with speed. The consistency of CPS across conditions implies that TD individuals have consistent kinematic variability despite changes in crank arm length, providing a robust metric for assessing movement patterns. Compared to the reported GPS score of 5.2 by Baker et al. (*27*), our CPS scores of 4.7 to 5.1 demonstrate similar kinematic variability between movement types in a TD population, validating the validity of CPS measurements in assessing overall movement patterns.

The present study also aimed to investigate the effects of asymmetric changes of crank arm lengths (170mm, 150mm, and 130mm) and cadence (slow vs. fast) on the VAF by one synergy. The VAF results showed a significant main effect of speed, with higher VAF at slower speeds, contrary to the hypothesis that VAF would increase with speed. This finding suggests that slower speeds may involve more consistent and simplified muscle activation patterns, possibly due to reduced demands on neuromuscular control. At higher cadences, the pedal stroke becomes more circular, meaning the force applied by the cyclist is more evenly distributed throughout the entire pedal cycle (*139*). During cycling, the pedal stroke consists of two main phases: the power phase, where the cyclist pushes down on the pedal, and the recovery phase, where the pedal is brought back up to the starting position (*140*). Ideally, the force applied should be as smooth and continuous as

possible, resembling a circular motion, to maximize efficiency. At lower cadences, cyclists often apply more force during the downstroke and less during the upstroke, leading to a more pronounced "mashing" motion. This can result in a less efficient pedal stroke, with more abrupt changes in force application. As cadence increases, cyclists generally need to apply force more evenly throughout the pedal cycle to maintain a smooth and efficient motion. The transition between the downstroke and upstroke becomes more fluid, and the force applied at each point in the cycle is more balanced. This results in a pedal stroke that is more "circular" in nature, with continuous and consistent force application (*205*, *233*). A more circular pedal stroke at higher cadences helps in reducing peak joint moments and distributing the workload more evenly across the muscles and joints involved, enhancing biomechanical efficiency and reducing the risk of overuse injuries (*139*). It also implies better coordination and muscle control, as the cyclist must engage various muscle groups in a more complex manner to achieve this smooth motion (*37, 139, 233, 234*). This may be the underlying mechanism for the decreased VAF, and increased complexity of neuromuscular control, during the increased cadence conditions.

Additionally, the significant main effect of crank arm length on VAF, although not revealing specific pairwise differences, indicates that varying crank arm lengths influence the complexity of muscle activation. This could be attributed to the altered mechanical demands and movement strategies required by different crank lengths. Longer crank arms generally provide greater leverage, which can reduce the force required to turn the crank but may require greater range of motion at the hip, knee, and ankle joints. Conversely, shorter crank arms necessitate higher cadences to maintain the same speed, potentially

decreasing the complexity of muscle coordination and activation patterns (*200*). This variation in crank arm length can significantly impact joint mechanics, as cyclists must adjust their pedaling technique and muscle engagement to accommodate the different mechanical demands.

Furthermore, it was hypothesized that the cadence would not change between crank arm lengths. Interestingly, the interaction effect between crank arm length and speed was significant, revealing that cadence increased as crank arm length decreased at slow speeds but remained relatively constant at fast speeds. This suggests that shorter crank arm lengths facilitate lower cadence at slower speeds, potentially due to reduced mechanical leverage on the limb with the shortened crank arm. However, at higher speeds, the limiting factor may be joint velocity on the limb with the longer crank arm. Joint velocities increase with longer crank arms (*39*) and the mechanical constraints imposed by the longer crank arm become more prominent at higher speeds, making the high cadence more consistent across participants.

Several limitations must be acknowledged. The relatively small sample size of 13 participants may limit the generalizability of the findings to a broader population and the disproportionate distribution of sex, with 11 female and 2 male participants, may introduce a sex bias in the results, further affecting the generalizability of the findings. Additionally, the age range of the participants may not fully represent the variability in biomechanics across all age groups. However, the selected age range was chosen to ensure that the participants were in a developmental stage characterized by fully matured gait and cycling biomechanics, minimizing the variability associated with growth and developmental

changes. This age group is also representative of a physically active population, which aligns with the study's focus on analyzing walking and cycling at different speeds. By selecting individuals within this age range, we aimed to standardize the biomechanical assessments and reduce the potential confounding effects of age-related biomechanical differences. Furthermore, this age range is critical in CP care, as adolescence and early adulthood are significant periods for managing physical abilities, increasing independence, and transitioning healthcare needs. This selection ensures that any observed differences between TD individuals and those with CP can be attributed more accurately to the condition rather than to age-related biomechanical variations. Differences in physical activity levels and familiarity with cycling among participants could have influenced the results. Furthermore, the fixed resistance of 70 Watts for all participants may not be appropriate for all fitness levels, potentially affecting the biomechanical data collected during cycling. The adaptation of gait analysis tools (GPS and VAF) to cycling may not fully capture the unique biomechanical aspects of cycling, potentially affecting the validity of CPS and CVS. The self-selected cadences may introduce variability that is not controlled for, impacting the comparability of the data across participants. However, this approach also adds to the strength of the results, as participants moved at a speed typical to their own pace, providing a more realistic representation of their natural movement patterns.

Future research should explore the application of these tools in clinical populations and investigate the potential benefits of incorporating speed training and cycling with varied crank arm lengths into rehabilitation programs, especially for individuals with unilateral CP. Such approaches could enhance mobility, independence,

and overall quality of life for individuals with CP, providing a comprehensive framework for movement analysis that bridges the gap between walking and cycling biomechanics. This study contributes to the growing body of knowledge on movement analysis, highlighting the versatility and applicability of established gait analysis tools in new contexts, and underscores the potential for tailored interventions that consider both walking and cycling biomechanics to enhance clinical outcomes for individuals with movement disorders.

Conclusion

This study utilized the adapted CPS and CVS, along with VAF, adapted from gait analysis tools, to evaluate the impact of asymmetric crank arm lengths on cycling biomechanics in TD individuals. The results indicate that while CPS and CVS metrics remain consistent across different crank arm lengths, suggesting that these adjustments do not substantially alter overall movement variability in this population, the VAF analysis revealed interesting nuances. The VAF analysis revealed higher values at slower speeds, indicating simplified muscle activation patterns. Interestingly, cadence increased with shorter crank arm lengths at slower speeds but remained constant at faster speeds, suggesting mechanical constraints and joint velocity considerations play a role in cycling dynamics.

These findings underscore the potential of adapting gait analysis tools for cycling, offering new avenues for biomechanical assessment and intervention in both research and clinical settings. By understanding the intricate relationships between crank arm length,

cadence, and muscle activation, this study paves the way for optimizing cycling mechanics, particularly for populations with movement disorders such as CP.

Chapter 6: Exploring Cycling Biomechanics in Unilateral Cerebral Palsy: Case Studies on Adapted Assessment Tools

Abstract

Cerebral palsy (CP) is the most common physical disability in childhood. Children with CP face biomechanical challenges that affect their walking ability. Quantitative analysis tools like the gait profile score (GPS) and gait variable score (GVS) evaluate these abnormalities, while the walk dynamic motor control index (Walk-DMC) assesses neuromuscular control.

Comparative biomechanical analysis between walking and cycling in CP is underexplored. This study adapts GPS/GVS and Walk-DMC to create the cycling profile score (CPS), cycling variable score (CVS), and cycling dynamic motor control (Cycle-DMC) to examine kinematic effects and neuromuscular control in cycling. This study investigates the influence of walking speed on GPS, GVS, and Walk-DMC, and adapts these scores for cycling. Additionally, the bike was adapted for individuals with unilateral CP by shortening the crank arm on the affected side to assess its impact on CPS, CVS, and Cycle-DMC. The findings suggest that shorter, asymmetric crank arms improve neuromuscular control and cycling efficiency, emphasizing the need for further research into asymmetric cycling in individuals with unilateral CP.

Introduction

Cerebral palsy (CP) is a broad term used to describe a group of persistent movement disorders caused by an injury to the developing fetal or infant brain and is the most common physical disability in childhood (*1-4, 6-9*). CP can also be classified into the specific regions, or topography of the body that are affected by the disease (*65*). Unilateral CP indicates that one entire side of the body, one arm and leg, is affected (*8, 75*) and is the most prevalent of topography (*65*).

Children with CP encounter a range of biomechanical challenges that significantly impact their ability to walk, with common patterns including increased knee flexion, hip flexion, and toe walking (*1, 11-14*). Muscle spasticity leads to involuntary muscle contractions and joint contractures that affect balance, and movement (*3, 17-19*). Quantitative biomechanical analysis, utilizing sophisticated data analysis tools like the gait profile score (GPS) and the gait variable score (GVS), provides a comprehensive evaluation of gait kinematic abnormalities (*27*). Additionally, the walk dynamic motor control index (Walk-DMC) analyzes patterns of coordinated muscle activations, to better understand the complexity of neuromuscular control (*28*). This quantitative analysis is crucial for the development and assessment of therapeutic interventions (*22*).

In previous chapters, these gait analysis tools were successfully adapted for use in cycling biomechanics. Chapter 4 demonstrated that GPS, GVS, and VAF can be effectively modified to assess kinematic and neuromuscular control patterns during cycling, establishing their validity for use beyond traditional gait analysis. Chapter 5 further extended this application by evaluating the impact of asymmetric crank arm

lengths on cycling biomechanics, revealing that these adapted tools (Cycling Profile Score, CPS; Cycling Variable Score, CVS) can accurately capture the effects of mechanical modifications on movement patterns and muscle activation.

An area that lacks in-depth exploration is the comparative biomechanical analysis between walking and cycling, particularly in individuals with CP. Cycling offers significant benefits to individuals with CP as the rhythmic and repetitive motion can help reduce muscle spasticity while simultaneously improving their muscle strength, endurance, and joint mobility (*31, 32*). However, research predominantly focuses on isolated aspects of CP mobility, often neglecting the interplay between different motor tasks (*1, 34, 35*).

Research has shown that asymmetric crank arms decrease joint ROM and velocities on the shorter limb side without affecting the unaltered side in healthy typically developing (TD) individuals (*38, 39*). The biomechanical effects of assistive technologies, such as asymmetric crank arm lengths in cycling for children with unilateral CP, despite positive outcomes seen in individuals with limb length. This lack of research on asymmetric crank arm cycling limits our ability to optimize assistive and therapeutic devices, and their prescriptions, which can significantly enhance mobility and independence for those with CP.

The purpose of this study was to explore the relationship between walking and cycling kinematic deviations at two different speeds in individuals with CP. Additionally, this study aimed to examine the complexity of neuromuscular control during both walking and cycling at these speeds. Furthermore, we sought to adapt bicycles for

individuals with unilateral CP by shortening the crank arm on the side with the affected limb and assess the impact of these modifications on kinematic deviations, neuromuscular control complexity, and self-selected cadence.

Methods

Thirteen TD individuals (11 female and 2 male, 18.0 ± 3.5 years, 1.68 ± 0.06 m, 62.4 ± 12.3 kg, 22.0 ± 4.0 kg/m^2) (Table 1) and two individuals with CP participated in this study. The first participant with CP (CP1) is a 21-year-old female (1.65, 58.4 kg, 21.6 kg/m^2) (Table 2). She has a diagnosis of right unilateral spastic CP gross motor functional scale (GMFCS) I with a selective control assessment of the lower extremity (SCALE) score of 2 for the right hip, knee, ankle, and subtalar and a 0 on the toes (Appendix Y). The second participant with CP (CP2) is a 23-year-old female (1.65, 74.1 kg, 27.2 kg/m^2). She has a diagnosis of left unilateral spastic CP GMFCS I and a SCALE of 2 at the left hip and knee, and a 1 at the ankle, subtalar, and toes (Appendix Z). The participants cycled on an electromagnetically braked stationary ergometer (Lode B.V., Groningen, Netherlands) in six conditions: at two different cadences of a self-selected revolution per minute (RPM) condition and a self-selected maximum RPM, in each of the three different lengths of the crank arms: 130mm, 150mm, and 170mm. The crank arm length was adjusted on the participants' dominant limb. The resistance was set at 70 Watts. Following cycling tests, participants performed five walking trials in each of two conditions. Participants walked at a self-selected typical walking speed and a self-selected fast speed.

A thirteen-camera motion capture system (Vicon Motion Analysis Inc., UK) was utilized to collect three-dimensional (3D) kinematic data during the testing sessions. Electromyography (EMG) data (Delsys Inc., Natick, MA, USA) was recorded from the rectus femoris, vastus lateralis, semitendinosus, medial gastrocnemius, and tibialis anterior muscles (*225*). 3D kinematics and EMG data were simultaneously collected during the cycling and gait trials and processed in Visual3D software (C-Motion Inc., Germantown, MD, USA).

The GPS/GVS (*27*) was adapted for cycling to create a cycling profile score (CPS) and cycling variable score (CVS). For this analysis, the traditional nine kinematic variables of GVS were included along with trunk segment position (trunk tilt, lateral bend, and rotation), for a total of twelve kinematic variables. Walk-DMC was calculated from the EMG data and applied to the cycling data to create a cycle dynamic motor control (Cycle-DMC) (*28, 235*).

Results

Participant CP1: For CP1, when comparing walking and cycling activities, both affected and unaffected limbs displayed significant variations in trunk tilt, trunk rotation, hip flexion, and ankle dorsiflexion, especially at faster speeds and longer crank arm lengths. The CPS scores for the affected limb were consistent across different speeds and crank arm lengths, showing differences of less than 2. In contrast, trunk tilt, trunk rotation, and hip flexion exhibited significant variation, indicating changes between different crank arm lengths and speeds. Similarly, the CPS scores for the unaffected limb

also remained consistent, while trunk tilt, trunk rotation, and hip flexion showed notable variation.

DMC scores for the affected limb were 83.1 for slow walking and 85.4 slow cycling. DMC scores decreased in the fast conditions to 77.5 for fast walking and 55.2 for fast cycling. For the asymmetric cycling, DMC scores for slow cycling increased from 85.4 in the symmetric condition to 95.7 and 94.7 in the 150mm and 130mm conditions, respectively. There was also an increase in DMC scores for the fast conditions from 55.2 in the symmetric condition to 81.9 and 91.3 in the 150mm and 130mm conditions, respectively.

Regarding cadence, in the slow condition, cadence increased from 32.5 RPM in the symmetric condition to 49.0 RPM and 48.7 RPM in the 150mm and 130mm conditions, respectively. In the fast condition the cadences were 74.4 for the symmetric condition and 75.9 RPM and 76.6 in the 150mm and 130mm conditions, respectively.

Participant CP2: For CP2, when comparing walking and cycling activities, both affected and unaffected limbs displayed significant variations in trunk tilt, trunk rotation, hip flexion, and ankle dorsiflexion, especially at faster speeds. The CPS scores for the affected limb were consistent across different speeds and crank arm lengths, showing differences of less than 2. In contrast, trunk tilt, trunk rotation, and hip flexion exhibited significant variation, indicating changes between different crank arm lengths and speeds. Similarly, the CPS scores for the unaffected limb also remained consistent, while trunk tilt, trunk rotation, and hip flexion showed notable variation.

DMC scores for the unaffected limb were 86.6 for slow walking and 67.6 for slow cycling. DMC scores decreased in the fast conditions to 82.3 for fast walking and 40.1 for fast cycling. For the asymmetric cycling, DMC scores for slow cycling increased from 67.6 in the symmetric condition to 76.9 and 79.4 in the 150mm and 130mm conditions, respectively. There was also an increase in DMC scores for the fast conditions from 40.1 in the symmetric condition to 52.0 and 67.0 in the 150mm and 130mm conditions, respectively.

Regarding cadence, in the slow condition, cadence increased from 60.3 RPM in the symmetric condition to 60.2 RPM and 76.6 RPM in the 150mm and 130mm conditions, respectively. In the fast condition, the cadences were 86.2 RPM for the symmetric condition and 84.4 RPM and 82.8 RPM in the 150mm and 130mm conditions, respectively.

Discussion

This study represents the first attempt to apply clinical gait analysis tools, such as GPS/GVS and Walk-DMC, to cycling in individuals with CP, thereby creating the CPS/CVS and Cycle-DMC in individuals with CP. Additionally, it is the first study to analyze the effects of asymmetric crank arm lengths, on individuals with unilateral CP.

Our results showed that GPS and CPS had small variations between conditions in our participants. CP1 saw increased the CPS increased compared to GPS on the affected limb with the opposite outcome on the unaffected limb. CP2 showed the decreased CPS compared to the GPS, but only for the self-selected slow condition. The minimally

clinically important difference (MCID) for GPS is 1.6 (*236*) and all differences between GPS and CPS were within that limit for both participants. However, a detailed examination of the kinematic variables that make up the CPS and GPS, there are clinically relevant differences between CVS and GVS. For CP1, on the affected limb, hip rotation worsened by 2.1 degrees in the slow condition and 3.58 degrees in the fast condition, knee flexion worsened by 2.24 degrees in the slow condition and 2.2 degrees in the fast condition, and ankle dorsiflexion worsened by 4.0 degrees in the slow condition and 4.86 degrees in the fast condition. These kinematic measurements deteriorated with cycling in both the slow and fast conditions. Interestingly, CP2 showed improved hip rotation with decreases of 2.82 degrees during cycling in the slow condition and 3.28 degrees in the fast condition, and knee flexion improved with decreases of 3.42 degrees in the slow condition and 1.84 degrees in the fast condition. However, ankle dorsiflexion worsened, with decreases of 5.44 degrees in the slow condition and 6.58 degrees in the fast condition.

In the asymmetric cycling CPS scores were similar between crank arm lengths for both participants in both the unaffected limb and the affected limbs. CVS scores for CP1 showed an improvement in trunk tilt and lateral bend during the asymmetric conditions. The opposite effect was observed at the ankle with scores becoming worse in the asymmetric crank arm conditions. The other metrics remained similar between conditions. For CP2, most metrics were similar throughout all crank arm length conditions. However, the knee deviations decreased as crank arm decreased. Interestingly the ankle had the lowest score during the 150mm crank arm condition.

While overall CPS and GPS scores showed no MCID, detailed analysis of individual kinematic variables revealed differences that highlight the impact of crank arm length on specific joint movements and postural control. It was hoped that CVS scores would improve with the shorter crank arm because it would decrease the required joint ROM and joint velocities, thereby compensating for the side affected by CP. These findings underscore the complex interplay between joints and segments and emphasize the importance of individualized assessments and adaptations in managing CP through cycling.

Dynamic Motor Control (DMC) scores provide insights into the complexity of neuromuscular control during walking and cycling. CP1 had a score of Walk-DMC score of 83.1 and a Cycle-DMC of 85.4 at self-selected speeds, while CP2 had a Walk-DMC score of 86.6 and a Cycle-DMC score of 67.6. A change in walk-DMC score of 2.6 points is considered the MCID for walk-DMC (*28, 235*). Therefore, there was no clinically relevant difference in the Walk-DMC score for CP1, while there was a large increase of 19 from Walk-DMC to Cycle-DMC for CP2 demonstrating increased complexity of neuromuscular control. When both participants were tasked with increasing their speed, their DMC scores for both walking and cycling decreased. Steele et al. (*28*) noted that for unimpaired individuals, walk-DMC increased with increasing walking speed. Future research should validate these findings and further explore these concepts by including a larger participant pool and examining how CP and its severity influence changes in DMC scores, both as a diagnostic tool and for intervention planning.

The introduction of shorter crank arms significantly improved Cycle-DMC scores for individuals with unilateral CP. For CP1, the Cycle-DMC score increased from 85.4 in the symmetric condition to 95.7 and 94.7 for the 150mm and 130mm crank arm conditions, respectively. Similarly, for CP2, the score improved from 67.6 in the symmetric condition to 76.9 and 79.4 for the 150mm and 130mm conditions, respectively. In the Cycle-DMC metric, a score of 100 or above indicates gait on par with the normative mean, while lower scores point to greater deviations from typical gait patterns. The scale is set so that every 10 points below 100 corresponds to one standard deviation away from the normative mean. This change demonstrates an entire standard deviation improvement in neuromuscular control complexity with a 20mm reduction in crank arm length.

Interestingly, these improvements in neuromuscular control were accompanied by increases in self-selected cadence at slower speeds when using the shorter crank arms. For instance, CP1's cadence increased from 32.5 RPM with the 170mm crank arm to approximately 49 RPM with both the 150mm and 130mm crank arms. CP2's cadence increased from 60.3 RPM with the 170mm crank arm to 76.6 RPM with the 130mm crank arm. These changes suggest that shorter crank arm lengths facilitate a higher cadence at slower speeds, likely due to the reduced joint range of motion and velocities required, which compensates for the limitations posed by CP (*36*).

The ability to pedal more efficiently with shorter crank arms at slower speeds may have significant training benefits. By increasing self-selected cadence, individuals with CP can engage in a more intense cardiovascular workout. This could enhance

cardiovascular fitness and overall cycling performance. Moreover, improved neuromuscular control with shorter crank arms could translate to better motor coordination, further contributing to the overall physical health of individuals with CP.

The observed improvements at slower speeds indicate that shorter crank arms may reduce the mechanical constraints, particularly on the affected limb. However, at higher speeds, the differences in cadence between crank arm lengths were less pronounced. For CP1, the cadence remained relatively stable across all crank arm lengths. Similarly, CP2's cadence slightly decreased from 86.2 RPM with the 170mm crank arm to 82.8 RPM with the 130mm crank arm, indicating a potential adaptation challenge or reduced efficiency at higher speeds with shorter crank arms.

The use of asymmetric crank arms allows individuals with CP to improve their complexity of neuromuscular control and increase their self-selected cadence at slower speeds. Future research should continue to explore these findings, including a larger and more diverse participant pool, to validate the clinical relevance and practical applications of CPS, CVS, and Cycle-DMC scores in managing CP through cycling.

Conclusion

This study represents a pioneering effort to apply clinical gait analysis tools such as GPS/GVS and Walk-DMC to cycling, resulting in the creation of CPS/CVS and Cycle-DMC for individuals with unilateral CP. Additionally, it is the first to explore the effects of asymmetric crank arm lengths on this population. The findings suggest that shorter, asymmetric crank arms may provide significant improvements in complexity of

neuromuscular control and cycling efficiency, highlighting the importance of individualized assessments and adaptations in managing CP through cycling.

Chapter 7: Conclusion

The purpose of this dissertation was to determine if clinical gait analysis tools, the gait analysis profile (GPS), gait variable score (GVS), and dynamic motor control (DMC), could be adapted for cycling. Once these tools were adapted to cycling, the dissertation sought to examine the impact of cycling with asymmetric crank arms with these adapted tools. Chapter 4 showed that walking and cycling have distinct movement profiles and there was no strong correlation between any of the kinematic variables between walking and cycling. Additionally, complexity of neuromuscular control is decreased in walking compared to cycling. Chapter 5 found no significant changes in kinematic deviations between different lengths of asymmetric crank lengths. However, complexity of neuromuscular control increased with speed and decreased with shorter crank lengths. Finally, chapter 6 showed the two individuals with cerebral palsy have varying changes in cycling deviations, from typically developing individuals, across different asymmetric crank arm lengths. However, complexity of neuromuscular control decreased with speed and increased with shorter crank arms for the two individuals analyzed. Future research should continue to explore these findings, including a larger and more diverse participant pool of individuals with cerebral palsy, to validate the clinical relevance and practical applications of cycling with individuals with cerebral palsy.

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Appendices

Appendix A: Tables

Table 1: Typically Developing Participant Demographics

Participant	Sex	Age (years)	Height (cm)	Mass (kg)	BMI (kg/m^2)
S101	F	19	164.5	49.5	18.3
S102	F	20	175.9	81.4	26.3
S103	F	11	164.5	49.5	18.3
S104	F	25	165.1	49.2	18.0
S105	F	21	163.8	71.5	26.6
S106	F	20	177.8	54.2	17.1
S107	F	16	166.4	58.7	21.2
S108	M	16	168.9	56.4	19.8
S109	F	16	162.6	51.1	19.3
S110	M	16	179.7	80.2	24.8
S111	F	15	167.0	60.9	21.8
S112	F	18	167.6	71.2	25.3
S113	F	21	163.8	77.8	29.0

Table 2: Participants with Cerebral Palsy Demographics

Participant	Sex	Age (years)	Height (cm)	Mass (kg)	BMI (kg/m^2)	Affected Limb	GMFCS	FAQ	FMS 5	FMS 50	FMS 500
S201	F	21	164.5	58.4	21.6	R	I	10	6	6	6
S202	F	23	165.1	74.1	27.2	L	I	10	6	6	6

Table 3: Inclusion and Exclusion Criteria for Participants with Cerebral Palsy

Inclusion Criteria:

- Male or female
- Ages: 10-30
- Diagnosis of unilateral CP
- GMFCS level I or II

Exclusion Criteria:

- For participants aged 18 years or above: A BMI of 30 or greater.
- For participants aged 12 to 17 years: A BMI at or above the 95th percentile for their specific age, as per standardized pediatric BMI charts (**Error! Reference source not found.** -**Error! Reference source not found.**).
- GMFCS greater than II
- Less than 12 months post lower extremity orthopedic surgery
- Lower extremity injury within the past 6 months
- Currently taking and/or took baclofen in the past 10 weeks
- Has undergone lower extremity Botox injections within the past 10 weeks
- Has a neurological or cardiovascular condition that prevents walking or cycling
- Pregnant or nursing

Table 4: Inclusion and Exclusion Criteria for Typically Developing Participants

Inclusion Criteria:

- Male or female
- Ages: 10-30
- Recreationally active defined as at least 30 minutes of exercise at least two days a week

Exclusion Criteria:

- For participants aged 18 years or above: A BMI of 30 or greater.
- For participants aged 12 to 17 years: A BMI at or above the 95th percentile for their specific age, as per standardized pediatric BMI charts (**Error! Reference source not found.** -**Error! Reference source not found.**).
- Lower extremity surgery within the past 12 months
- Lower extremity injury within the past 6 months
- Has a neurological or cardiovascular condition that prevents walking or cycling
- Pregnant or nursing

Table 5: GVS and CVS Scores of Typically Developing Participants During Walking and Cycling at Two Different Speeds (mean ± STD)

Dependent Variable	Slow Walking	Fast Walking	Slow Cycling	Fast Cycling	Level p-value	Flatness p-value	Parallelism p-value
Trunk Tilt	2.8 ± 0.9	2.9 ± 1.0	6.5 ± 3.8	7.8 ± 5.6 [a b c]			
Trunk Lateral Bend	1.8 ± 0.8	2.3 ± 1.1	2.2 ± 1.5	3.0 ± 1.3			
Trunk Rotation	3.2 ± 1.3	4.4 ± 1.5	3.6 ± 4.8	2.8 ± 1.4 b			
Pelvic Tilt	3.7 ± 2.6	4.8 ± 3.2	8.8 ± 5.4 [a]	8.9 ± 6.2 [a b]			
Pelvic Obliquity	2.5 ± 1.2	2.8 ± 1.2	2.1 ± 1.4	2.2 ± 1.5			
Pelvic Rotation	3.6 ± 1.3	4.4 ± 2.0	2.5 ± 1.5	2.5 ± 1.4	**<0.001**	**<0.001**	**<0.001**
Hip Flexion	5.2 ± 2.6	6.4 ± 2.8	8.2 ± 4.3	8.0 ± 4.6			
Hip Abduction	3.0 ± 2.0	3.5 ± 1.9	3.2 ± 1.8	3.2 ± 1.4			
Hip Rotation	6.2 ± 3.1	7.0 ± 3.2	6.4 ± 3.7	6.4 ± 3.2			
Knee Flexion	4.7 ± 2.0	4.5 ± 1.9	5.6 ± 3.7	5.6 ± 4.2			
Ankle Dorsiflexion	3.8 ± 1.7	4.2 ± 1.7	8.1 ± 3.1 [a]	6.8 ± 3.1 [a b]			
Foot Progression	3.5 ± 0.9	3.5 ± 1.0	2.6 ± 1.9	2.5 ± 1.5			

'a' indicates a significant difference from Slow Walking, 'b' indicates a significant difference from Fast Walking, and 'c' indicates a significant difference from Slow Cycling with Bonferroni adjusted $p<0.0083$.

Table 6: GPS/CPS Scores of Typically Developing Participants During Walking and Cycling at Two Different Speeds (mean ± STD)

Speed	Walk	Cycle	Movement p-value (η^2)	Speed p-value (η^2)	Interaction p-value (η^2)
Slow	3.7 ± 0.7	5.0 ± 1.3	**0.027**	0.125	0.126
Fast	4.2 ± 0.8	5.0 ± 1.5	(0.347)	(0.184)	(0.184)

Table 7: Variance Accounted for by One Synergy for Typically Developing Participants During Walking and Cycling at Two Different Speeds (mean ± STD)

Speed	Walk	Cycle	Movement p-value (η^2)	Speed p-value (η^2)	Interaction p-value (η^2)
Slow	0.68 ± 0.07	0.66 ± 0.07	**0.0497** (0.306)	0.450 (0.053)	0.110 (0.216)
Fast	0.69 ± 0.06	0.64 ± 0.04			

Table 8: Correlation Coefficients for GPS/GVS CPS/CVS for Typically Developing Participants During Walking and Cycling at Two Different Speeds

Comparison	GPS		Trunk Tilt		Trunk Lateral Bend		Trunk Rotation	
	R-Value	p-Value	R-Value	p-Value	R-Value	p-Value	R-Value	p-Value
Slow Walk vs Fast Walk	0.34	0.254	-0.05	0.868	0.84	**< 0.001**	0.54	0.057
Slow Walk vs Slow Cycle	-0.37	0.210	-0.01	0.966	0.56	**0.046**	-0.07	0.831
Slow Walk vs Fast Cycle	-0.08	0.799	-0.33	0.276	0.56	**0.047**	0.00	0.989
Fast Walk vs Slow Cycle	0.11	0.718	-0.23	0.447	0.58	**0.039**	0.63	**0.020**
Fast Walk vs Fast Cycle	0.30	0.323	-0.18	0.550	0.45	0.121	0.14	0.647
Slow Cycle vs Fast Cycle	0.80	**0.001**	0.44	0.134	0.43	0.140	0.15	0.616

Pelvic Tilt		Pelvic Obliquity		Pelvic Rotation	
R-Value	p-Value	R-Value	p-Value	R-Value	p-Value
0.66	**0.014**	0.85	**< 0.001**	0.43	0.144
-0.21	0.481	0.50	0.085	-0.10	0.746
-0.33	0.279	0.40	0.172	-0.07	0.827
0.37	0.218	0.44	0.129	0.41	0.164
0.26	0.391	0.50	0.085	0.04	0.892
0.58	**0.038**	0.88	**< 0.001**	0.42	0.155

Hip Flexion		Hip Abduction		Hip Rotation	
R-Value	p-Value	R-Value	p-Value	R-Value	p-Value
0.49	0.092	0.85	**< 0.001**	0.96	**< 0.001**
-0.26	0.386	0.26	0.386	0.53	0.065
-0.42	0.156	0.46	0.113	0.61	**0.028**
0.00	0.999	0.64	0.019	0.48	0.098
-0.01	0.968	0.60	**0.030**	0.54	0.058
0.62	**0.025**	0.75	**0.003**	0.95	**< 0.001**

Knee Flexion		Ankle Plantarflexion		Foot Progression	
R-Value	p-Value	R-Value	p-Value	R-Value	p-Value
0.47	0.103	0.67	**0.013**	0.61	**0.026**
0.16	0.596	0.15	0.630	0.42	0.158
0.26	0.398	0.07	0.825	0.25	0.411
-0.04	0.902	0.37	0.218	0.41	0.159
-0.05	0.878	-0.23	0.460	0.42	0.149

Table 8: Continued

0.89	**< 0.001**	0.20	0.508	0.89	**< 0.001**

Table 9: CVS Scores of Typically Developing Participants During Cycling at Three Crank Arm Lengths and Two Speeds (mean ± STD)

Dependent Variable	170 Slow	170 Fast	150 Slow	150 Fast	130 Slow	130 Fast	Level p-value	Flatness p-value	Parallelism p-value
Trunk Tilt	6.5 ± 3.8	7.8 ± 5.6	6.6 ± 4.2	8.0 ± 6.8	6.5 ± 3.8	9.6 ± 6.2	0.926	**<0.001**	0.983
Trunk Obliquity	2.2 ± 1.5	3.0 ± 1.3	2.4 ± 0.8	2.4 ± 1.1	2.6 ± 1.5	3.1 ± 1.7			
Trunk Rotation	3.6 ± 4.8	2.8 ± 1.4	2.0 ± 1.2	2.6 ± 1.5	2.5 ± 1.6	3.2 ± 2.3			
Pelvic Tilt	8.8 ± 5.4	8.9 ± 6.2	7.0 ± 6.0	8.6 ± 7.0	6.1 ± 5.2	8.4 ± 6.3			
Pelvic Obliquity	2.1 ± 1.4	2.2 ± 1.5	2.2 ± 1.5	2.5 ± 1.8	2.4 ± 1.5	2.5 ± 1.4			
Pelvic Rotation	2.5 ± 1.5	2.5 ± 1.4	2.2 ± 0.8	2.1 ± 0.7	2.3 ± 0.7	2.6 ± 1.0			
Hip Flexion	8.2 ± 4.3	8.0 ± 4.6	6.6 ± 4.8	8.0 ± 5.7	6.4 ± 4.0	8.2 ± 4.9			
Hip Abduction	3.2 ± 1.8	3.2 ± 1.4	2.8 ± 1.6	3.0 ± 1.7	2.7 ± 1.1	3.1 ± 1.4			
Hip Rotation	6.4 ± 3.7	6.4 ± 3.2	5.6 ± 3.4	5.9 ± 3.2	5.3 ± 3.2	5.7 ± 3.0			
Knee Flexion	5.6 ± 3.7	5.6 ± 4.2	5.7 ± 3.3	5.3 ± 3.5	5.7 ± 2.8	5.0 ± 2.4			
Ankle Dorsiflexion	8.1 ± 3.1	6.8 ± 3.1	9.2 ± 6.1	7.6 ± 2.3	10.7 ± 4.9	7.3 ± 2.3			
Foot Progression	2.6 ± 1.9	2.5 ± 1.5	2.6 ± 1.5	2.9 ± 2.1	3.1 ± 1.6	3.1 ± 1.7			

Table 10: CPS Scores of Typically Developing Participants During Cycling at Three Crank Arm Lengths and Two Speeds (mean ± STD)

Speed	170mm	150mm	130mm	Crank Length p-value (η^2)	Speed p-value (η^2)	Interaction p-value (η^2)
Slow	5.0 ± 1.3	4.6 ± 1.5	4.7 ± 1.0	0.400 (0.058)	0.304 (0.088)	0.374 (0.079)
Fast	5.0 ± 1.5	4.9 ± 1.7	5.1 ± 1.5			

Table 11: Variance Accounted for by One Synergy for Typically Developing Participants During Cycling at Three Crank Arm Lengths and Two Speeds (mean ± STD)

Speed	170mm	150mm	130mm	Crank Length p-value (η^2)	Speed p-value (η^2)	Interaction p-value (η^2)
Slow	0.66 ± 0.07	0.69 ± 0.10	0.70 ± 0.10	**0.034** (0.264)	**0.033** (0.351)	0.378 (0.085)
Fast	0.64 ± 0.04	0.64 ± 0.05 †	0.67 ± 0.06			

'†' indicates a significant difference from Slow Speed.

Table 12: Cadence (RPM) for Typically Developing Participants During Cycling at Three Crank Arm Lengths and Two Speeds (mean ± STD)

Speed	170mm	150mm	130mm	Crank Length p-value (η^2)	Speed p-value (η^2)	Interaction p-value (η^2)
Slow	44.1 ± 8.2	49.3 ± 10.2	51.4 ± 9.0	0.075 (0.194)	< **0.001** (0.924)	< **0.001** (0.509)
Fast	84.0 ± 12.8 †	83.4 ± 13.3 †	82.9 ± 12.0 †			

'†' indicates a significant difference from Slow Speed.

Table 13: GPS/GVS and CPS/CVS Scores During Walking and Cycling at Two Speeds: CP1 (mean ± STD)

Dependent Variable	Slow Walking		Fast Walking		Slow Cycling		Fast Cycling	
	Affected	Unaffected	Affected	Unaffected	Affected	Unaffected	Affected	Unaffected
GPS	4.26 ± 0.23	5.9 ± 0.23	4.94 ± 0.34	5.52 ± 0.41	5.32 ± 0.26	4.78 ± 0.31	5.68 ± 0.25	4.6 ± 0.2
Trunk Tilt	3.1 ± 0.92	3.78 ± 1.45	3.84 ± 2.65	3.28 ± 2.89	7.76 ± 3.12	8.52 ± 2.82	2.7 ± 1.4	2.12 ± 1.2
Trunk Lateral Bend	6.12 ± 0.92	5.48 ± 1.54	4.66 ± 1.12	4.82 ± 1.12	6.16 ± 1.46	5.85 ± 1.03	2.44 ± 1.37	2.54 ± 1.1
Trunk Rotation	3.02 ± 0.77	3.04 ± 0.68	4.98 ± 1.57	4.74 ± 1.54	5.48 ± 0.87	5.25 ± 1.05	1.56 ± 0.88	1.64 ± 0.84
Pelvic Tilt	4.8 ± 0.69	4.96 ± 1.09	4.22 ± 1.07	4.24 ± 1.15	1.5 ± 0.51	1.68 ± 0.34	4.76 ± 0.79	5.2 ± 0.77
Pelvic Obliquity	2.28 ± 0.75	2.7 ± 0.57	2.86 ± 0.25	2.86 ± 0.17	1.14 ± 0.61	0.88 ± 0.3	2.34 ± 0.3	2.26 ± 0.32
Pelvic Rotation	3.12 ± 1.51	2.76 ± 0.84	3.56 ± 1.15	2.66 ± 1.15	4.06 ± 0.48	3.75 ± 0.49	2.94 ± 0.38	2.72 ± 0.31
Hip Flexion	5.64 ± 0.65	11.2 ± 1.06	6.5 ± 0.94	9.56 ± 1.26	2.78 ± 0.48	3.65 ± 0.34	8.8 ± 1.05	5.68 ± 1.23
Hip Abduction	2.12 ± 0.51	3.52 ± 0.65	3.64 ± 0.51	3.48 ± 0.54	4.0 ± 0.83	1.75 ± 0.44	4.88 ± 0.11	3.14 ± 0.26
Hip Rotation	4.74 ± 0.71	8.56 ± 0.61	4.58 ± 0.45	8.86 ± 0.88	6.8 ± 0.6	7.18 ± 0.4	8.16 ± 0.3	11.12 ± 0.5
Knee Flexion	6.24 ± 0.57	9.62 ± 1.03	6.56 ± 0.87	7.06 ± 0.34	8.48 ± 0.38	5.12 ± 0.35	8.76 ± 0.65	5.92 ± 0.58
Ankle Dorsiflexion	6.6 ± 0.55	7.04 ± 0.19	9.66 ± 0.23	5.68 ± 0.33	10.6 ± 0.97	4.35 ± 1.41	14.52 ± 0.44	3.74 ± 0.63
Foot Progression	3.08 ± 1.14	8.36 ± 1.04	3.88 ± 0.61	8.84 ± 0.77	5.18 ± 0.08	9.32 ± 0.49	6.26 ± 0.26	9.16 ± 0.22

Table 14: GPS/GVS and CPS/CVS Scores During Walking and Cycling at Two Speeds: CP2 (mean ± STD)

Dependent Variable	Slow Walking		Fast Walking		Slow Cycling		Fast Cycling	
	Affected	Unaffected	Affected	Unaffected	Affected	Unaffected	Affected	Unaffected
GPS	5.68 ± 0.11	4.64 ± 0.25	5.4 ± 0.21	4.98 ± 0.31	4.58 ± 0.08	4.08 ± 0.42	6.18 ± 0.22	5.32 ± 0.22
Trunk Tilt	3.18 ± 0.91	2.6 ± 0.41	3.04 ± 1.3	2.74 ± 1.08	4.16 ± 0.63	3.86 ± 0.93	9.0 ± 0.45	9.7 ± 0.29
Trunk Lateral Bend	1.62 ± 0.25	1.1 ± 0.37	1.34 ± 0.21	1.16 ± 0.44	4.04 ± 1.31	4.42 ± 1.45	4.02 ± 1.04	3.76 ± 0.81
Trunk Rotation	3.92 ± 0.85	3.86 ± 0.8	5.2 ± 0.85	4.86 ± 1.08	3.96 ± 0.9	4.06 ± 0.76	2.62 ± 0.68	2.6 ± 0.42
Pelvic Tilt	2.68 ± 0.66	2.58 ± 0.55	2.48 ± 0.22	2.7 ± 0.07	4.26 ± 0.56	4.52 ± 0.86	10.5 ± 0.43	10.72 ± 0.41
Pelvic Obliquity	6.72 ± 0.29	6.94 ± 0.49	5.34 ± 0.4	5.88 ± 0.25	1.82 ± 0.79	1.96 ± 0.89	1.4 ± 0.19	1.4 ± 0.21
Pelvic Rotation	3.98 ± 0.91	3.94 ± 0.97	2.92 ± 1.11	4.96 ± 0.43	3.38 ± 0.74	3.2 ± 0.47	4.16 ± 0.15	3.82 ± 0.36
Hip Flexion	8.68 ± 0.65	5.56 ± 0.92	6.48 ± 0.36	3.78 ± 0.5	3.62 ± 0.77	3.96 ± 0.36	9.24 ± 0.48	9.66 ± 0.36
Hip Abduction	5.82 ± 0.31	6.9 ± 0.56	4.64 ± 0.43	6.96 ± 0.56	1.78 ± 0.59	4.46 ± 0.19	2.1 ± 0.16	4.06 ± 0.19
Hip Rotation	12.4 ± 0.45	4.56 ± 0.33	11.52 ± 0.61	4.5 ± 0.19	9.58 ± 0.35	2.22 ± 0.6	8.24 ± 0.43	2.26 ± 0.17
Knee Flexion	8.58 ± 0.94	4.78 ± 0.61	6.3 ± 0.98	6.46 ± 1.04	5.16 ± 0.4	4.86 ± 0.23	4.46 ± 0.11	4.08 ± 0.19
Ankle Dorsiflexion	6.08 ± 0.31	5.08 ± 0.28	9.3 ± 0.14	6.34 ± 0.83	11.52 ± 0.77	5.88 ± 2.66	15.88 ± 0.11	5.08 ± 0.56
Foot Progression	4.64 ± 0.93	7.92 ± 1.07	6.42 ± 0.41	9.5 ± 0.82	1.64 ± 0.15	5.44 ± 0.48	2.48 ± 0.18	6.94 ± 0.26

Table 15: CPS/CVS Scores of Affected Limb During Cycling at Three Crank Lengths at Two Speeds: CP1 (mean ± STD)

Dependent Variable	170 Slow	170 Fast	150 Slow	150 Fast	130 Slow	130 Fast
CPS	4.78 ± 0.31	4.6 ± 0.2	5.54 ± 0.32	4.45 ± 0.58	4.16 ± 0.22	3.9 ± 0.14
Trunk Tilt	8.52 ± 2.82	2.12 ± 1.2	2.9 ± 1.17	4.04 ± 1.69	3.06 ± 0.69	5.94 ± 1.73
Trunk Lateral Bend	5.85 ± 1.03	2.54 ± 1.1	2.28 ± 0.54	3.34 ± 0.54	3.38 ± 1.01	2.52 ± 1.17
Trunk Rotation	5.25 ± 1.05	1.64 ± 0.84	6.5 ± 0.59	3.74 ± 0.34	5.72 ± 0.88	3.38 ± 0.79
Pelvic Tilt	1.68 ± 0.34	5.2 ± 0.77	5.3 ± 2.0	3.04 ± 0.91	2.6 ± 0.55	1.92 ± 0.33
Pelvic Obliquity	0.88 ± 0.3	2.26 ± 0.32	2.72 ± 0.41	3.1 ± 0.16	1.18 ± 0.28	1.68 ± 0.48
Pelvic Rotation	3.75 ± 0.49	2.72 ± 0.31	3.44 ± 0.89	3.78 ± 0.11	2.86 ± 0.19	2.12 ± 0.3
Hip Flexion	3.65 ± 0.34	5.68 ± 1.23	7.94 ± 2.82	3.76 ± 0.37	4.24 ± 0.4	1.46 ± 0.25
Hip Abduction	1.75 ± 0.44	3.14 ± 0.26	2.52 ± 0.73	2.24 ± 0.59	1.92 ± 0.35	1.22 ± 0.3
Hip Rotation	7.18 ± 0.4	11.12 ± 0.5	8.06 ± 0.62	7.98 ± 0.52	7.48 ± 0.45	9.38 ± 0.56
Knee Flexion	5.12 ± 0.35	5.92 ± 0.58	3.48 ± 1.02	5.08 ± 0.54	2.1 ± 0.56	3.02 ± 0.54
Ankle Dorsiflexion	4.35 ± 1.41	3.74 ± 0.63	12.28 ± 2.2	4.52 ± 1.8	4.4 ± 0.63	2.8 ± 0.51
Foot Progression	9.32 ± 0.49	9.16 ± 0.22	8.9 ± 0.72	8.8 ± 0.14	11.18 ± 0.13	11.52 ± 0.53

Table 16: CPS/CVS Scores of Unaffected Limb During Cycling at Three Crank Lengths at Two Speeds: CP1 (mean ± STD)

Dependent Variable	**170 Slow**	**170 Fast**	**150 Slow**	**150 Fast**	**130 Slow**	**130 Fast**
CPS	5.32 ± 0.26	5.68 ± 0.25	5.36 ± 0.39	5.61 ± 1.11	4.44 ± 0.21	4.96 ± 0.09
Trunk Tilt	7.76 ± 3.12	2.7 ± 1.4	3.28 ± 1.4	4.32 ± 1.74	2.96 ± 0.88	6.1 ± 1.61
Trunk Lateral Bend	6.16 ± 1.46	2.44 ± 1.37	2.3 ± 0.82	3.2 ± 0.69	3.12 ± 0.93	2.42 ± 1.11
Trunk Rotation	5.48 ± 0.87	1.56 ± 0.88	6.36 ± 0.61	3.86 ± 0.44	5.62 ± 0.86	3.48 ± 0.79
Pelvic Tilt	1.5 ± 0.51	4.76 ± 0.79	5.9 ± 1.84	3.2 ± 0.92	2.56 ± 0.69	2.0 ± 0.53
Pelvic Obliquity	1.14 ± 0.61	2.34 ± 0.3	2.72 ± 0.41	2.9 ± 0.55	1.48 ± 0.15	1.62 ± 0.49
Pelvic Rotation	4.06 ± 0.48	2.94 ± 0.38	3.22 ± 0.57	3.82 ± 0.28	2.6 ± 0.43	2.22 ± 0.29
Hip Flexion	2.78 ± 0.48	8.8 ± 1.05	5.54 ± 2.12	6.2 ± 0.36	1.18 ± 0.38	3.66 ± 0.54
Hip Abduction	4.0 ± 0.83	4.88 ± 0.11	2.76 ± 0.75	6.5 ± 0.42	3.38 ± 0.18	5.9 ± 0.2
Hip Rotation	6.8 ± 0.6	8.16 ± 0.3	4.9 ± 0.33	5.58 ± 0.18	5.84 ± 0.05	6.9 ± 0.31
Knee Flexion	8.48 ± 0.38	8.76 ± 0.65	9.4 ± 0.24	8.36 ± 0.7	6.14 ± 0.37	5.92 ± 0.62
Ankle Dorsiflexion	10.6 ± 0.97	14.52 ± 0.44	13.88 ± 1.1	14.76 ± 0.28	14.54 ± 1.16	14.74 ± 0.39
Foot Progression	5.18 ± 0.08	6.26 ± 0.26	3.78 ± 0.4	4.64 ± 0.09	4.0 ± 0.23	4.74 ± 0.27

Table 17: CPS/CVS Scores of Affected Limb During Cycling at Three Crank Lengths at Two Speeds: CP2 (mean ± STD)

Dependent Variable	**170 Slow**	**170 Fast**	**150 Slow**	**150 Fast**	**130 Slow**	**130 Fast**
CPS	4.08 ± 0.42	5.32 ± 0.22	4.24 ± 0.09	6.18 ± 0.15	4.26 ± 0.15	5.84 ± 0.21
Trunk Tilt	3.86 ± 0.93	9.7 ± 0.29	2.88 ± 1.24	10.1 ± 0.67	4.36 ± 0.52	12.2 ± 0.25
Trunk Lateral Bend	4.42 ± 1.45	3.76 ± 0.81	4.04 ± 0.62	5.3 ± 0.56	4.98 ± 0.65	5.32 ± 0.29
Trunk Rotation	4.06 ± 0.76	2.6 ± 0.42	7.98 ± 1.07	4.74 ± 0.53	9.16 ± 0.95	4.92 ± 0.08
Pelvic Tilt	4.52 ± 0.86	10.72 ± 0.41	4.26 ± 0.65	11.7 ± 0.85	3.1 ± 0.44	9.28 ± 0.28
Pelvic Obliquity	1.96 ± 0.89	1.4 ± 0.21	1.1 ± 0.58	1.66 ± 0.37	0.9 ± 0.32	1.62 ± 0.19
Pelvic Rotation	3.2 ± 0.47	3.82 ± 0.36	3.86 ± 0.42	4.4 ± 0.29	2.78 ± 0.68	3.32 ± 0.31
Hip Flexion	3.96 ± 0.36	9.66 ± 0.36	5.32 ± 0.79	10.98 ± 0.58	3.8 ± 0.48	8.44 ± 0.32
Hip Abduction	4.46 ± 0.19	4.06 ± 0.19	4.48 ± 0.61	5.24 ± 0.4	3.3 ± 0.17	3.94 ± 0.26
Hip Rotation	2.22 ± 0.6	2.26 ± 0.17	1.62 ± 0.39	1.34 ± 0.21	2.1 ± 0.14	1.84 ± 0.11
Knee Flexion	4.86 ± 0.23	4.08 ± 0.19	4.68 ± 0.24	5.12 ± 0.27	4.78 ± 0.16	5.02 ± 0.46
Ankle Dorsiflexion	5.88 ± 2.66	5.08 ± 0.56	5.3 ± 1.31	8.52 ± 0.91	4.46 ± 1.06	7.18 ± 1.79
Foot Progression	5.44 ± 0.48	6.94 ± 0.26	5.46 ± 0.17	4.72 ± 0.25	7.26 ± 0.29	7.34 ± 0.33

Table 18: CPS/CVS Scores of Unaffected Limb During Cycling at Three Crank Lengths at Two Speeds: CP2 (mean ± STD)

Dependent Variable	**170 Slow**	**170 Fast**	**150 Slow**	**150 Fast**	**130 Slow**	**130 Fast**
CPS	4.58 ± 0.08	6.18 ± 0.22	4.46 ± 0.11	7.32 ± 0.22	4.74 ± 0.22	6.76 ± 0.15
Trunk Tilt	4.16 ± 0.63	9.0 ± 0.45	2.54 ± 1.04	10.3 ± 0.75	4.44 ± 0.3	12.14 ± 0.17
Trunk Lateral Bend	4.04 ± 1.31	4.02 ± 1.04	3.82 ± 0.72	5.26 ± 0.62	4.86 ± 0.77	5.26 ± 0.44
Trunk Rotation	3.96 ± 0.9	2.62 ± 0.68	8.0 ± 1.23	4.7 ± 0.31	9.34 ± 0.8	4.82 ± 0.16
Pelvic Tilt	4.26 ± 0.56	10.5 ± 0.43	4.26 ± 0.68	12.14 ± 1.03	2.96 ± 0.39	9.54 ± 0.26
Pelvic Obliquity	1.82 ± 0.79	1.4 ± 0.19	1.26 ± 0.52	1.64 ± 0.36	1.3 ± 0.24	1.68 ± 0.19
Pelvic Rotation	3.38 ± 0.74	4.16 ± 0.15	3.88 ± 0.4	4.48 ± 0.4	3.04 ± 0.49	3.76 ± 0.17
Hip Flexion	3.62 ± 0.77	9.24 ± 0.48	6.08 ± 0.81	10.78 ± 0.98	1.38 ± 0.22	5.36 ± 0.18
Hip Abduction	1.78 ± 0.59	2.1 ± 0.16	1.58 ± 0.08	2.4 ± 0.22	2.68 ± 0.23	2.08 ± 0.24
Hip Rotation	9.58 ± 0.35	8.24 ± 0.43	8.5 ± 0.21	8.54 ± 0.11	10.32 ± 0.25	10.28 ± 0.15
Knee Flexion	5.16 ± 0.4	4.46 ± 0.11	2.88 ± 0.16	4.82 ± 0.08	2.16 ± 0.36	4.9 ± 0.22
Ankle Dorsiflexion	11.52 ± 0.77	15.88 ± 0.11	7.46 ± 0.36	17.76 ± 0.63	10.46 ± 1.0	16.08 ± 1.38
Foot Progression	1.64 ± 0.15	2.48 ± 0.18	3.08 ± 0.13	5.08 ± 0.25	3.8 ± 0.07	5.38 ± 0.16

Table 19: Dynamic Motor Control for Walking and Cycling at Two Different Speeds (mean ± STD) and Effect Size (Cohen's d)

		DMC Score (mean ± STD)		**Effect Size (Cohen's d)**		
Participant	Speed	Walking	Cycling	Walking v Cycling	Slow Walk v Fast Walk	Slow Cycle v Fast Cycle
CP1	Slow	83.1 ± 3.2	85.4 ± 3.4	-0.7	2.1	9.8
	Fast	77.5 ± 1.9	55.2 ± 2.7	9.6		
CP2	Slow	86.6 ± 2.7	67.6 ± 2.2	7.7	1.1	12.5
	Fast	82.3 ± 4.9	40.1 ± 2.2	11.1		

Table 20: Dynamic Motor Control for Cycling at Three Crank Arm Lengths and Two Different Speeds (mean ± STD) and Effect Size (Cohen's d)

		DMC Score (mean ± STD)			**Effect Size (Cohen's d)**					
Participant	Speed	170mm	150mm	130mm	170 v 150	170 v 130	150 v 130	170 mm Slow v Fast	150mm Slow v Fast	130mm Slow v Fast
CP1	Slow	85.4 ± 3.4	95.7 ± 3.3	94.7 ± 0.9	-3.07	-3.74	0.41	9.84	4.18	1.54
	Fast	55.2 ± 2.7	81.9 ± 3.3	91.3 ± 3.0	-8.86	-12.65	-2.98			
CP2	Slow	67.6 ± 2.2	76.9 ± 0.9	79.4 ± 2.2	-5.53	-5.36	-1.49	12.50	10.29	6.45
	Fast	40.1 ± 2.2	52.0 ± 3.3	67. ± 1.6	-4.24	-13.98	-5.78			

Table 21: Self-Selected Cadence (RPM) for Cycling at Three Crank Arm Lengths and Two Different Speeds (mean ± STD) and Effect Size (Cohen's d)

		Cadence Score (mean ± STD)			**Effect Size (Cohen's d)**					
Participant	Speed	170mm	150mm	130mm	170 v 150	170 v 130	150 v 130	170 mm Slow v Fast	150mm Slow v Fast	130mm Slow v Fast
CP1	Slow	32.5 ± 0.3	49.0 ± 0.2	48.7 ± 0.6	-64.40	-36.08	0.69	-31.34	-13.35	-54.33
	Fast	74.4 ± 1.9	75.9 ± 2.8	76.6 ± 0.5	-0.62	-1.62	-0.34			
CP2	Slow	60.3 ± 0.4	60.2 ± 0.6	76.6 ± 0.4	0.20	-39.65	-30.84	-34.24	-50.67	-7.83
	Fast	86.2 ± 1.0	84.4 ± 0.3	82.8 ± 1.0	2.44	3.35	2.11			

Appendix B: Figures

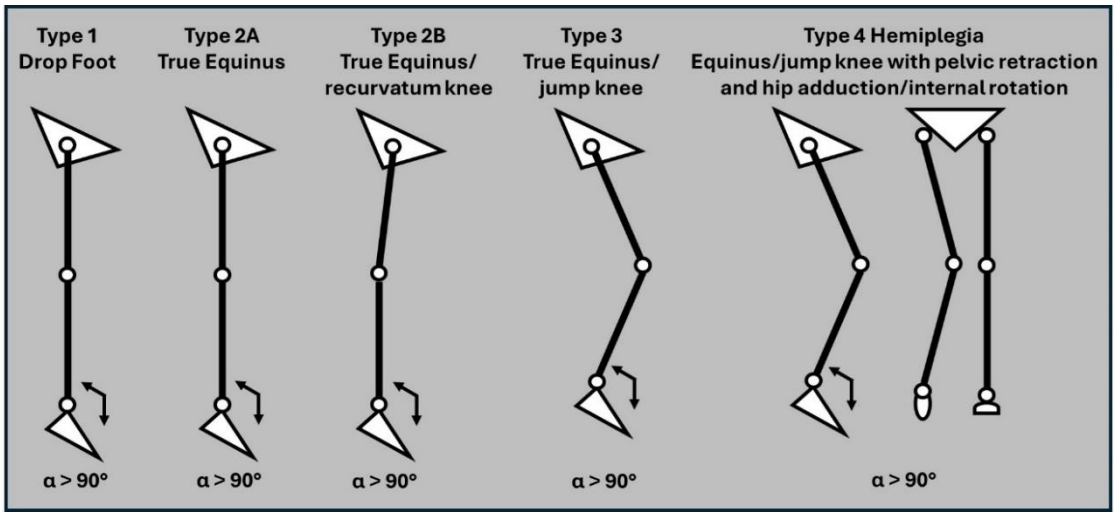


Figure 1: Classification of gait patterns in individuals with Unilateral CP.

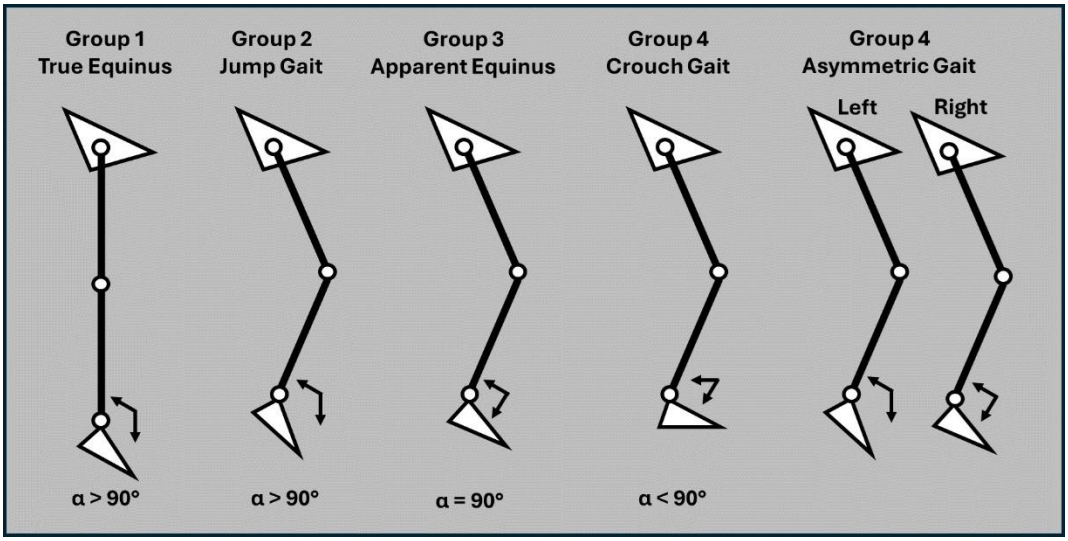


Figure 2: Classification of sagittal plane gait patterns in individuals with bilateral CP.

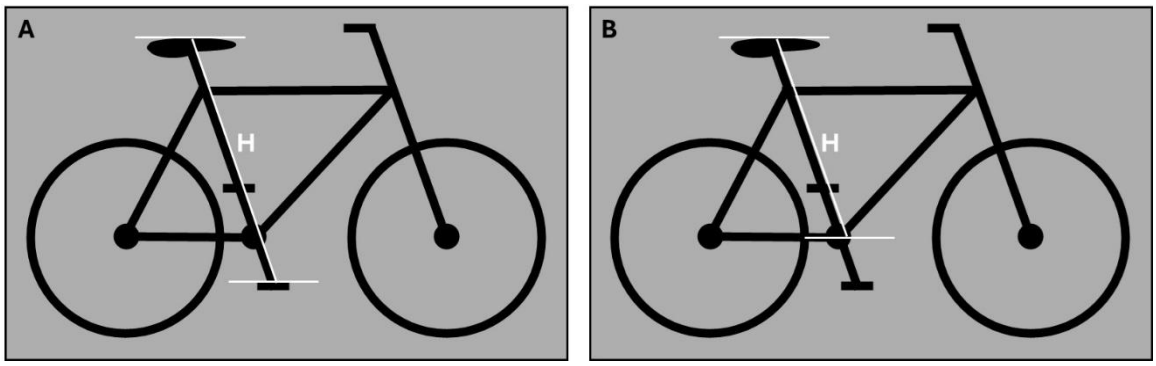


Figure 3: Saddle Height Measurement

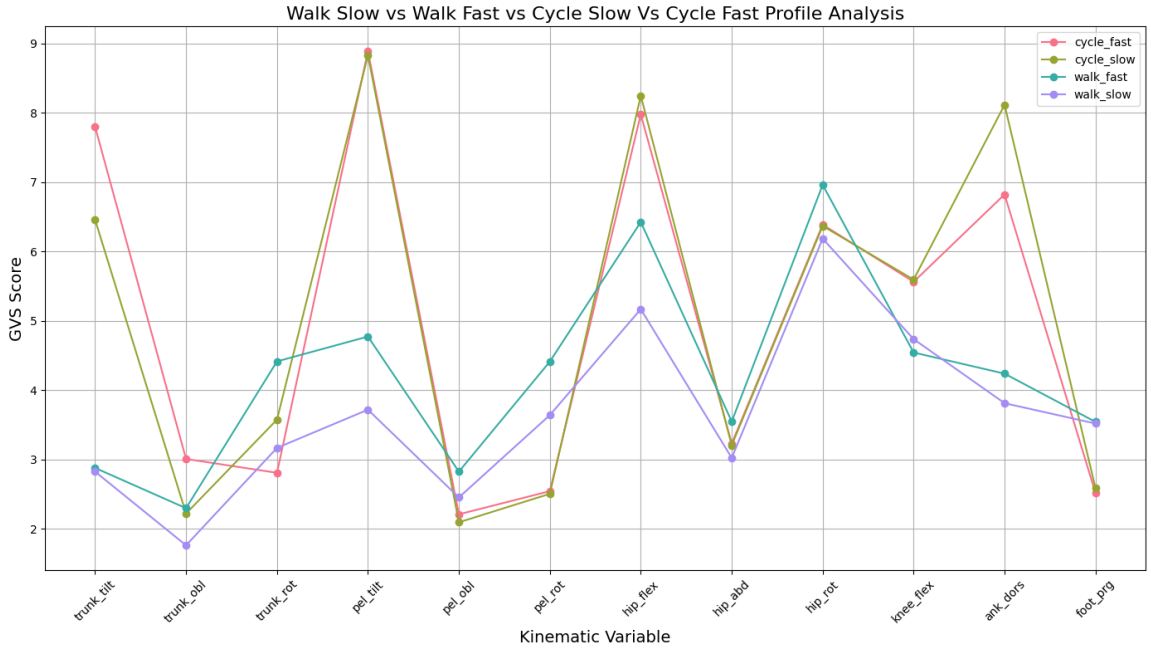


Figure 4: Profile Analysis of Gait Variable Scores for Slow Walk, Fast Walk, Slow Cycle, and Fast Cycle in Typically Developing Participants

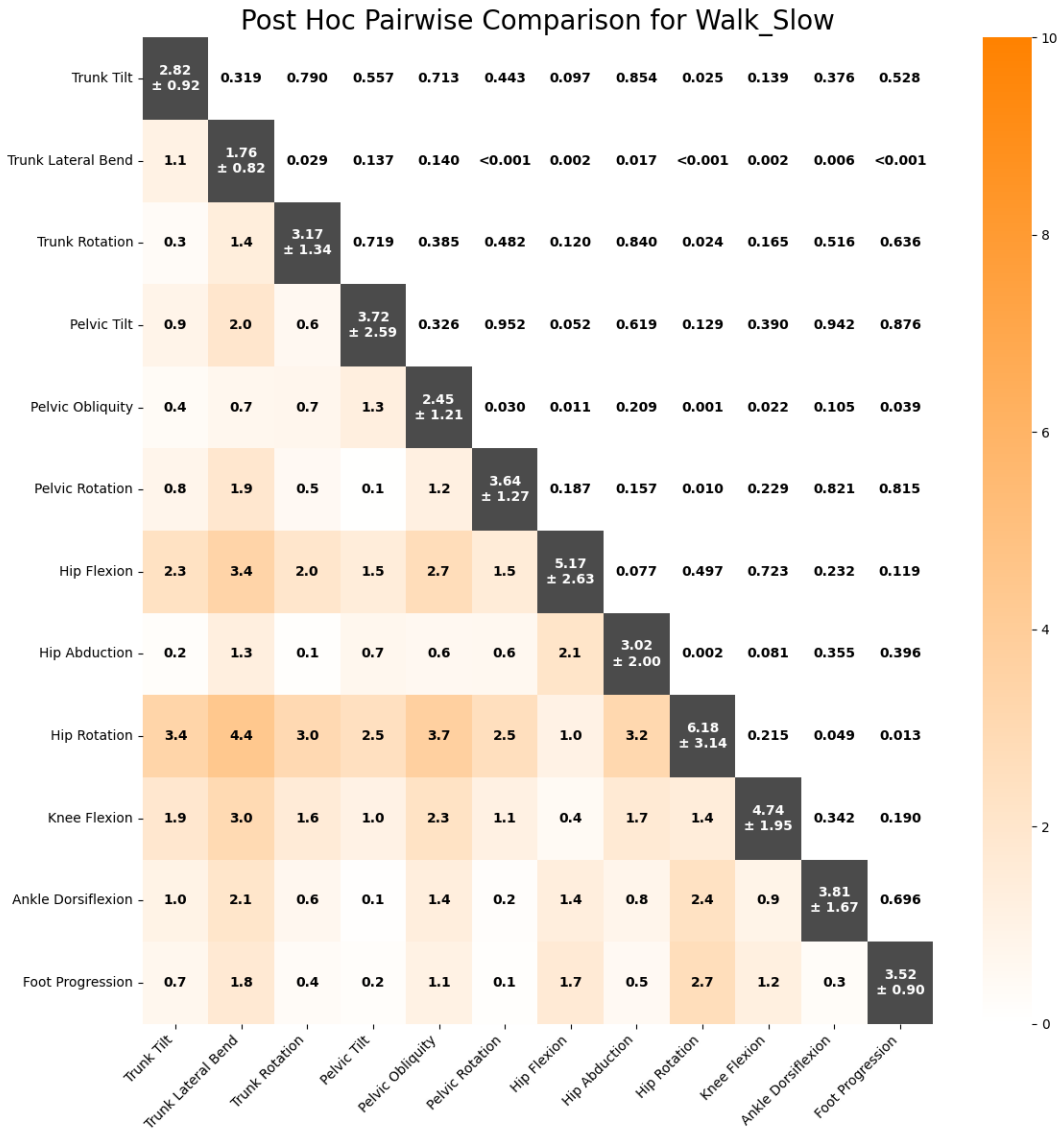


Figure 5: Pairwise post hoc comparison of GVS scores for Slow Walk. The lower triangle shows mean differences, the diagonal shows mean ± STD, and the upper triangle shows p-values.

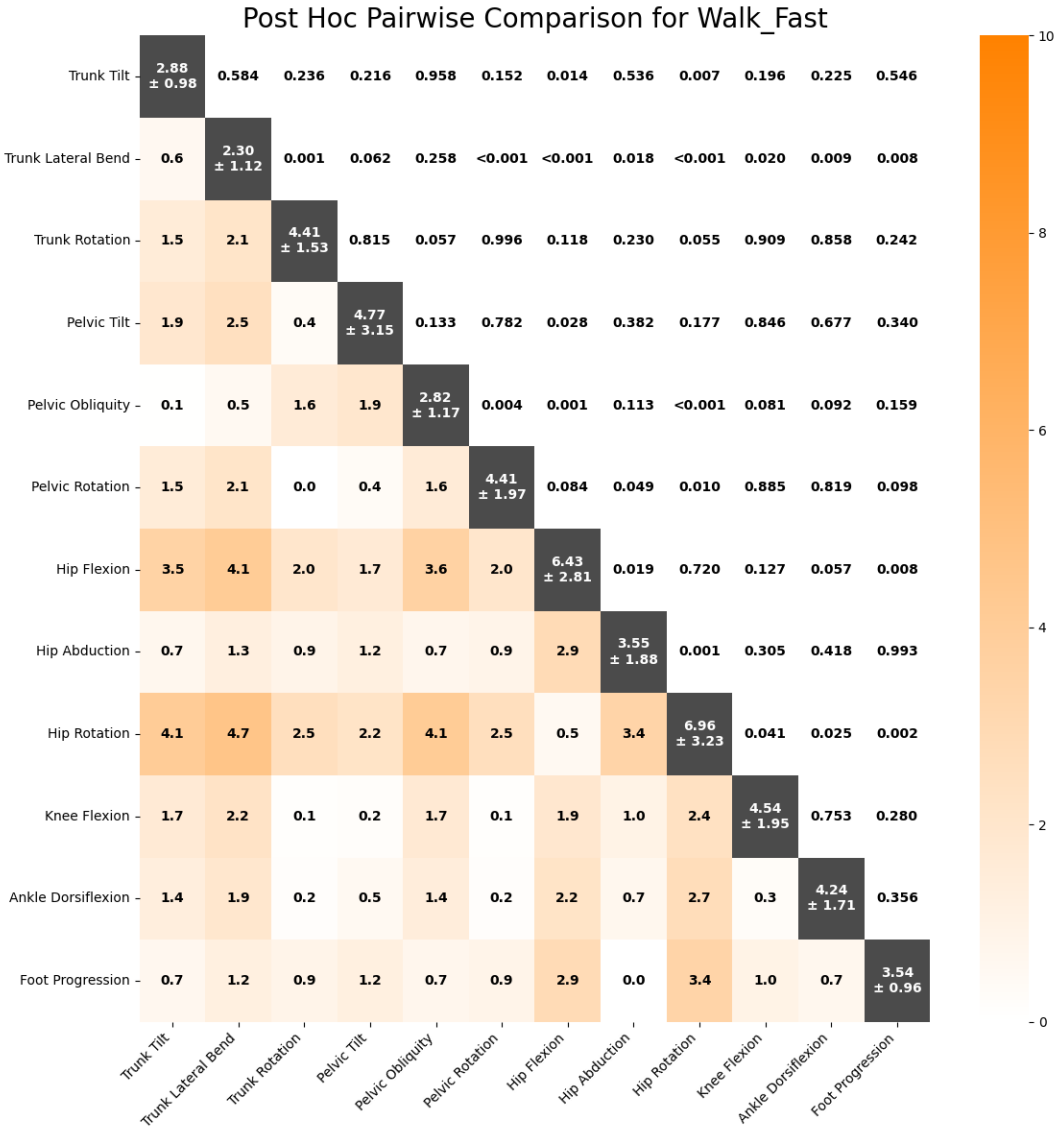


Figure 6: Pairwise post hoc comparison of GVS scores for Fast Walk. The lower triangle shows mean differences, the diagonal shows mean ± STD, and the upper triangle shows p-values.

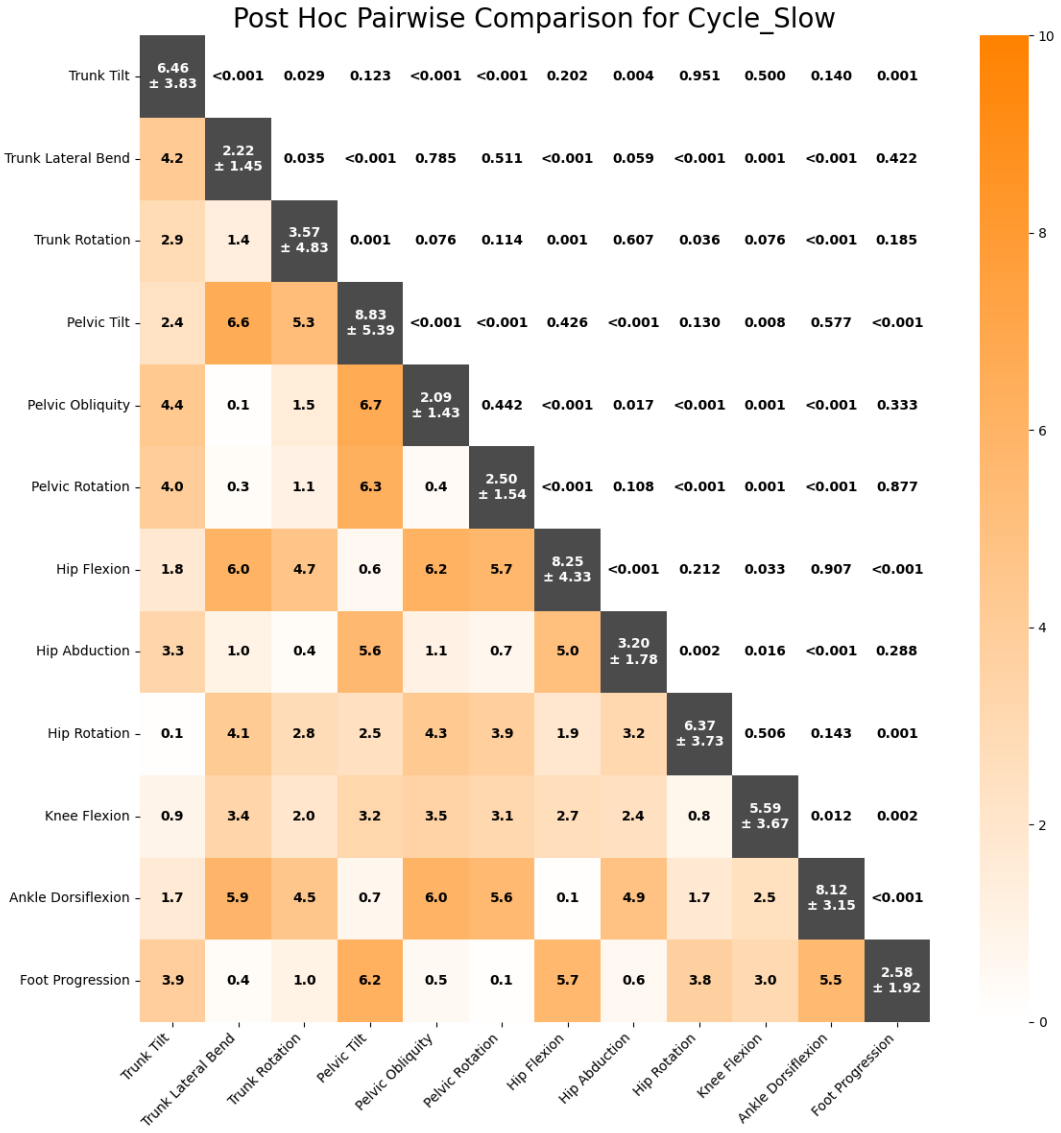


Figure 7: Pairwise post hoc comparison of CVS scores for Slow Cycle. The lower triangle shows mean differences, the diagonal shows mean ± STD, and the upper triangle shows p-values.

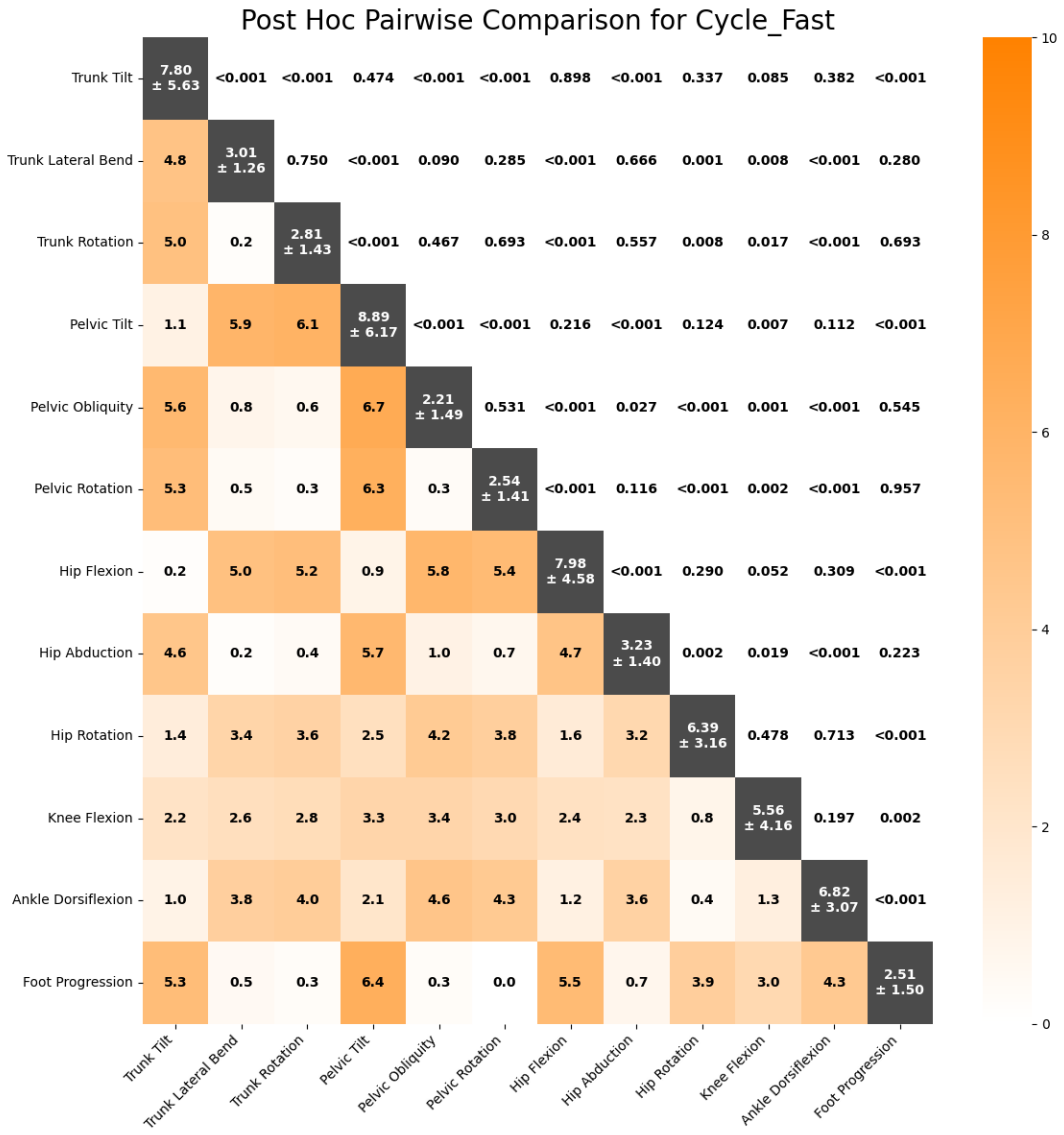


Figure 8: Pairwise post hoc comparison of CVS scores for Fast Cycle. The lower triangle shows mean differences, the diagonal shows mean ± STD, and the upper triangle shows p-values.

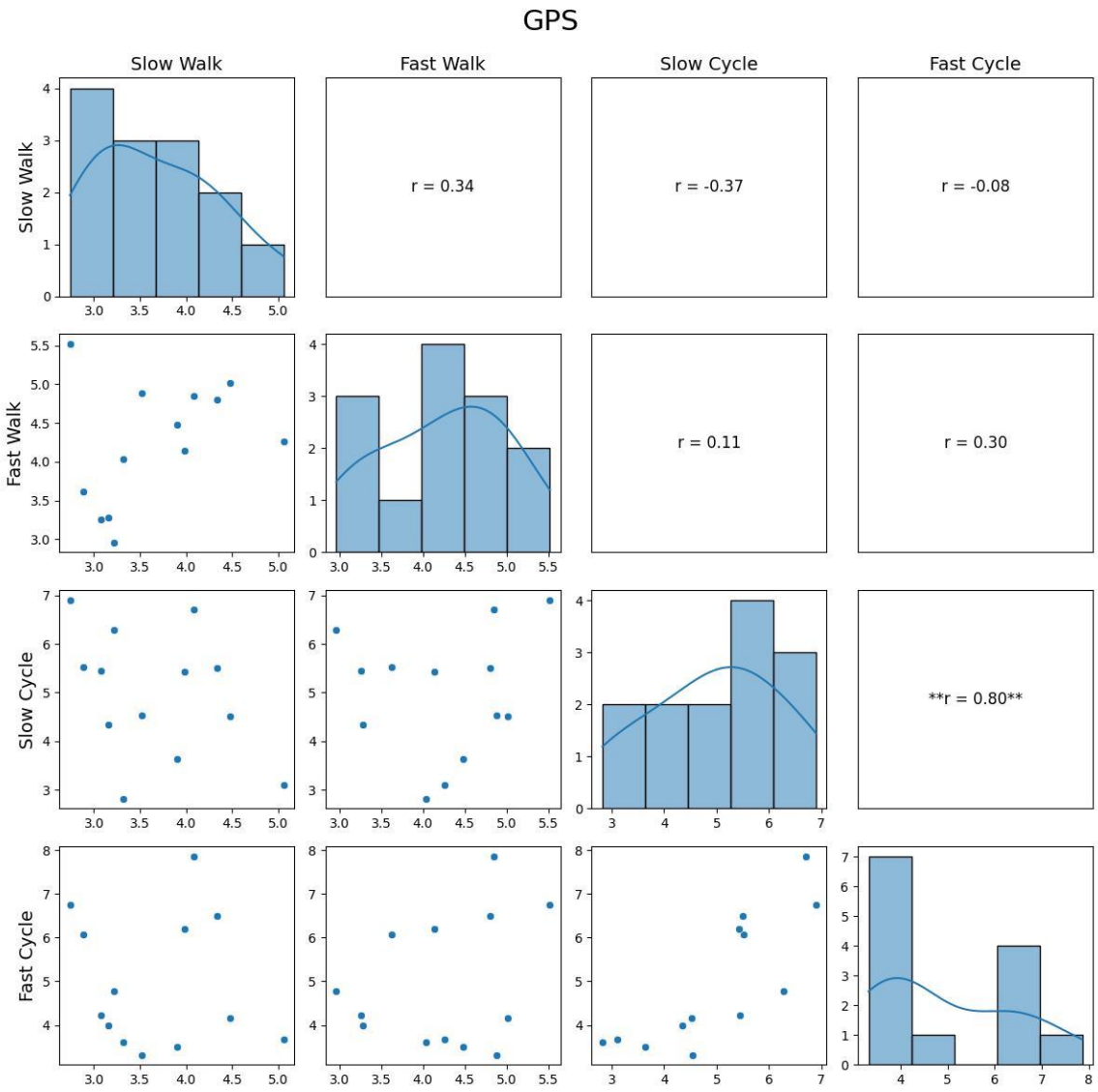


Figure 9: Correlation Matrix of Gait/Cycling Profile Scores for Different Walking and Cycling Speeds in Typically Developing Participants

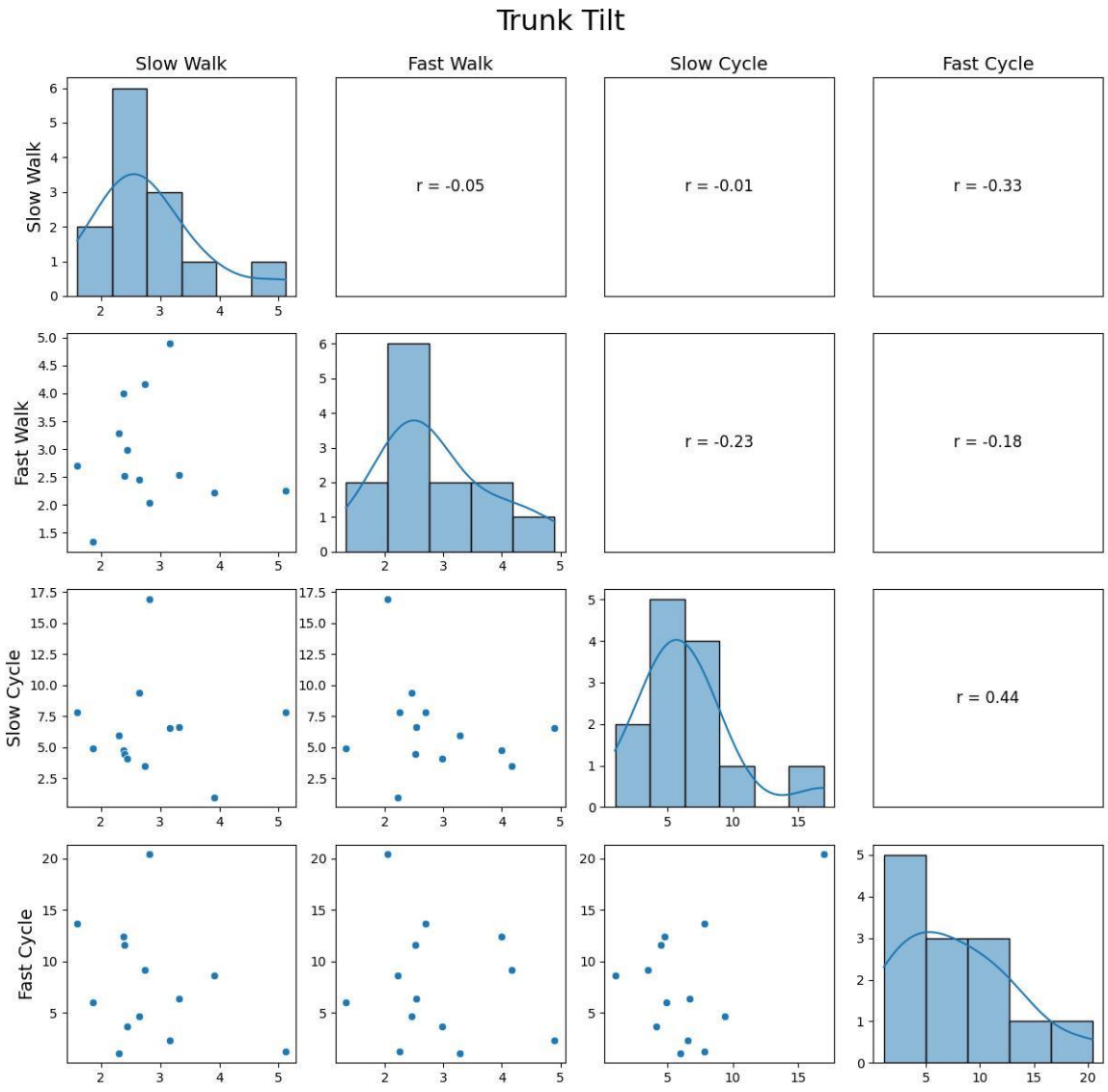


Figure 10: Correlation Matrix of Trunk Tilt Gait/Cycling Variable Scores for Different Walking and Cycling Speeds in Typically Developing Participants

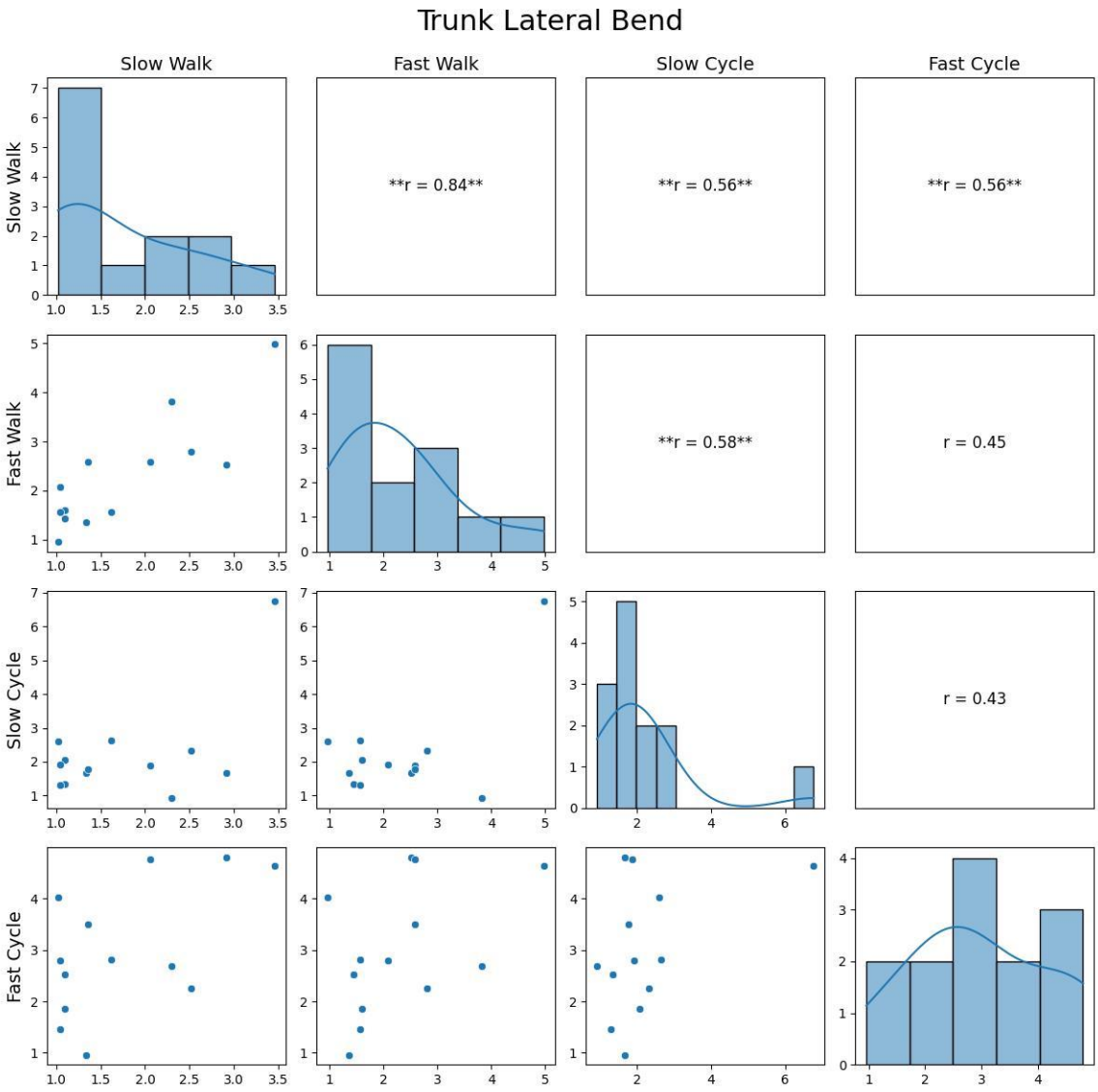


Figure 11: Correlation Matrix of Trunk Lateral Bend Gait/Cycling Variable Scores for Different Walking and Cycling Speeds in Typically Developing Participants

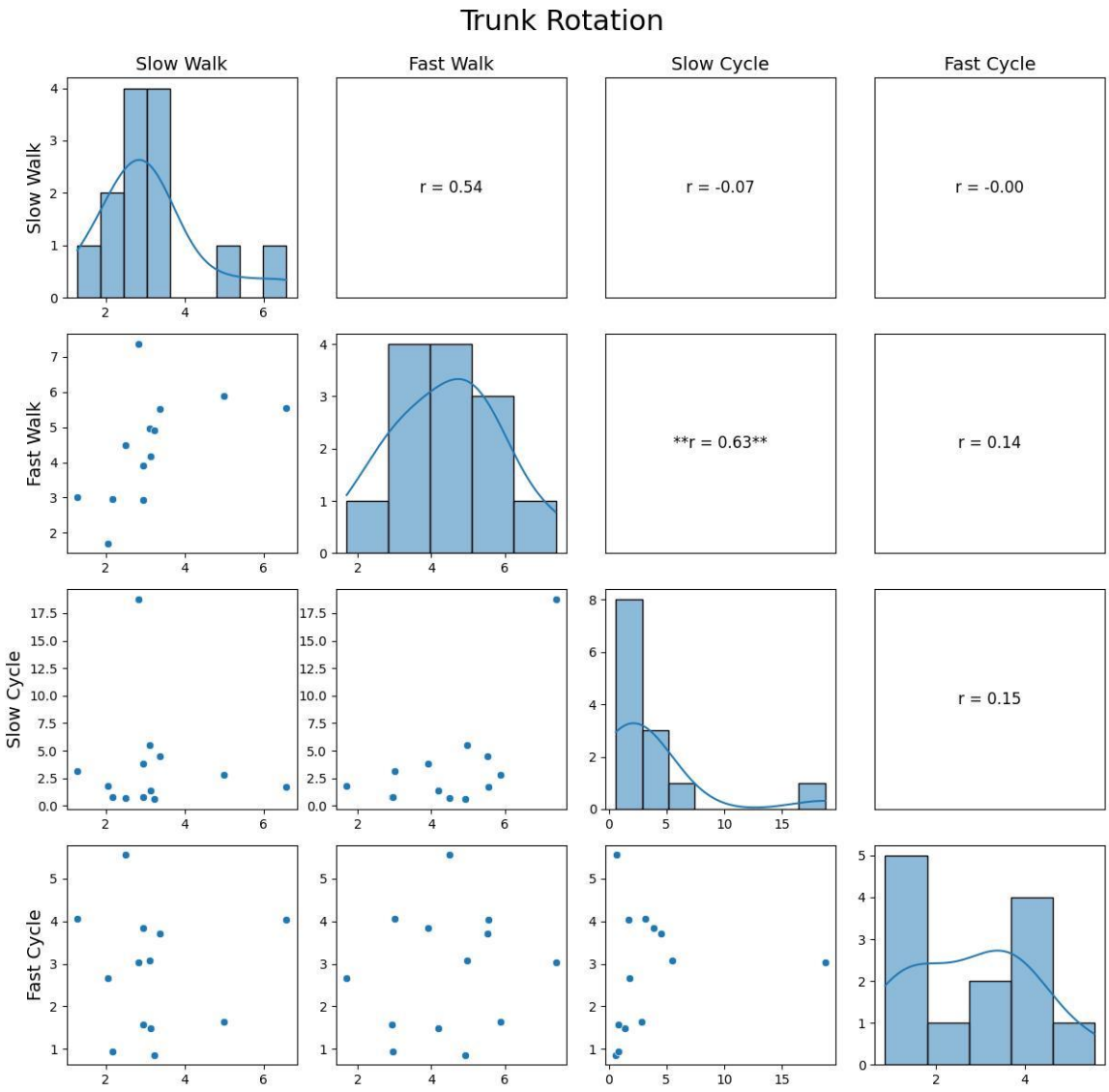


Figure 12: Correlation Matrix of Trunk Rotation Gait/Cycling Variable Scores for Different Walking and Cycling Speeds in Typically Developing Participants

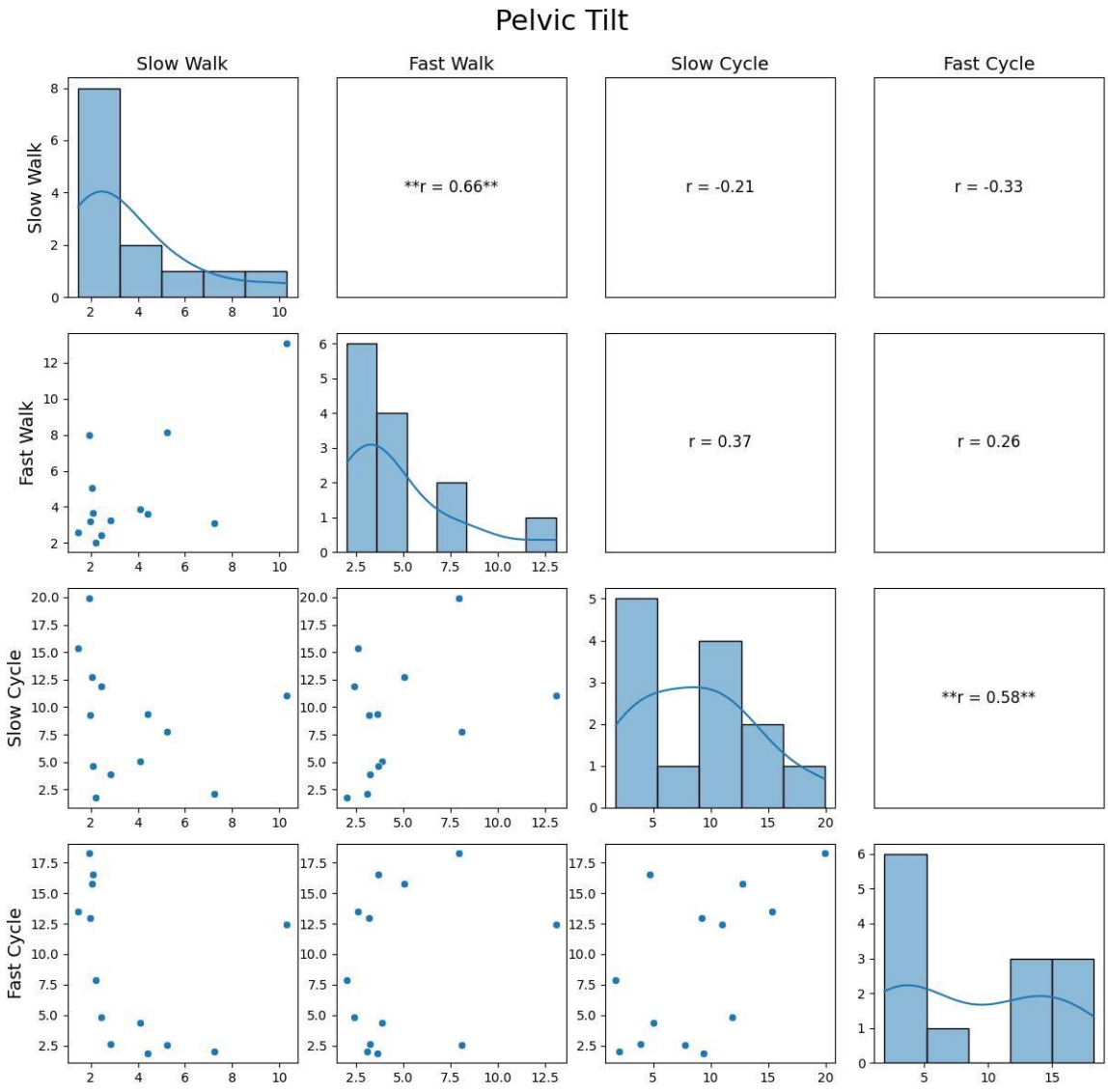


Figure 13: Correlation Matrix of Pelvic Tilt Gait/Cycling Variable Scores for Different Walking and Cycling Speeds in Typically Developing Participants

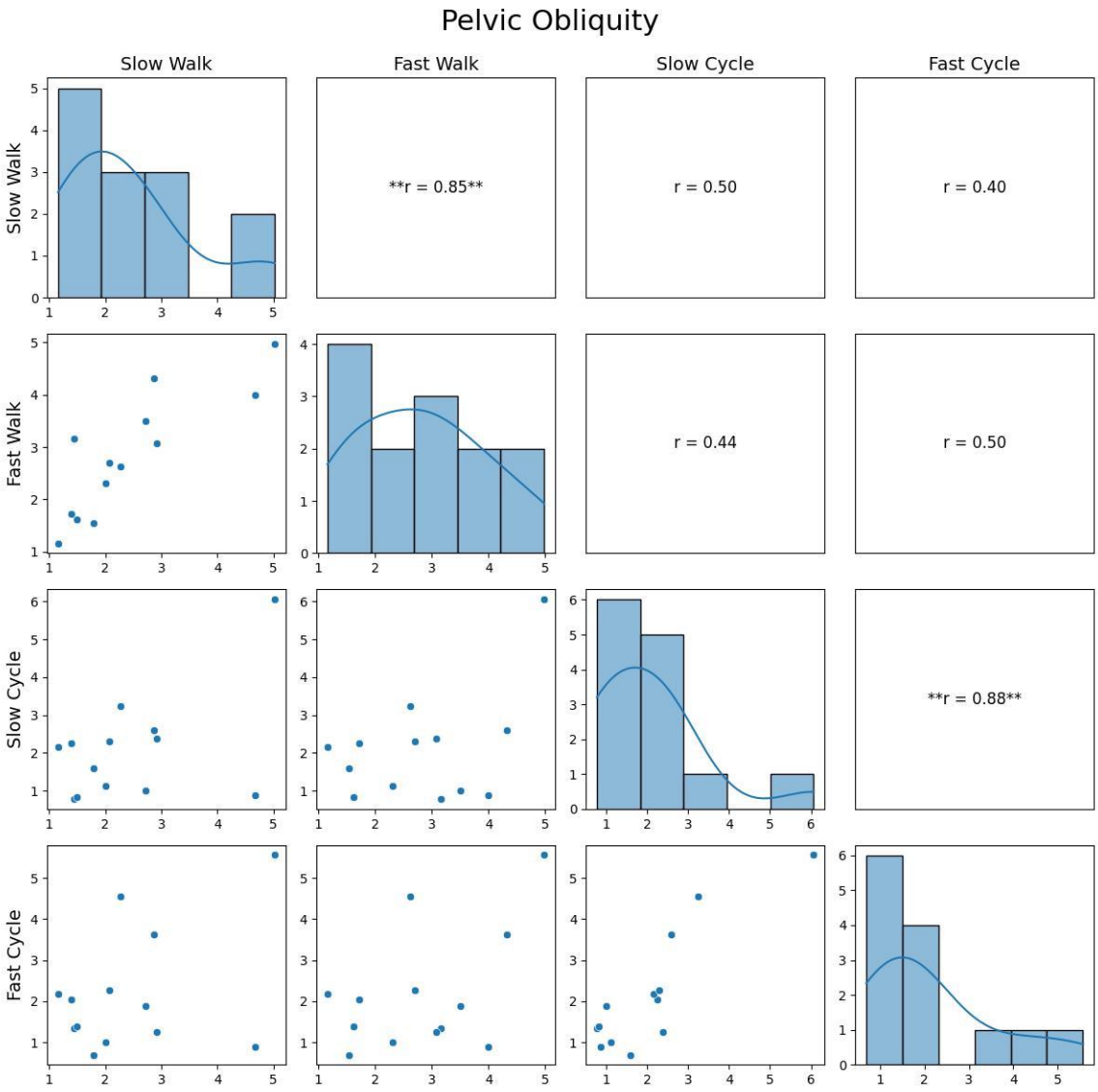


Figure 14: Correlation Matrix of Pelvic Obliquity Gait/Cycling Variable Scores for Different Walking and Cycling Speeds in Typically Developing Participants

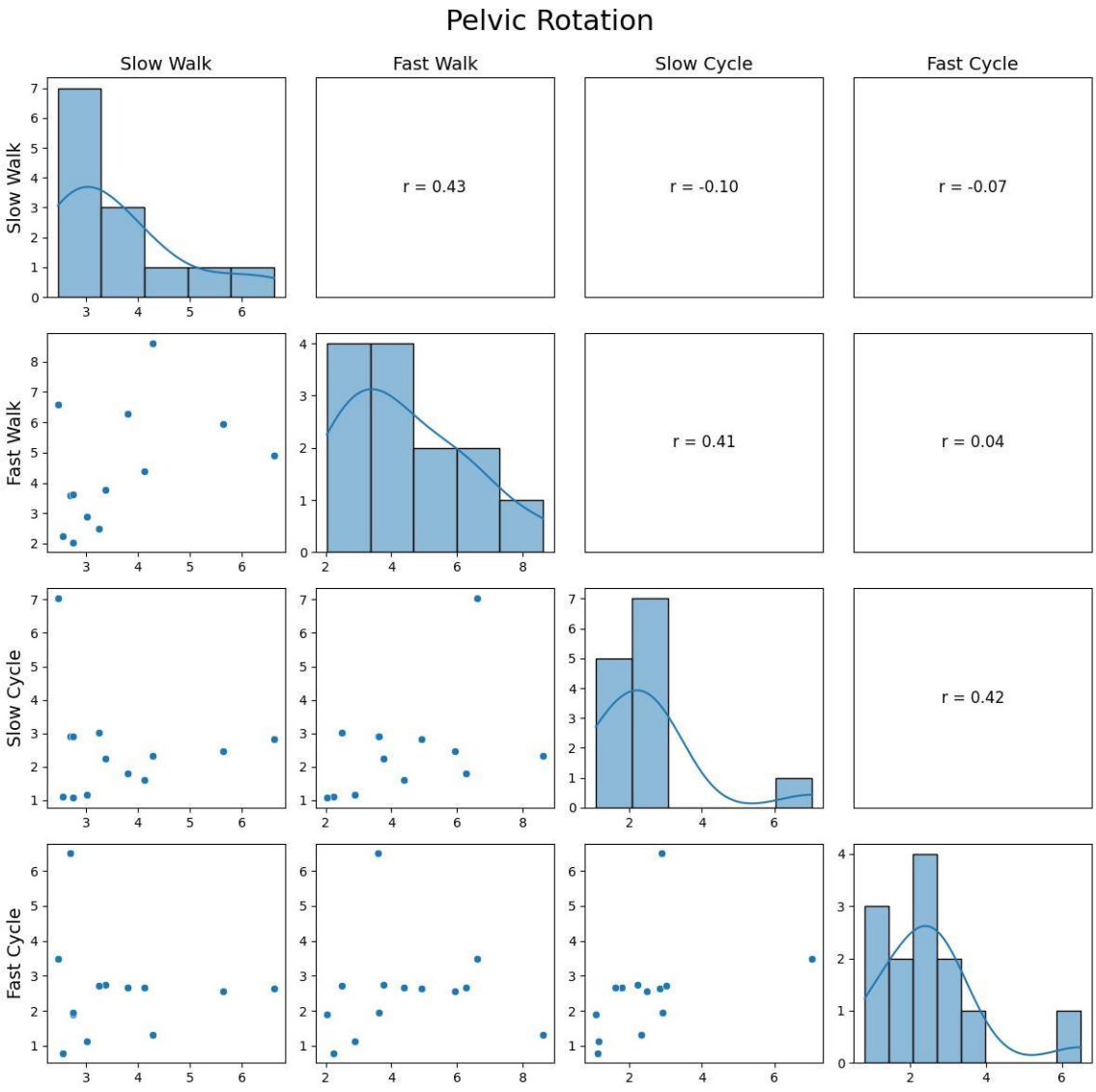


Figure 15: Correlation Matrix of Pelvic Rotation Gait/Cycling Variable Scores for Different Walking and Cycling Speeds in Typically Developing Participants

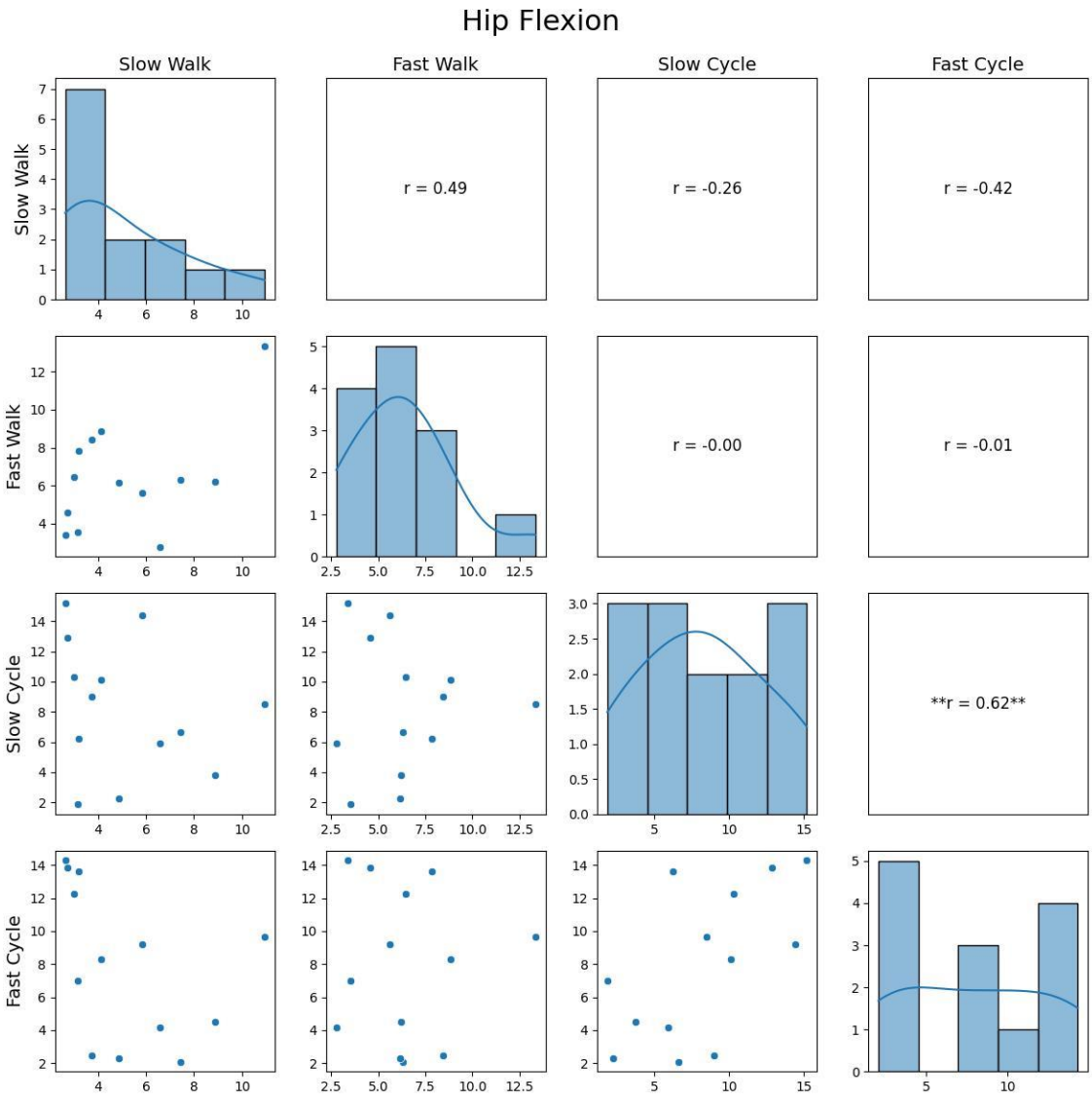


Figure 16: Correlation Matrix of Hip Flexion Gait/Cycling Variable Scores for Different Walking and Cycling Speeds in Typically Developing Participants

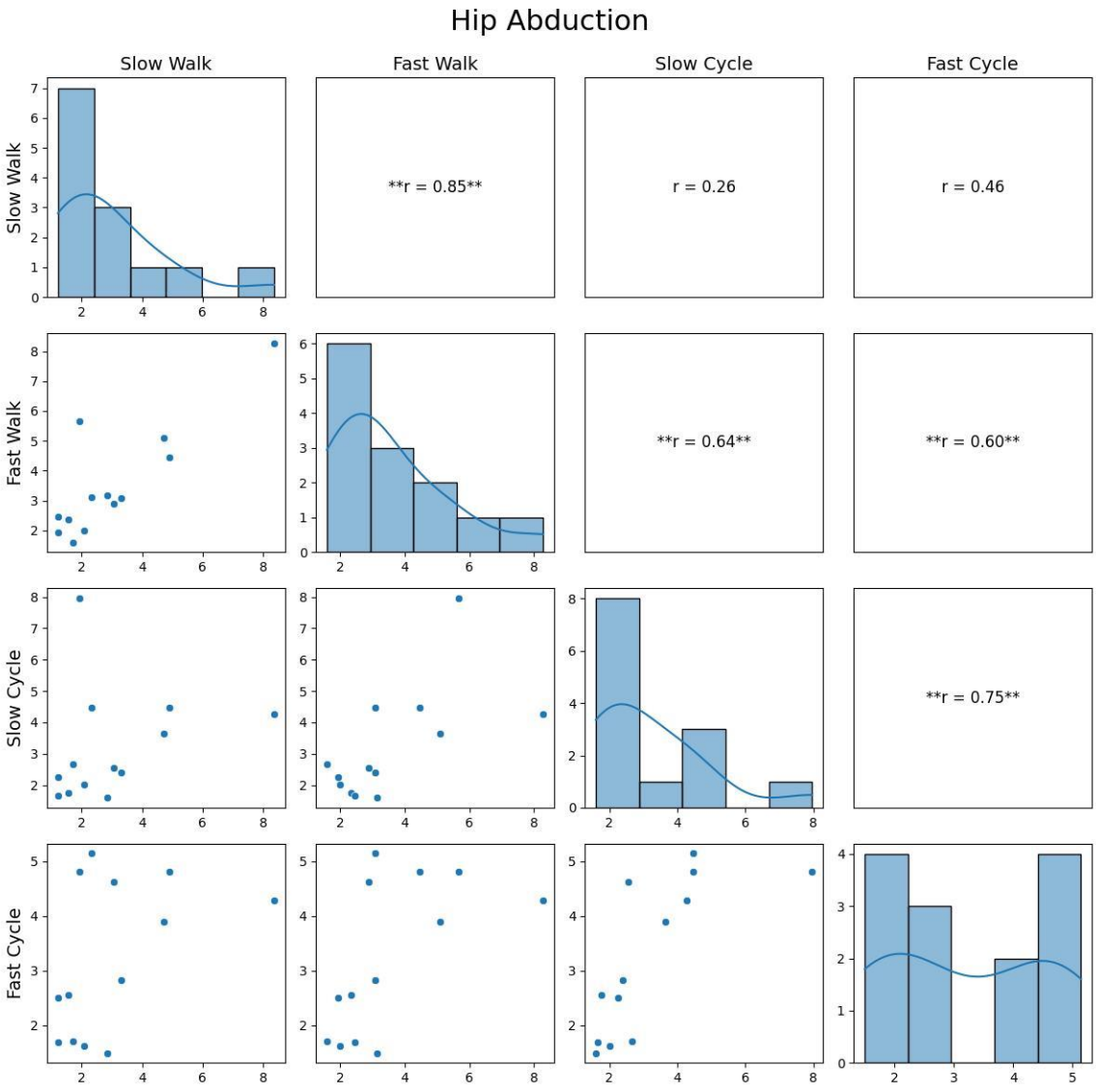


Figure 17: Correlation Matrix of Hip Abduction Gait/Cycling Variable Scores for Different Walking and Cycling Speeds in Typically Developing Participants

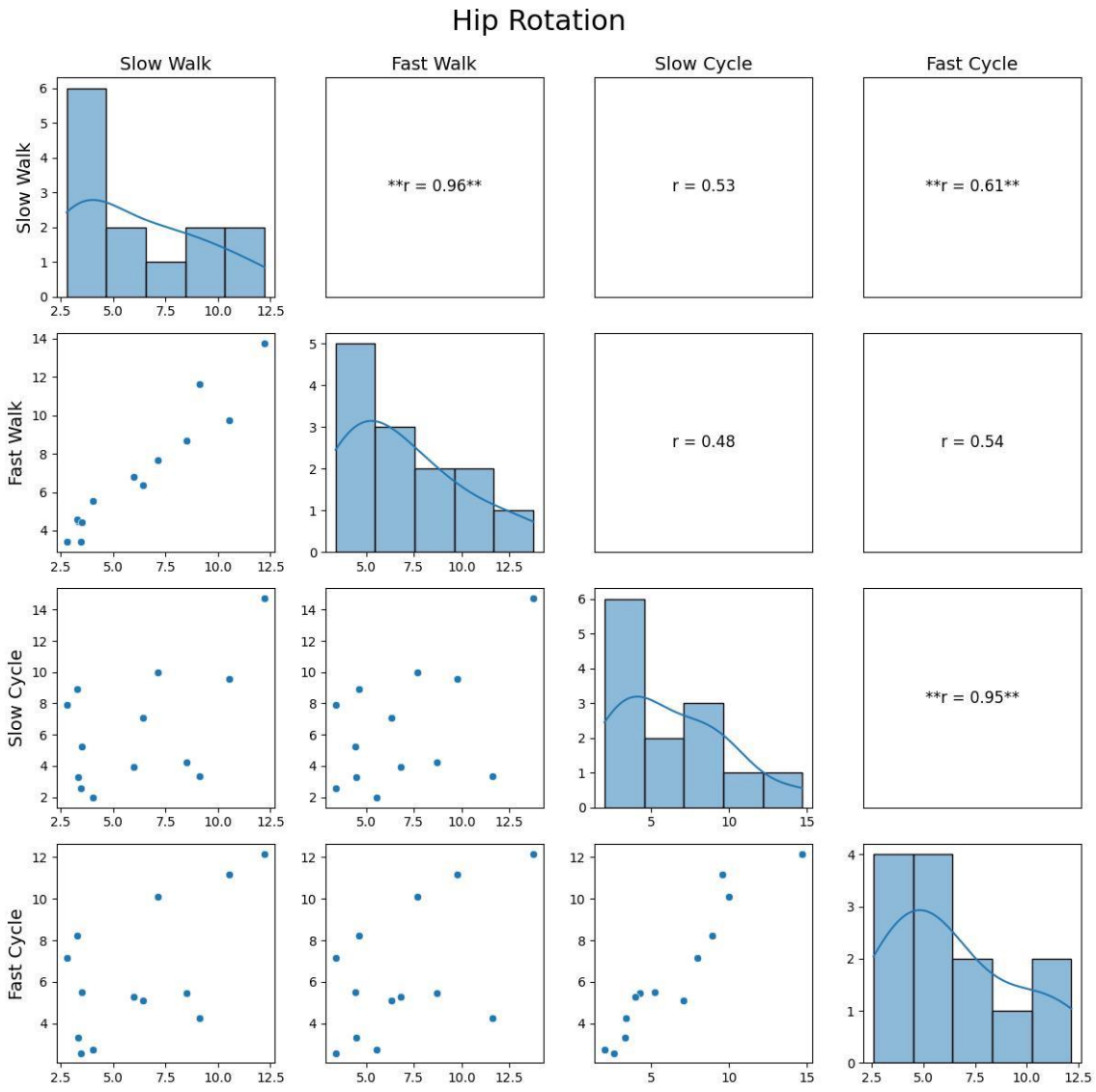


Figure 18: Correlation Matrix of Hip Rotation Gait/Cycling Variable Scores for Different Walking and Cycling Speeds in Typically Developing Participants

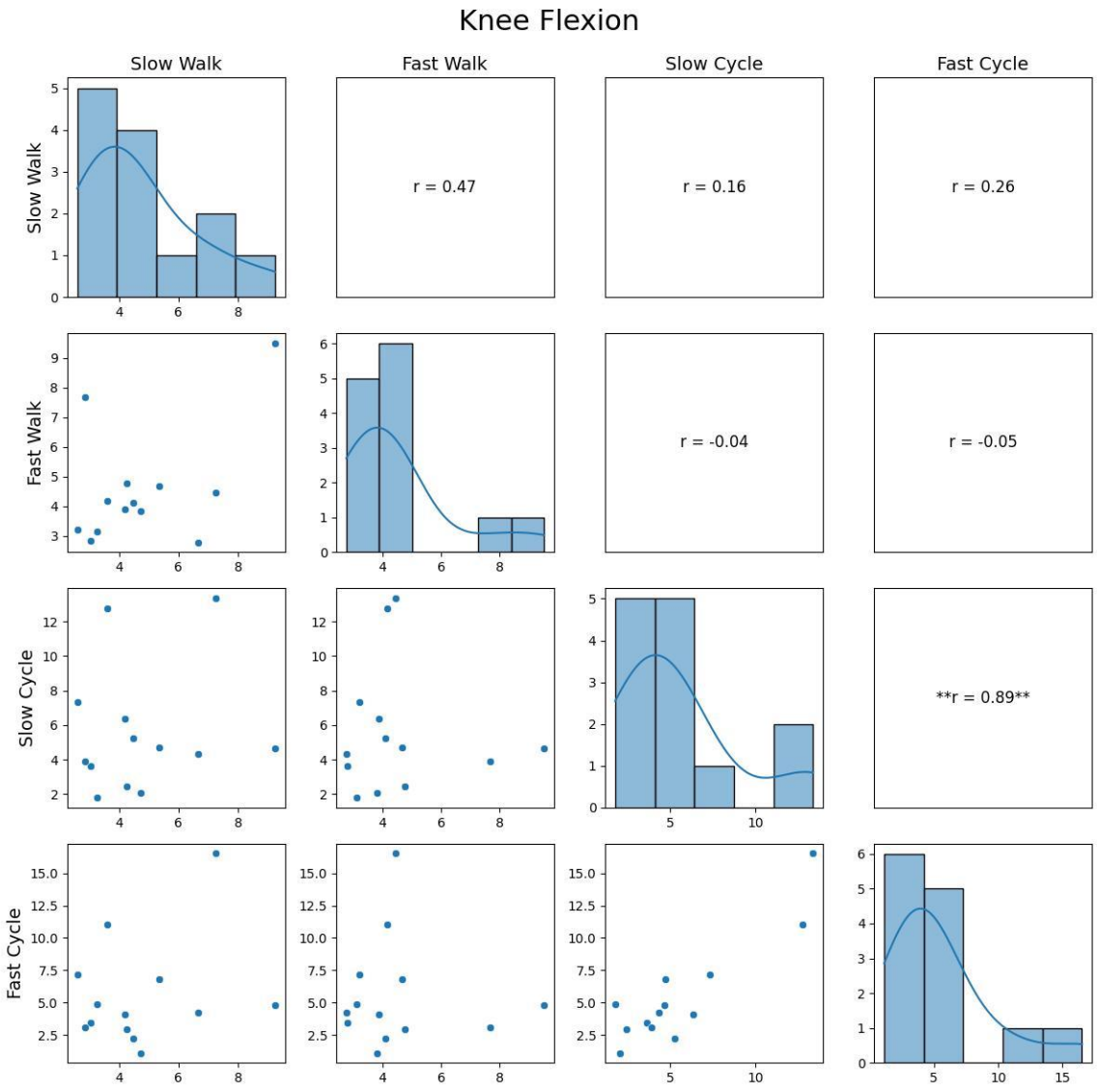


Figure 19: Correlation Matrix of Knee Flexion Gait/Cycling Variable Scores for Different Walking and Cycling Speeds in Typically Developing Participants

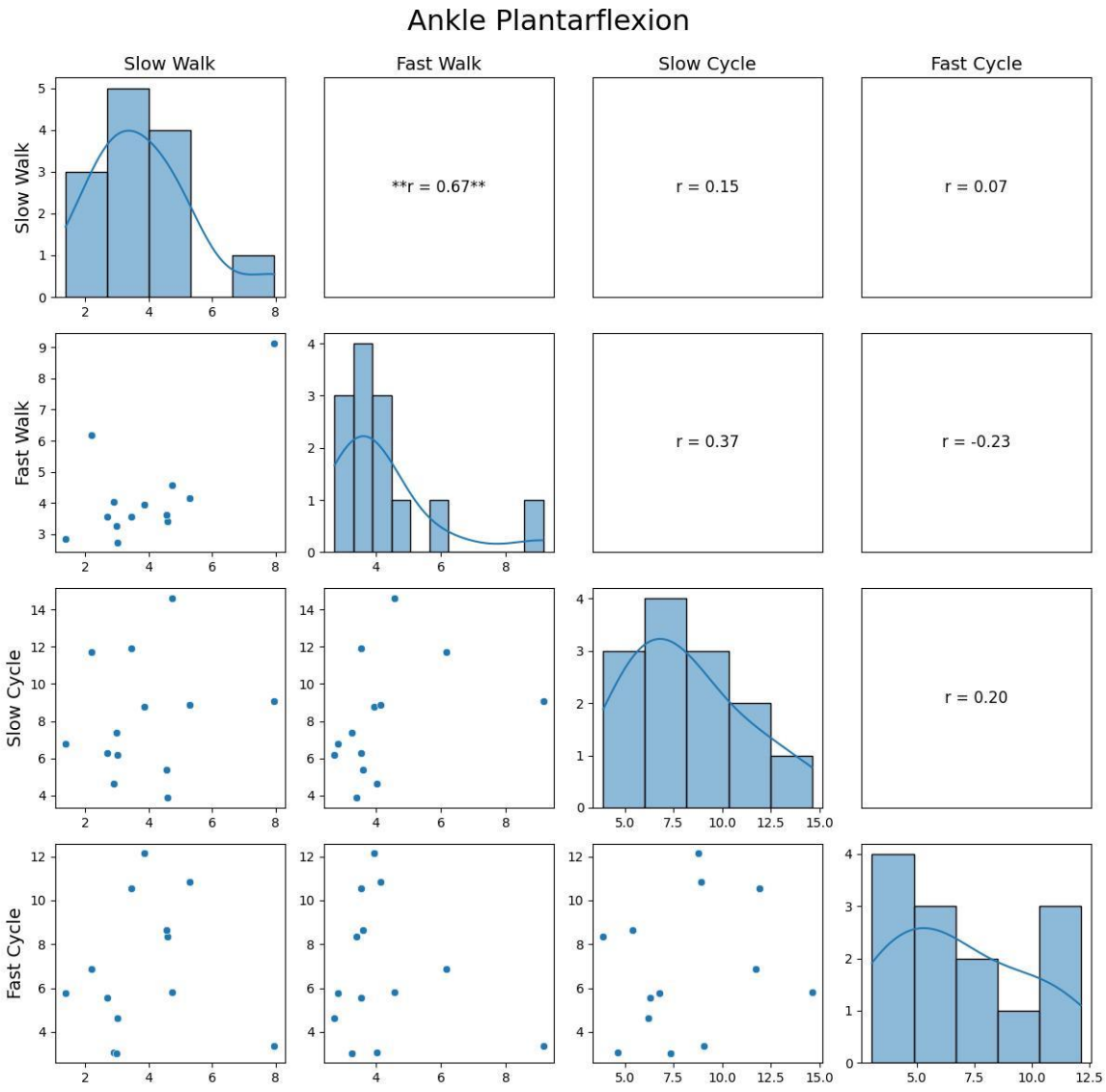


Figure 20: Correlation Matrix of Ankle Plantarflexion Gait/Cycling Variable Scores for Different Walking and Cycling Speeds in Typically Developing Participants

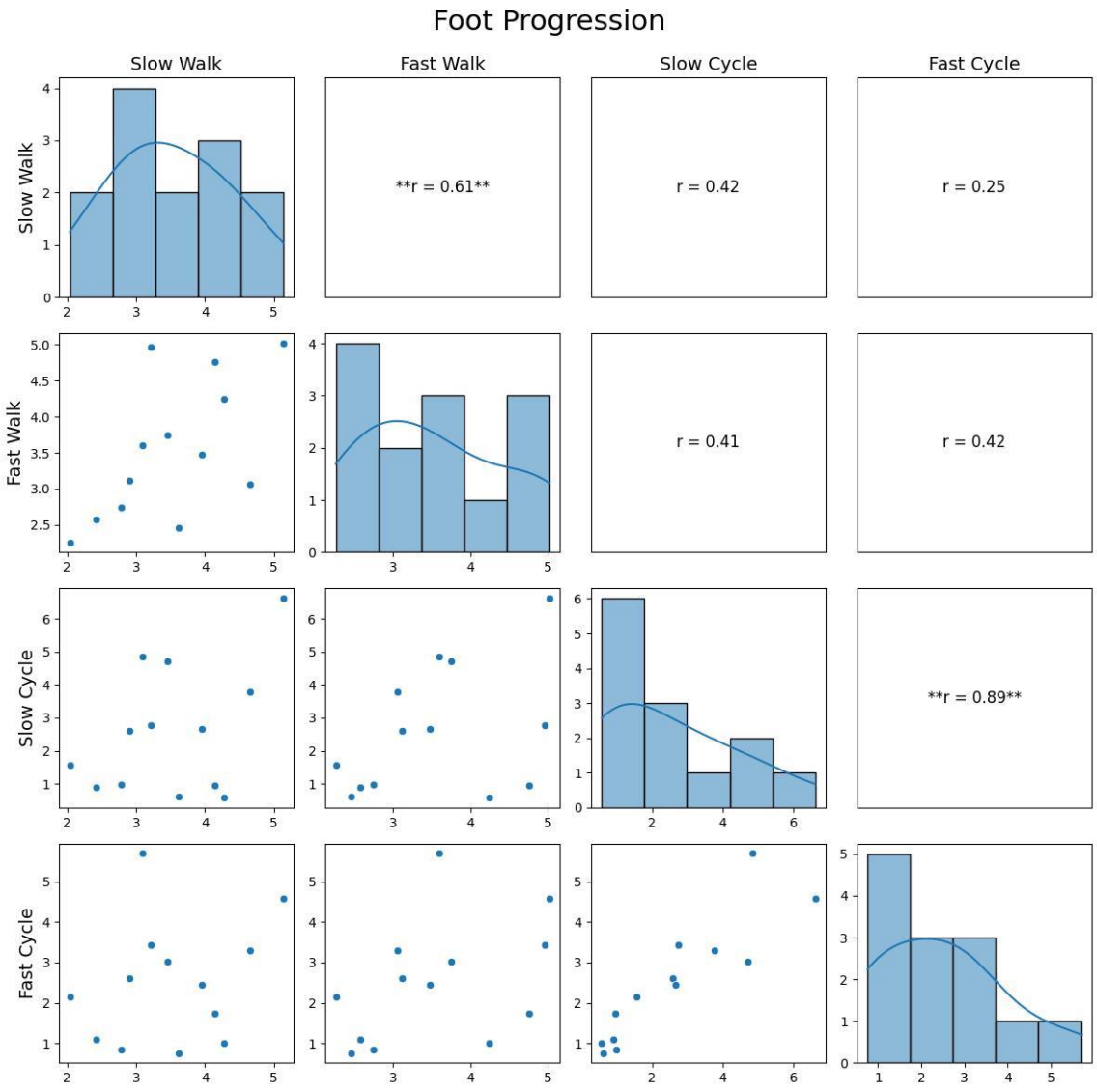


Figure 21: Correlation Matrix of Foot Progression Angle Gait/Cycling Variable Scores for Different Walking and Cycling Speeds in Typically Developing Participants

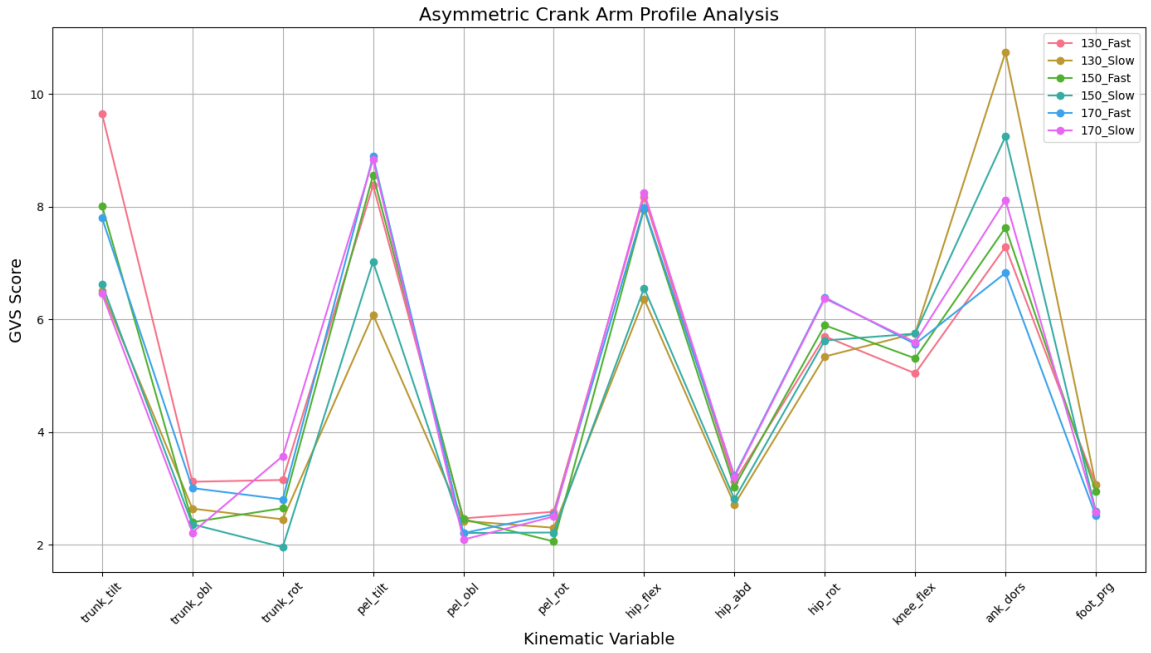


Figure 22: Profile Analysis of Gait Variable Scores for the Adjusted Crank Arm (170mm, 150mm, 130mm) During Cycling at Two Speeds in Typically Developing Participants

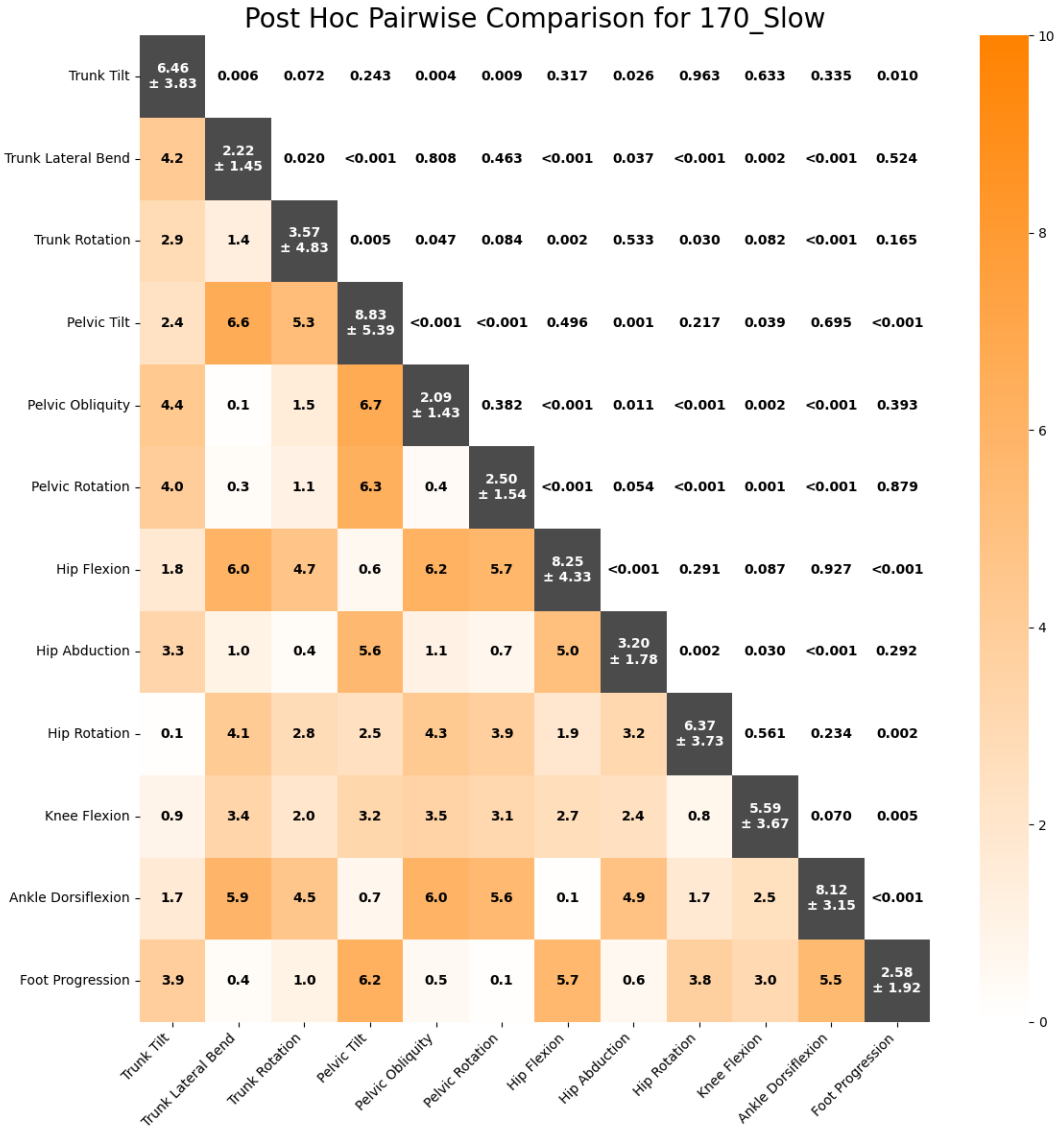


Figure 23: Pairwise post hoc comparison of CVS scores for 170mm Slow. The lower triangle shows mean differences, the diagonal shows mean ± STD, and the upper triangle shows p-values.

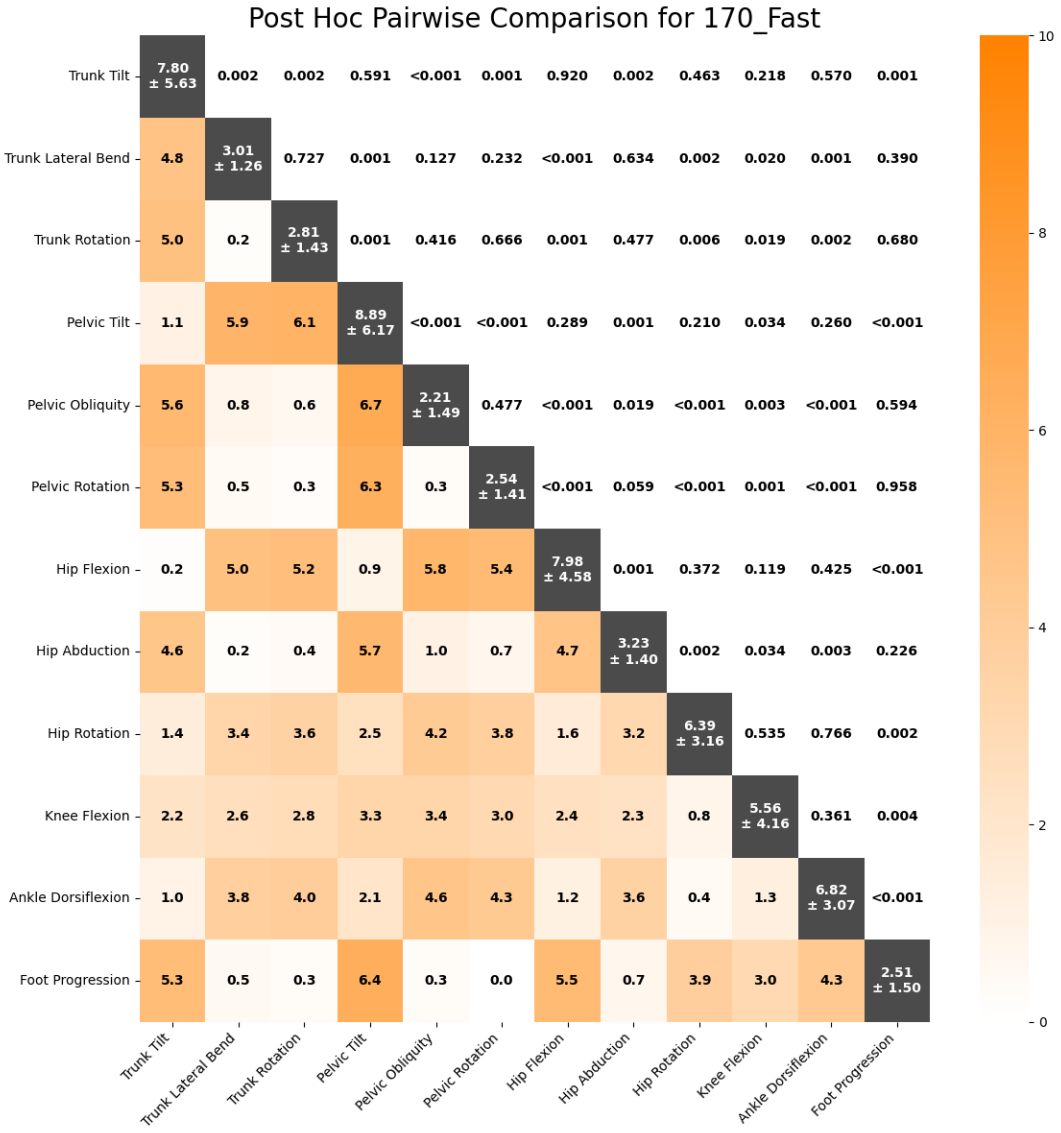


Figure 24: Pairwise post hoc comparison of CVS scores for 170mm Fast. The lower triangle shows mean differences, the diagonal shows mean ± STD, and the upper triangle shows p-values.

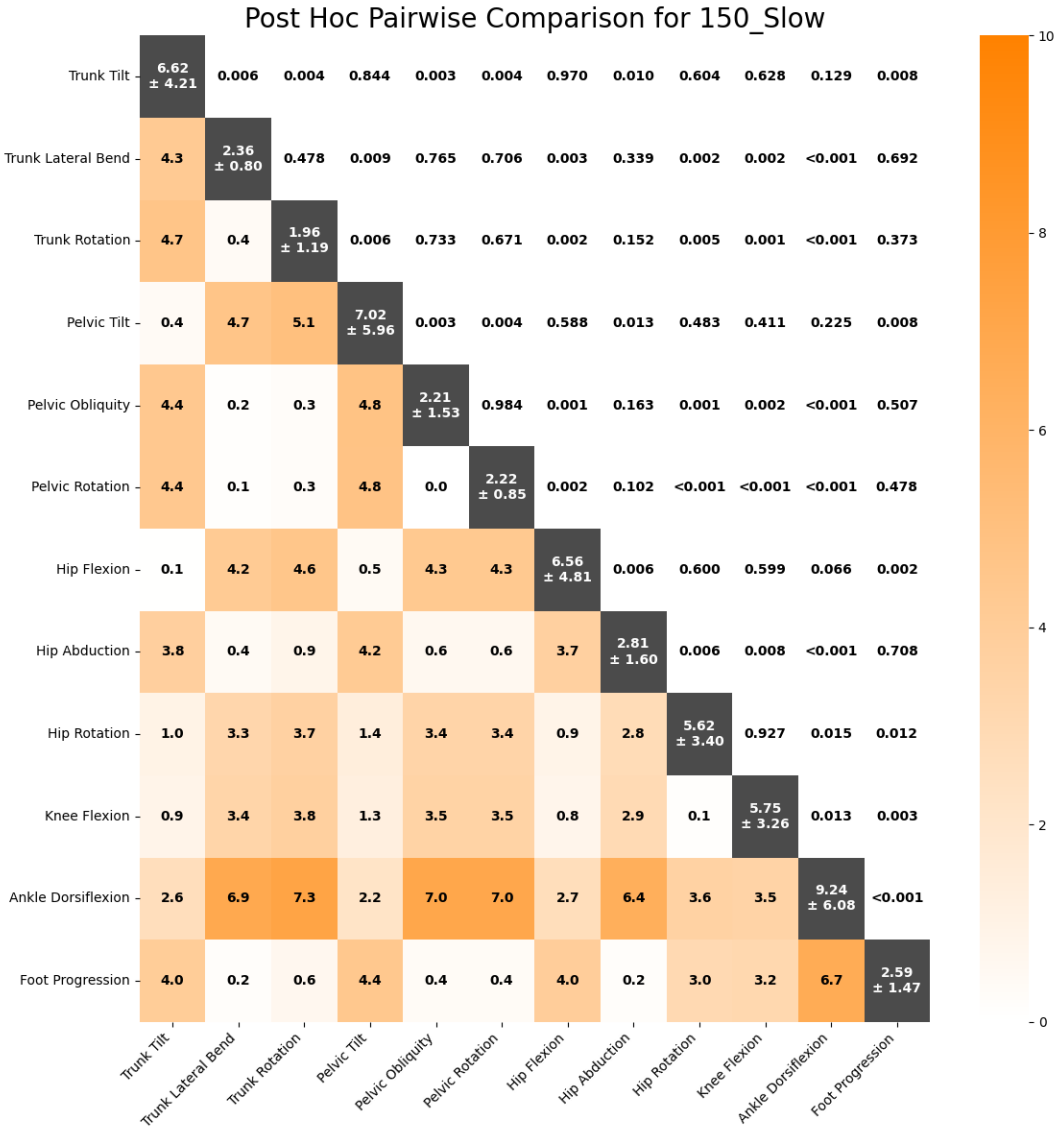


Figure 25: Pairwise post hoc comparison of CVS scores for 150mm Slow. The lower triangle shows mean differences, the diagonal shows mean ± STD, and the upper triangle shows p-values.

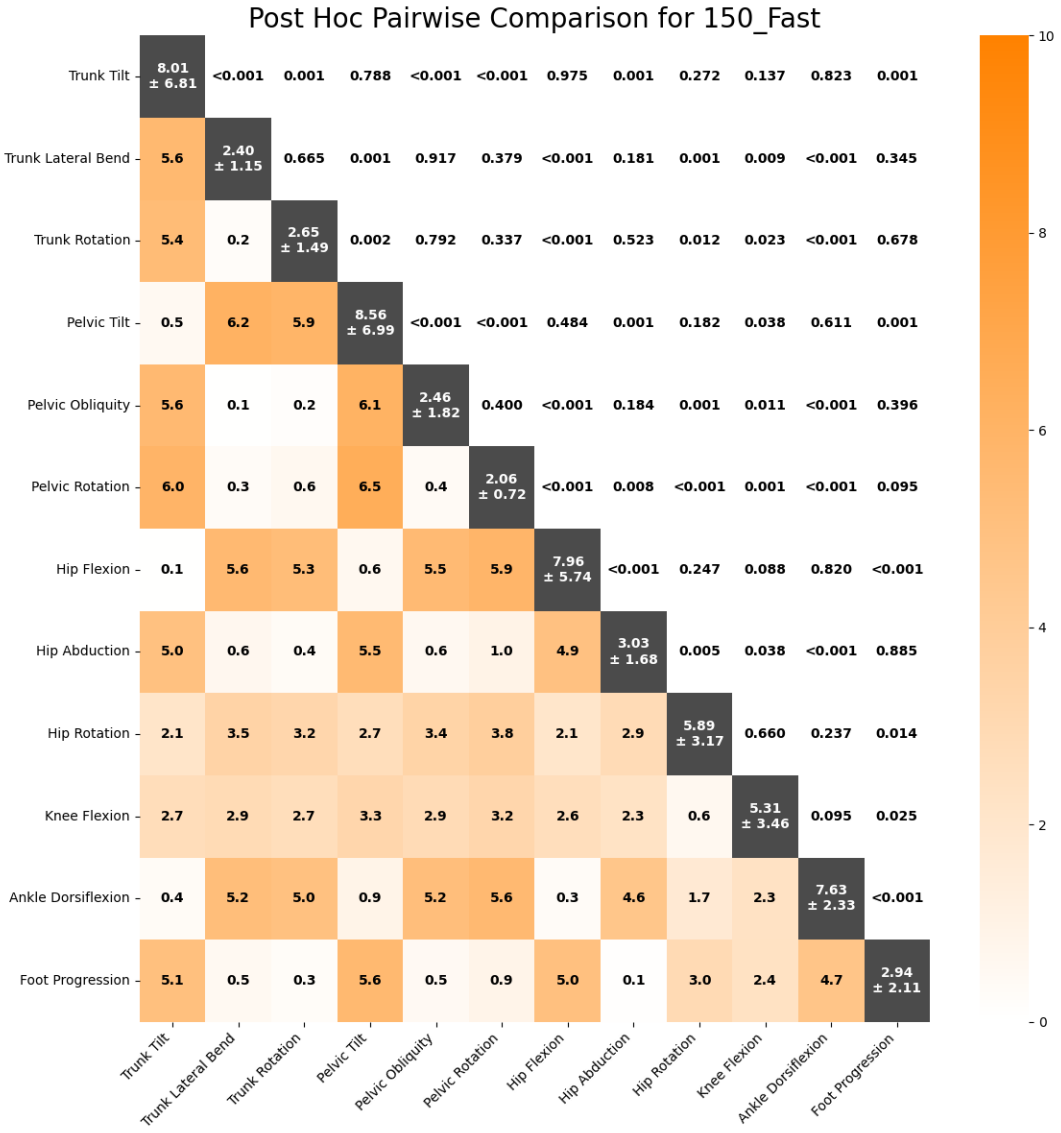


Figure 26: Pairwise post hoc comparison of CVS scores for 150mm Fast. The lower triangle shows mean differences, the diagonal shows mean ± STD, and the upper triangle shows p-values.

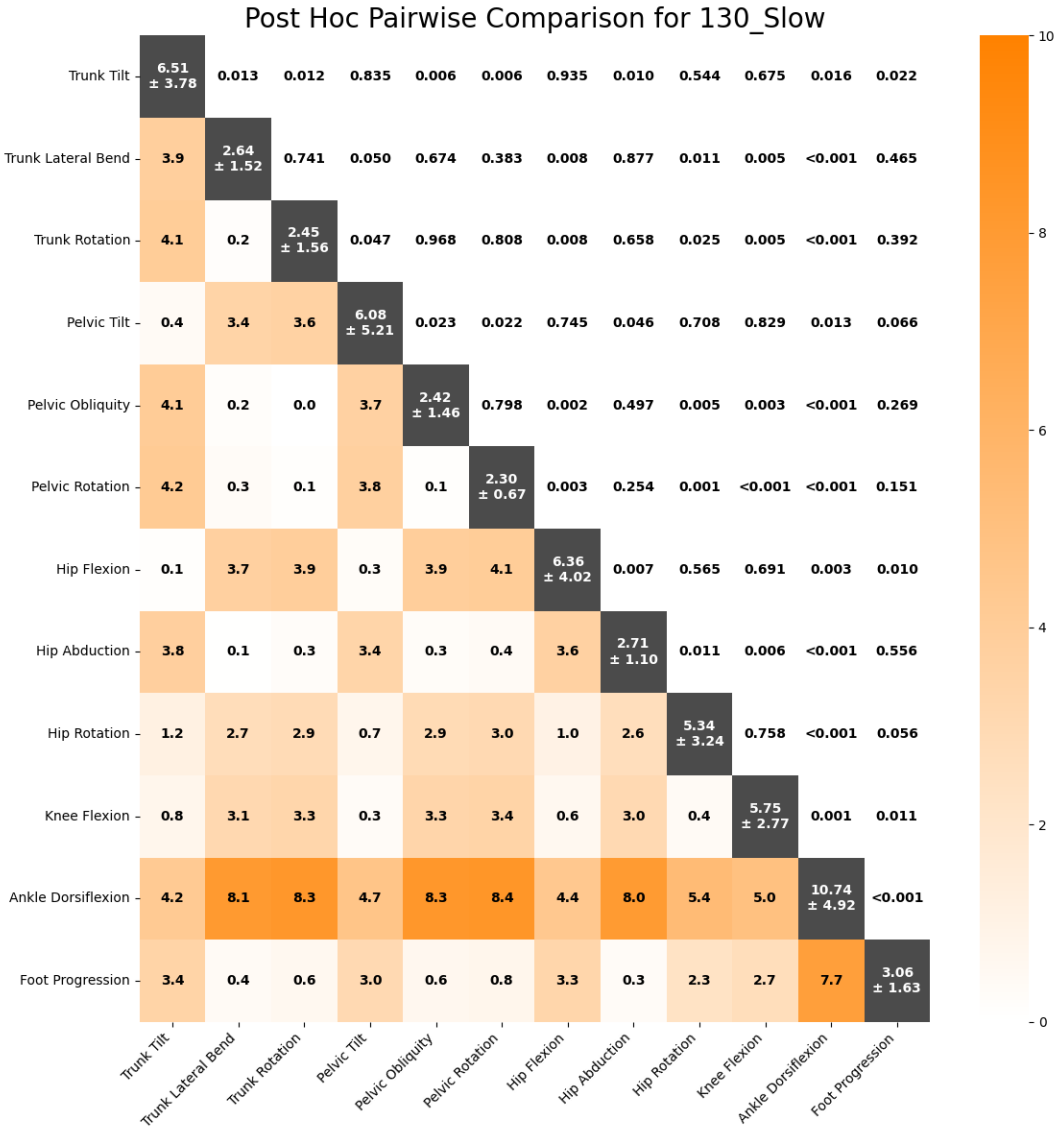


Figure 27: Pairwise post hoc comparison of CVS scores for 130mm Slow. The lower triangle shows mean differences, the diagonal shows mean ± STD, and the upper triangle shows p-values.

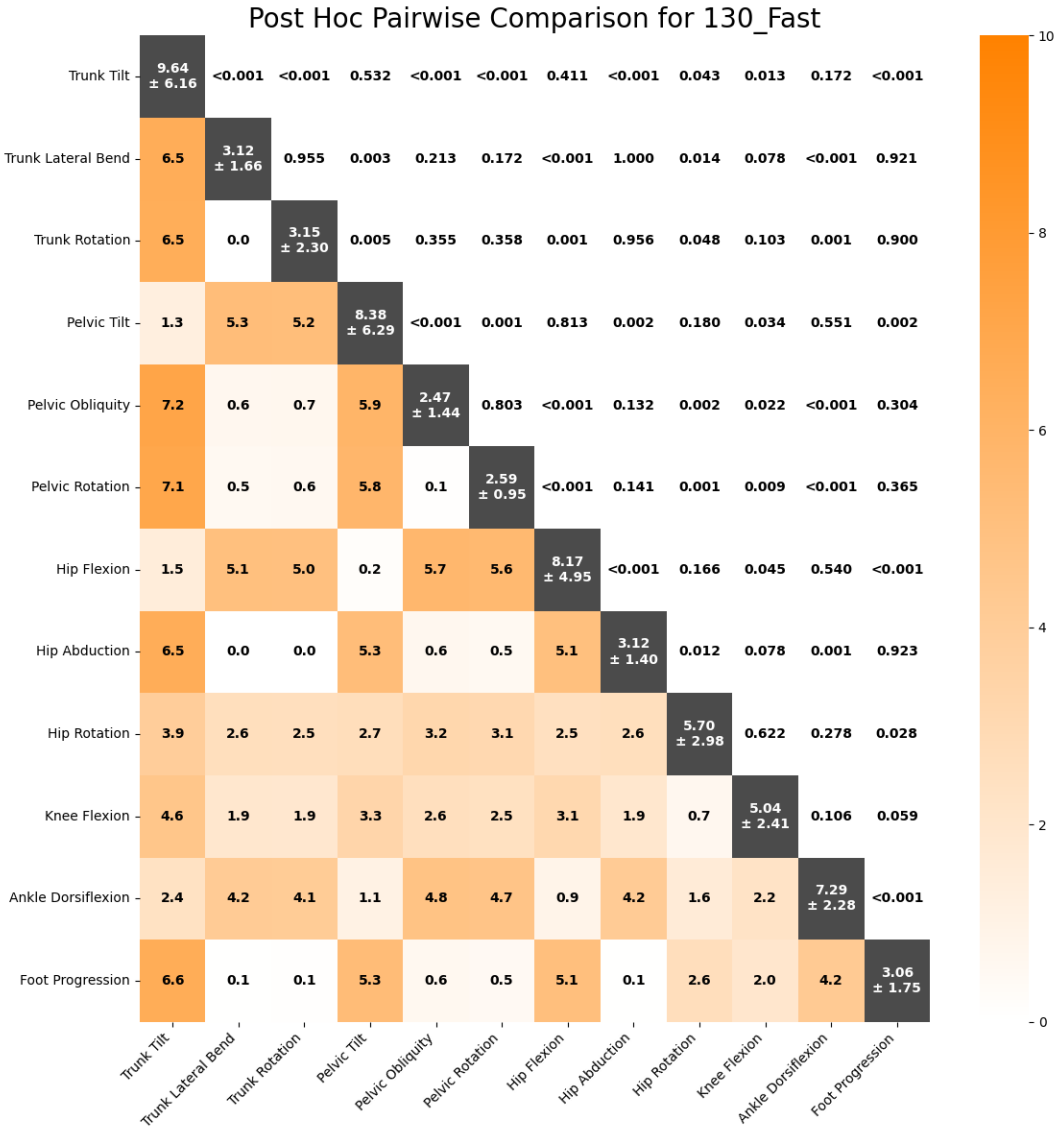


Figure 28: Pairwise post hoc comparison of CVS scores for 130mm Fast. The lower triangle shows mean differences, the diagonal shows mean ± STD, and the upper triangle shows p-values.

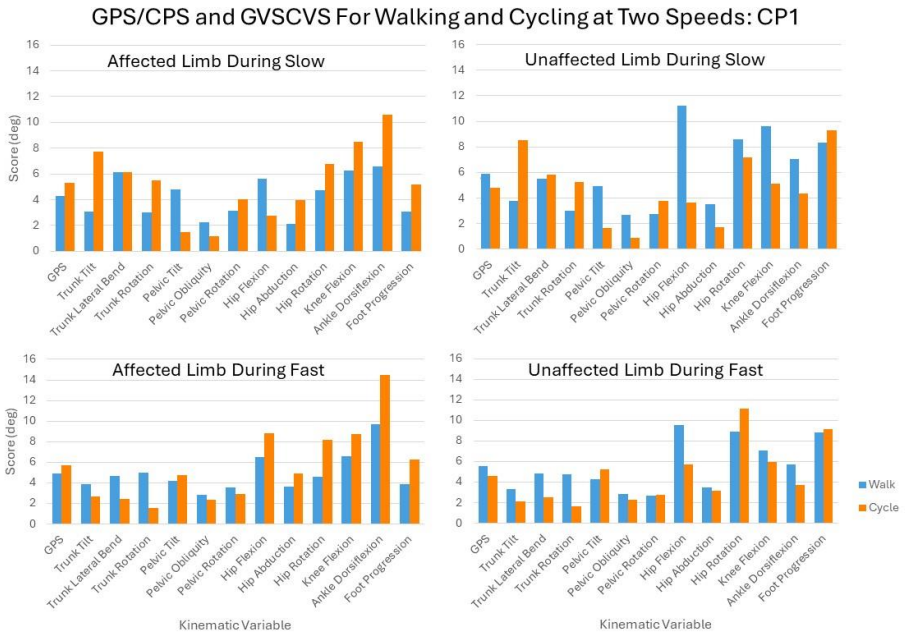


Figure 29: GPS/GVS and CPS/CVS During Walking and Cycling at Two Speeds: CP1

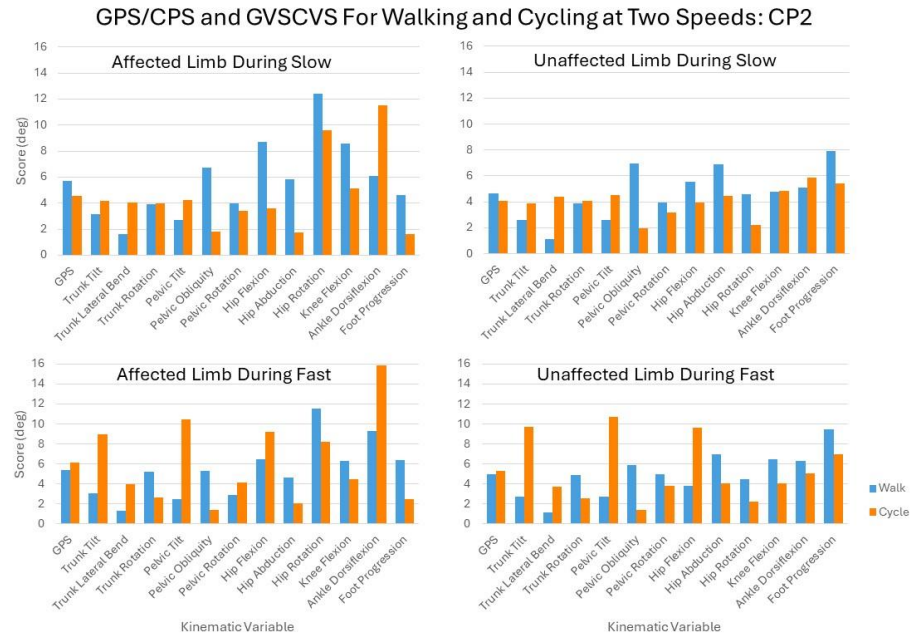


Figure 30:: GPS/GVS and CPS/CVS During Walking and Cycling at Two Speeds: CP2

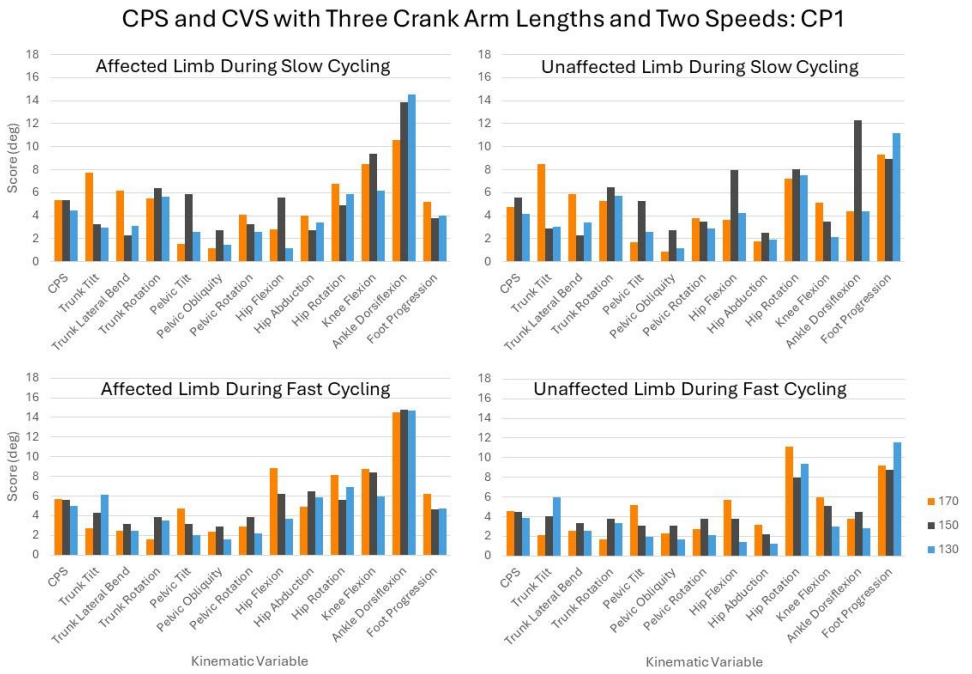


Figure 31: CPS/CVS Scores During Cycling at Three Crank Lengths at Two Speeds: CP1

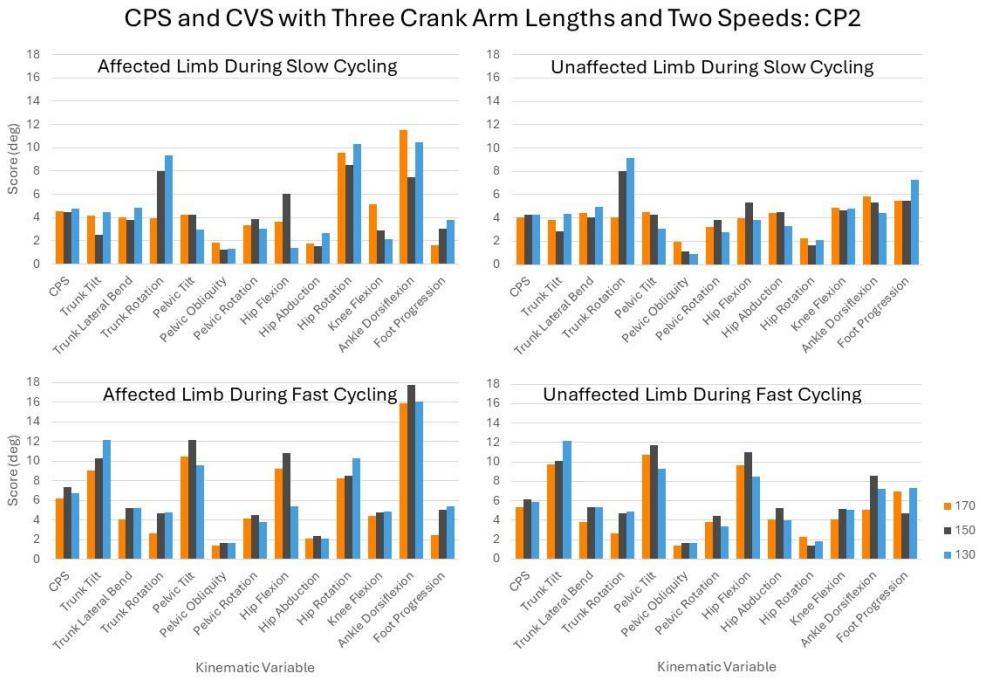


Figure 32: CPS/CVS Scores During Cycling at Three Crank Lengths at Two Speeds: CP2

Appendix C: IRB Approval Letter



February 05,

2024

Songning

Zhang, PhD
UTK - Coll of Education, Hlth, & Human - Kinesiology, Recreation & Sports Studies

Re: UTK IRB-23-07900-FB
Study Title: Are gait deviations associated with cycling deviations in children with cerebral palsy?

Dear Songning Zhang:

The IRB has received your written acceptance of and/or response to the provisos outlined in our previous correspondence concerning the application for the above referenced project, reviewed by the IRB at its 02/05/2024 convened meeting. The IRB has reviewed these materials and determined that they comply with proper consideration for the rights and welfare of human subjects and the regulatory requirements for the protection of human subjects. The use of children as subjects is approved under 45 CFR 46.404, in that it involves no more than minimal risk.

Therefore, this letter constitutes full approval by the IRB of your application (version 1.2) including:

- Informed Consent CP_Child version 3.0
- Informed Consent CP_Adult version 3.0
- Informed Consent TD_Adult version 3.0
- Informed Consent_TD_Child version 3.0
- Child/Youth Assent form version 2.0
- Inclusion criteria phone_TD_3.0 version 3.0
- Inclusion criteria phon_CP_3.0 version 3.0
- Inclusion criteria email_TD_3.0 version 3.0
- Inclusion criteria email_CP_3.0 version 3.0
- Recruitment email_TD_2.0 version 2.0
- Recruitment email_CP_2.0 version 2.0
- Physician script version 1.0
- Recruitment Flyer_TD version 2.0

- Recruitment Flyer_CP version 2.0
- Recruitment survey screenshots version 1.0
- Parqplus 2020 version 1.0

that have been dated and stamped IRB-approved. You are approved to enroll a maximum of 40 participants. Approval of this study will be valid from 02/05/2024 to 02/04/2025.

Any revisions in the approved application, consent forms, instruments, recruitment materials, etc., must be submitted to and

approved by the IRB prior to implementation. In addition, you are responsible for reporting any unanticipated serious adverse events or other problems involving risks to subjects or others in the manner required by the local IRB policy.

Finally, **re-approval** of your project is required by the IRB in accord with the conditions specified above. You may not continue the research study beyond the time or other limits specified unless you obtain prior written approval of the IRB.

Sincerely,



Lora Beebe, Ph.D., PMHNP-BC, FAAN
Chair



Appendix D: Informed Consent for Typically Developing Adult

Consent for Research Participation

Research Study Title: Are gait deviations associated with cycling deviations in children with cerebral palsy?

Researcher(s): Dr. Songning Zhang, University of Tennessee, Knoxville
Sean Brown, University of Tennessee, Knoxville
Walt Menke, University of Tennessee, Knoxville
Kaileigh Estler, University of Tennessee, Knoxville

Why am I being asked to be in this research study?

We are asking you to be in this research study because you have met all the inclusion and exclusion criteria, and we believe that you would be a good candidate for the study.

What is this research study about?

There are two purposes to this study. The first purpose of the study is to understand how changes of different asymmetric crank arm lengths will affect how your legs move compared to individuals with cerebral palsy during stationary cycling. The second purpose of the study is to learn if deviations in walking in participants with cerebral palsy are similar to deviations they may have in cycling.

Who is conducting this research study?

This study is being conducted by researchers from the Biomechanics/Sports Medicine Lab at the University of Tennessee, Knoxville.

How long will I be in the research study?

If you agree to be in the study, your participation will last for 1.5 - 2 hours.

What will happen if I say "Yes, I want to be in this research study"?

If you agree to be in this study, we will first make sure that you meet our criteria listed below:

- To be included in the study you must be:
  - Between the ages: 10-30.
  - Male or female.
  - Recreationally active. This means that you perform at least 30 minutes of exercise at least two days a week.

IRB NUMBER: UTK IRB-23-07900-FB
IRB APPROVAL DATE: 04/30/2024
IRB EXPIRATION DATE: 02/04/2025

- However, you will be excluded if:
    - Your weight in kilograms divided by height in meters squared is greater than 30. This is a measure of body mass index and may indicate obesity.
    - You have had surgery on your legs within the past 12 months.
    - You have had an injury to your legs within the past 6 months.
    - You have a neurological or cardiovascular condition that prevents walking or cycling.
    - You are pregnant or nursing.

If you agree to be in this study, we will ask you to do the following:

- Participate in one visit to the biomechanics/sports medicine lab on the UTK campus. The visit will last up to 2 hours.
- All participation will take place in our lab in the HPER building.
- Complete a physical readiness questionnaire to ensure your safety for exercise.
- Change into appropriate attire either owned by you or provided by the lab.
- Complete a brief 3-minute warm-up of walking on a treadmill at your own pace.
- You will be fitted with retroreflective markers and electromyography (EMG) sensors. The markers have a small base and sensors are small boxes, which will be taped to your skin and pose no risk. Shaving of the skin may be required for attachment of the EMG sensors.
- Cycling Activity Description: You will participate in 6 cycling trials where we will adjust a part of the bike on one leg to see how it affects your cycling. The part that we will adjust is called the crank arm. It attaches to the pedal to the bike and adjusts the size of the circle that the pedal moves through when you pedal. You will do 3 trials pedaling at a moderate speed that we will set, and 3 trials you will pedal as fast as you can. Each trial will last for a maximum of 2 minutes.
- Walking activity Description: You will participate in 5 walking trials at your typical pace and then 5 more walking trials at a fast pace. The walking will occur on the floor of the laboratory.

What happens if I say "No, I do not want to be in this research study"?

Being in this study is up to you. You can say no now or leave the study later. Either way, your decision won't affect your relationship with the researchers or the University of Tennessee.

What happens if I say "Yes" but change my mind later?

Even if you decide to be in the study now, you can change your mind and stop at any time.

If you decide to stop before the study is completed, no negative consequences will occur to you. Any information we have collected so far will be destroyed and not used in the study.

Are there any possible risks to me?

There is minimal risk in this study. The length and intensity of exercise are kept at a mild to moderate level. Riding the bike with one crank arm longer than the other might make your leg feel a bit uncomfortable. We will have you fill out the PAR-Q+ form that will ask you a series of physical activity readiness questions, which will help ensure you are safe to exercise. Cycling poses a minimal risk to you during exercise. The researchers in this study are certified in first aid, CPR, and AED. Other people could potentially see you or find out about your participation in the study. We have procedures in place to minimize this risk such as locking all personal information in a locked cabinet. All information will be stored with no identifying information and will be kept using a subject code. All documents will be kept in a locked cabinet and only the investigator will have access to them.

Are there any benefits to being in this research study?

The potential benefits for you include the identification of any possible abnormalities during cycling. Any abnormalities will be reported to you. Your participation may help us to learn more about cycling with asymmetric crank arm lengths and the movement patterns of children with cerebral palsy. We hope the knowledge gained from this study will benefit others in the future.

You will also be given a $40 Visa gift card. The participant must complete data collection to receive compensation. Parking at the University of Tennessee will be provided to you at no cost.

Who can see or use the information collected for this research study?

We will protect the confidentiality of your information by deidentifying the data such that only a subject number will be assigned to it. If information from this study is published or presented at scientific meetings, your name and other personal information will not be used.

If information from this study is published or presented at scientific meetings, your name and other personal information will not be used.

We will make every effort to prevent anyone who is not on the research team from knowing that you gave us information or what information came from you. Although it is unlikely, there are times when others may need to see the information that we collect about you. These include:

- People at the University of Tennessee, Knoxville, who oversee research to make sure it is conducted properly.
- Government agencies (such as the Office for Human Research Protections in the U.S. Department of Health and Human Services), and others responsible for watching over the safety, effectiveness, and conduct of the research.

- If a law or court requires us to share the information, we would have to follow that law or final court ruling.

What will happen to my information after this study is over?

We will not keep your information to use for future research, presentations, and/or publications. Your name and other information that can directly identify you will be deleted from your research data collected as part of the study.

We may share your research data with other researchers without asking for your consent again, but it will not contain information that could directly identify you.

Will I be paid for being in this research study?

At the completion of the study, you will be given a $40 Visa gift card.

Will it cost me anything to be in this research study?

It will not cost you anything to be in this study.

What else do I need to know?

We use procedures to lower the possibility of these risks happening. Even so, you may still experience problems or injury, even when we are careful to avoid them. Please tell the researcher in charge, Sean Brown at (865) 974-2091, about any injuries or other problems that you have during this study.

The University of Tennessee does not automatically pay for medical claims or give other compensation for injuries or other problems.

Who can answer my questions about this research study?

If you have questions or concerns about this study, or have experienced a research related problem or injury, contact the researchers, Sean Brown at sbrow159@vols.utk.edu, or over the phone at (865) 974-2091. You may also contact my faculty advisor, Dr. Songning Zhang via email at szhang@utk.edu .

For questions or concerns about your rights or to speak with someone other than the research team about the study, please contact:

Institutional Review Board
The University of Tennessee, Knoxville
Phone: 865-974-7697
Email: utkirb@utk.edu

STATEMENT OF CONSENT

I have read this form and the research study has been explained to me. I have been given the chance to ask questions and my questions have been answered. If I have more questions, I have been told who to contact. By signing this document, I am agreeing to be in this study. I will receive a copy of this document after I sign it.

Name of Adult Participant	Signature of Adult Participant	Date

Researcher Signature (to be completed at time of informed consent)

I have explained the study to the participant and answered all of his/her questions. I believe that he/she understands the information described in this consent form and freely consents to be in the study.

Name of Research Team Member	Signature of Research Team Member	Date

Appendix E: Informed Consent for Typically Developing Child

Permission for Research Participation of a Minor

Research Study Title: Are gait deviations associated with cycling deviations in children with cerebral palsy?

Researcher(s): Dr. Songning Zhang, University of Tennessee, Knoxville
Sean Brown, University of Tennessee, Knoxville
Walt Menke, University of Tennessee, Knoxville
Kaileigh Estler, University of Tennessee, Knoxville

Why is my child being asked to be in this research study?

We are asking permission for your child to be a participant in a research study. In this document when we reference the term "you" we mean "your child." We are asking your child to be in this research study because you have met all the inclusion and exclusion criteria, and we believe that you would be a good candidate for the study.

What is this research study about?

There are two purposes to this study. The first purpose of the study is to understand how changes of different asymmetric crank arm lengths will affect how your legs move compared to individuals with cerebral palsy during stationary cycling. The second purpose of the study is to learn if deviations in walking in participants with cerebral palsy are similar to deviations they may have in cycling.

Who is conducting this research study?

This study is being conducted by researchers from the Biomechanics/Sports Medicine Lab at the University of Tennessee, Knoxville.

How long will my child be in the research study?

If you agree to be in the study, your participation will last for 1.5 - 2 hours.

What will happen if I say "Yes, I want my child to be in this research study"?

If you agree to be in this study, we will first make sure that you meet our criteria listed below:

- To be included in the study you must be:
  - Between the ages: 10-30.
  - Male or female.
  - Recreationally active. This means that you perform at least 30 minutes of exercise at least two days a week.

IRB NUMBER: UTK IRB-23-07900-FB
IRB APPROVAL DATE: 04/30/2024
IRB EXPIRATION DATE: 02/04/2025

- However, you will be excluded if:
    - Your weight in kilograms divided by height in meters squared is greater than 95th percentile for your age. This is a measure of body mass index and may indicate obesity.
    - You have had surgery on your legs within the past 12 months.
    - You have had an injury to your legs within the past 6 months.
    - You have a neurological or cardiovascular condition that prevents walking or cycling.
    - You are pregnant or nursing.

If you agree to be in this study, we will ask you to do the following:

- Participate in one visit to the biomechanics/sports medicine lab on the UTK campus. The visit will last up to 2 hours.
- All participation will take place in our lab in the HPER building.
- Complete a physical readiness questionnaire to ensure your safety for exercise.
- Change into appropriate attire either owned by you or provided by the lab.
- Complete a brief 3-minute warm-up of walking on a treadmill at your own pace.
- You will be fitted with retroreflective markers and electromyography (EMG) sensors. The markers have a small base and sensors are small boxes, which will be taped to your skin and pose no risk. Shaving of the skin may be required for attachment of the EMG sensors.
- Cycling Activity Description: You will participate in 6 cycling trials where we will adjust a part of the bike on one leg to see how it affects your cycling. The part that we will adjust is called the crank arm. It attaches to the pedal to the bike and adjusts the size of the circle that the pedal moves through when you pedal. You will do 3 trials pedaling at a moderate speed that we will set, and 3 trials you will pedal as fast as you can. Each trial will last for a maximum of 2 minutes.
- Walking activity Description: You will participate in 5 walking trials at your typical pace and then 5 more walking trials at a fast pace. The walking will occur on the floor of the laboratory.

What happens if I say "No, I do not want my child to be in this research study"?

Your child's being in this study is up to you. You can say no now or leave the study later. Either way, your decision won't affect your relationship with the researchers or the University of Tennessee.

What happens if I say "Yes" but change my mind later?

Even if you decide to allow your child to be in the study now, you can change your mind and stop at any time.

If you decide to stop before the study is completed, no negative consequences will occur to you. Any information we have collected so far will be destroyed and not used in the study.

Are there any possible risks to my child?

There is minimal risk in this study. The length and intensity of exercise are kept at a mild to moderate level. Riding the bike with one crank arm longer than the other might make your leg feel a bit uncomfortable. We will have you fill out the PAR-Q+ form that will ask you a series of physical activity readiness questions, which will help ensure you are safe to exercise. Cycling poses a minimal risk to you during exercise. The researchers in this study are certified in first aid, CPR, and AED. Other people could potentially see you or find out about your participation in the study. We have procedures in place to minimize this risk such as locking all personal information in a locked cabinet. All information will be stored with no identifying information and will be kept using a subject code. All documents will be kept in a locked cabinet and only the investigator will have access to them.

Are there any benefits to being in this research study?

The potential benefits for your child include the identification of any possible abnormalities during cycling. Any abnormalities will be reported to you. Your child's participation may help us to learn more about cycling with asymmetric crank arm lengths and the movement patterns of children with cerebral palsy. We hope the knowledge gained from this study will benefit others in the future.

Your child will also be given a $40 Visa gift card. The participant must complete data collection to receive compensation. Parking at the University of Tennessee will be provided to you at no cost.

Who can see or use the information collected for this research study?

We will protect the confidentiality of your child's information by deidentifying the data such that only a subject number will be assigned to it. If information from this study is published or presented at scientific meetings, your child's name and other personal information will not be used.

If information from this study is published or presented at scientific meetings, your child's name and other personal information will not be used.

We will make every effort to prevent anyone who is not on the research team from knowing that you and your child gave us information or what information came from you and your child. Although it is unlikely, there are times when others may need to see the information that we collect about you. These include:

- People at the University of Tennessee, Knoxville, who oversee research to make sure it is conducted properly.
- Government agencies (such as the Office for Human Research Protections in the U.S. Department of Health and Human Services), and others responsible for watching over the safety, effectiveness, and conduct of the research.
- If a law or court requires us to share the information, we would have to follow that law or final court ruling.

What will happen to my child's information after this study is over?

We will not keep your child's information to use for future research, presentations, and/or publications. Your child's name and other information that can directly identify your child will be deleted from your child's research data collected as part of the study.

We may share your research data with other researchers without asking for your consent again, but it will not contain information that could directly identify your child.

Will my child be paid for being in this research study?

At the completion of the study, your child will be given a $40 Visa gift card.

Will it cost me anything for my child to be in this research study?

It will not cost you and your child anything to be in this study.

What else do I need to know?

We use procedures to lower the possibility of these risks happening. Even so, you may still experience problems or injury, even when we are careful to avoid them. Please tell the researcher in charge, Sean Brown at (865) 974-2091, about any injuries or other problems that you have during this study.

The University of Tennessee does not automatically pay for medical claims or give other compensation for injuries or other problems.

Who can answer my questions about this research study?

If you have questions or concerns about this study, or have experienced a research related problem or injury, contact the researchers, Sean Brown at sbrow159@vols.utk.edu, or over the phone at (865) 974-2091. You may also contact my faculty advisor, Dr. Songning Zhang via email at szhang@utk.edu .

For questions or concerns about your rights or to speak with someone other than the research team about the study, please contact:

Institutional Review Board
The University of Tennessee, Knoxville
Knoxville, TN 37996-1529
Phone: 865-974-7697
Email: utkirb@utk.edu

STATEMENT OF PERMISSION

I have read this form and the research study has been explained to me. I have been given the chance to ask questions and my questions have been answered. If I have more questions, I have been told who to contact. By signing this document, I am giving permission for my child to be in this study. I will receive a copy of this document after I sign it.

Child's Name (printed) _____

Parent's Name (printed) _____

Parent's Signature _____ Date _____

Researcher Signature (to be completed at time of informed consent)

I have explained the study to the participant and answered all of his/her questions. I believe that he/she understands the information described in this consent form and freely consents to be in the study.

Name of Research Team Member	Signature of Research Team Member	Date

Appendix F: Informed Consent for Adult with Cerebral Palsy

Consent for Research Participation

Research Study TItle: Are gait deviations associated with cycling deviations in children with cerebral palsy?

Researcher(s): Dr. Songning Zhang, University of Tennessee, Knoxville
Sean Brown, University of Tennessee, Knoxville
Walt Menke, University of Tennessee, Knoxville
Kaileigh Estler, University of Tennessee, Knoxville

Why am I being asked to be in this research study?

We are asking you to be in this research study because you have met all the inclusion and exclusion criteria, and we believe that you would be a good candidate for the study.

What is this research study about?

We are seeking both typically developing individuals and individuals with cerebral palsy for a study looking at the possible relationship between difficulties with cycling and walking.

Who is conducting this research study?

This study is being conducted by researchers from the Biomechanics/Sports Medicine Lab at the University of Tennessee, Knoxville.

How long will I be in the research study?

If you agree to be in the study, your participation will last for 1.5 - 2 hours.

What will happen if I say "Yes, I want to be in this research study"?

If you agree to be in this study, we will first make sure that you meet our criteria listed below:

- To be included in the study you must be:
  - Between the ages: 10-30.
  - Have a diagnosis of unilateral cerebral palsy.
  - Gross motor function classification system level I and II, indicated by the ability to walk independently without the use of hand-held device (walker or crutches).
  - Male or female.
- However, you will be excluded if:
  - Your weight in kilograms divided by height in meters squared is greater than 30. This is a measure of body mass index and may indicate obesity.

IRB NUMBER: UTK IRB-23-07300-XP
IRB APPROVAL DATE: 04/30/2024
IRB EXPIRATION DATE: 02/04/2025

- Gross motor function classification system level III or higher, indicated by the inability to walk without the use of a hand-held mobility device (walker or crutches).
- You have had surgery on your legs within the past 12 months.
- You have had an injury to your legs within the past 6 months.
- You are currently taking and/or took baclofen in the past 10 weeks.
- You have had botulinum toxin (Botox) injections in your legs to reduce the stiffness of your muscles within the past 10 weeks.
- You have a neurological or cardiovascular condition that prevents walking or cycling.
- You are pregnant or nursing.

If you agree to be in this study, we will ask you to do the following:

- Participate in one visit to the biomechanics/sports medicine lab on the UTK campus. The visit will last up to 2 hours.
- All participation will take place in our lab in the HPER building.
- Complete a physical readiness questionnaire to ensure your safety for exercise.
- Change into appropriate attire either owned by you or provided by the lab.
- Complete a brief 3-minute warm-up of walking on a treadmill at your own pace.
- You will be fitted with retroreflective markers and electromyography (EMG) sensors. The markers have a small base and sensors are small boxes, which will be taped to your skin and pose no risk. Shaving of the skin may be required for attachment of the EMG sensors.
- Cycling Activity Description: You will participate in 6 cycling trials where we will adjust a part of the bike on one leg to see how it affects your cycling. The part that we will adjust is called the crank arm. It attaches to the pedal to the bike and adjusts the size of the circle that the pedal moves through when you pedal. You will do 3 trials pedaling at a moderate speed that we will set, and 3 trials you will pedal as fast as you can. Each trial will last for a maximum of 2 minutes.
- Walking activity Description: You will participate in 5 walking trials at your typical pace and then 5 more walking trials at a fast pace. The walking will occur on the floor of the laboratory.
- Physical Exam: We will check three things while you're on the exam table. First, we will measure the range of motion of the joints in your legs with a plastic tool that will tell me an angle. Then, we will assess the strength of your muscles in your legs. Lastly, we will check how well you can control your joints in your legs.

What happens if I say "No, I do not want to be in this research study"?

Being in this study is up to you. You can say no now or leave the study later. Either way, your decision won't affect your relationship with the researchers or the University of Tennessee.

What happens if I say "Yes" but change my mind later?

Even if you decide to be in the study now, you can change your mind and stop at any time.

If you decide to stop before the study is completed, no negative consequences will occur to you. Any information we have collected so far will be destroyed and not used in the study.

Are there any possible risks to me?

There is minimal risk in this study. The length and intensity of exercise are kept at a mild to moderate level. Riding the bike with one crank arm longer than the other might make your leg feel a bit uncomfortable. We will have you fill out the PAR-Q+ form that will ask you a series of physical activity readiness questions, which will help ensure you are safe to exercise. Cycling poses a minimal risk to you during exercise. The researchers in this study are certified in first aid, CPR, and AED. Other people could potentially see you or find out about your participation in the study. We have procedures in place to minimize this risk such as locking all personal information in a locked cabinet. All information will be stored with no identifying information and will be kept using a subject code. All documents will be kept in a locked cabinet and only the investigator will have access to them.

Are there any benefits to being in this research study?

The potential benefits for you include the identification of any possible abnormalities during cycling. Any abnormalities will be reported to you. Your participation may help us to learn more about cycling with asymmetric crank arm lengths and the movement patterns of children with cerebral palsy. We hope the knowledge gained from this study will benefit others in the future.

You will also be given a $40 Visa gift card. The participant must complete data collection to receive compensation. Parking at the University of Tennessee will be provided to you at no cost.

Who can see or use the information collected for this research study?

We will protect the confidentiality of your information by deidentifying the data such that only a subject number will be assigned to it. If information from this study is published or presented at scientific meetings, your name and other personal information will not be used.

If information from this study is published or presented at scientific meetings, your name and other personal information will not be used.

We will make every effort to prevent anyone who is not on the research team from knowing that you gave us information or what information came from you. Although it is unlikely, there are times when others may need to see the information that we collect about you. These include:

- People at the University of Tennessee, Knoxville, who oversee research to make sure it is conducted properly.
- Government agencies (such as the Office for Human Research Protections in the U.S. Department of Health and Human Services), and others responsible for watching over the safety, effectiveness, and conduct of the research.
- If a law or court requires us to share the information, we would have to follow that law or final court ruling.

What will happen to my information after this study is over?

We will not keep your information to use for future research, presentations, and/or publications. Your name and other information that can directly identify you will be deleted from your research data collected as part of the study.

We may share your research data with other researchers without asking for your consent again, but it will not contain information that could directly identify you.

Will I be paid for being in this research study?

At the completion of the study, you will be given a $40 Visa gift card.

Will it cost me anything to be in this research study?

It will not cost you anything to be in this study.

What else do I need to know?

We use procedures to lower the possibility of these risks happening. Even so, you may still experience problems or injury, even when we are careful to avoid them. Please tell the researcher in charge, Sean Brown at (865) 974-2091, about any injuries or other problems that you have during this study.

The University of Tennessee does not automatically pay for medical claims or give other compensation for injuries or other problems.

Who can answer my questions about this research study?

If you have questions or concerns about this study, or have experienced a research related problem or injury, contact the researchers, Sean Brown at sbrow159@vols.utk.edu, or over the phone at (865) 974-2091. You may also contact my faculty advisor, Dr. Songning Zhang via email at szhang@utk.edu .

For questions or concerns about your rights or to speak with someone other than the research team about the study, please contact:

Institutional Review Board
The University of Tennessee, Knoxville
Phone: 865-974-7697
Email: utkirb@utk.edu

STATEMENT OF CONSENT

I have read this form and the research study has been explained to me. I have been given the chance to ask questions and my questions have been answered. If I have more questions, I have been told who to contact. By signing this document, I am agreeing to be in this study. I will receive a copy of this document after I sign it.

Name of Adult Participant	Signature of Adult Participant	Date

Researcher Signature (to be completed at time of informed consent)

I have explained the study to the participant and answered all of his/her questions. I believe that he/she understands the information described in this consent form and freely consents to be in the study.

Name of Research Team Member	Signature of Research Team Member	Date

Appendix G: Informed Consent for Child with Cerebral Palsy

Permission for Research Participation of a Minor

Research Study Title: Are gait deviations associated with cycling deviations in children with cerebral palsy?

Researcher(s): Dr. Songning Zhang, University of Tennessee, Knoxville
Sean Brown, University of Tennessee, Knoxville
Walt Menke, University of Tennessee, Knoxville
Kaileigh Estler, University of Tennessee, Knoxville

Why is my child being asked to be in this research study?

We are asking permission for your child to be a participant in a research study. In this document when we reference the term "you" we mean "your child." We are asking your child to be in this research study because you have met all the inclusion and exclusion criteria, and we believe that you would be a good candidate for the study.

What is this research study about?

There are two purposes to this study. The first purpose of the study is to understand how changes of different asymmetric crank arm lengths will affect how your legs move compared to individuals that do not have a diagnosis of cerebral palsy during stationary cycling. The second purpose of the study is to learn if deviations in walking in participants with cerebral palsy are similar to deviations they may have in cycling.

Who is conducting this research study?

This study is being conducted by researchers from the Biomechanics/Sports Medicine Lab at the University of Tennessee, Knoxville.

How long will my child be in the research study?

If you agree to be in the study, your participation will last for 1.5 - 2 hours.

What will happen if I say "Yes, I want my child to be in this research study"?

If you agree to be in this study, we will first make sure that you meet our criteria listed below:

- To be included in the study you must be:
  - Between the ages: 10-30.
  - Have a diagnosis of unilateral cerebral palsy.
  - Gross motor function classification system level I and II, indicated by the ability to walk independently without the use of hand-held devices (walker or crutches).

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IRB EXPIRATION DATE: 02/04/2025

- Male or female.

- However, you will be excluded if:
  - Your weight in kilograms divided by height in meters squared is greater than 95th percentile for your age. This is a measure of body mass index and may indicate obesity.
  - Gross motor function classification system level III or higher, indicated by the inability to walk without the use of a hand-held mobility device (walker or crutches).
  - You have had surgery on your legs within the past 12 months.
  - You have had an injury to your legs within the past 6 months.
  - You are currently taking and/or took baclofen in the past 10 weeks.
  - You have had botulinum toxin (Botox) injections in your legs to reduce the stiffness of your muscles within the past 10 weeks.
  - You have a neurological or cardiovascular condition that prevents walking or cycling.
  - You are pregnant or nursing.

If you agree to be in this study, we will ask you to do the following:

- Participate in one visit to the biomechanics/sports medicine lab on the UTK campus. The visit will last up to 2 hours.
- All participation will take place in our lab in the HPER building.
- Complete a physical readiness questionnaire to ensure your safety for exercise.
- Change into appropriate attire either owned by you or provided by the lab.
- Complete a brief 3-minute warm-up of walking on a treadmill at your own pace.
- You will be fitted with retroreflective markers and electromyography (EMG) sensors. The markers have a small base and sensors are small boxes, which will be taped to your skin and pose no risk. Shaving of the skin may be required for attachment of the EMG sensors.
- Cycling Activity Description: You will participate in 6 cycling trials where we will adjust a part of the bike on one leg to see how it affects your cycling. The part that we will adjust is called the crank arm. It attaches to the pedal to the bike and adjusts the size of the circle that the pedal moves through when you pedal. You will do 3 trials pedaling at a moderate speed that we will set, and 3 trials you will pedal as fast as you can. Each trial will last for a maximum of 2 minutes.
- Walking activity Description: You will participate in 5 walking trials at your typical pace and then 5 more walking trials at a fast pace. The walking will occur on the floor of the laboratory.

- Physical Exam: We will check three things while you're on the exam table. First, we will measure the range of motion of the joints in your legs with a plastic tool that will tell me an angle. Then, we will assess the strength of your muscles in your legs. Lastly, we will check how well you can control your joints in your legs.

What happens if I say "No, I do not want my child to be in this research study"?

Your child's being in this study is up to you. You can say no now or leave the study later. Either way, your decision won't affect your relationship with the researchers or the University of Tennessee.

What happens if I say "Yes" but change my mind later?

Even if you decide to allow your child to be in the study now, you can change your mind and stop at any time.

If you decide to stop before the study is completed, no negative consequences will occur to you. Any information we have collected so far will be destroyed and not used in the study.

Are there any possible risks to my child?

There is minimal risk in this study. The length and intensity of exercise are kept at a mild to moderate level. Riding the bike with one crank arm longer than the other might make your leg feel a bit uncomfortable. We will have you fill out the PAR-Q+ form that will ask you a series of physical activity readiness questions, which will help ensure you are safe to exercise. Cycling poses a minimal risk to you during exercise. The researchers in this study are certified in first aid, CPR, and AED. Other people could potentially see you or find out about your participation in the study. We have procedures in place to minimize this risk such as locking all personal information in a locked cabinet. All information will be stored with no identifying information and will be kept using a subject code. All documents will be kept in a locked cabinet and only the investigator will have access to them.

Are there any benefits to being in this research study?

The potential benefits for your child include the identification of any possible abnormalities during cycling. Any abnormalities will be reported to you. Your child's participation may help us to learn more about cycling with asymmetric crank arm lengths and the movement patterns of children with cerebral palsy. We hope the knowledge gained from this study will benefit others in the future.

Your child will also be given a $40 Visa gift card. The participant must complete data collection to receive compensation. Parking at the University of Tennessee will be provided to you at no cost.

Who can see or use the information collected for this research study?

We will protect the confidentiality of your child's information by deidentifying the data such that only a subject number will be assigned to it. If information from this study is published or presented at scientific meetings, your child's name and other personal information will not be used.

If information from this study is published or presented at scientific meetings, your child's name and other personal information will not be used.

We will make every effort to prevent anyone who is not on the research team from knowing that you and your child gave us information or what information came from you and your child. Although it is unlikely, there are times when others may need to see the information that we collect about you. These include:

- People at the University of Tennessee, Knoxville, who oversee research to make sure it is conducted properly.
- Government agencies (such as the Office for Human Research Protections in the U.S. Department of Health and Human Services), and others responsible for watching over the safety, effectiveness, and conduct of the research.
- If a law or court requires us to share the information, we would have to follow that law or final court ruling.

What will happen to my child's information after this study is over?

We will not keep your child's information to use for future research, presentations, and/or publications. Your child's name and other information that can directly identify your child will be deleted from your child's research data collected as part of the study.

We may share your research data with other researchers without asking for your consent again, but it will not contain information that could directly identify your child.

Will my child be paid for being in this research study?

At the completion of the study, your child will be given a $40 Visa gift card.

Will it cost me anything for my child to be in this research study?

It will not cost you and your child anything to be in this study.

What else do I need to know?

We use procedures to lower the possibility of these risks happening. Even so, you may still experience problems or injury, even when we are careful to avoid them. Please tell the researcher in charge, Sean Brown at (865) 974-2091, about any injuries or other problems that you have during this study.

The University of Tennessee does not automatically pay for medical claims or give other compensation for injuries or other problems.

Who can answer my questions about this research study?

If you have questions or concerns about this study, or have experienced a research related problem or injury, contact the researchers, Sean Brown at sbrow159@vols.utk.edu, or over the phone at (865) 974-2091. You may also contact my faculty advisor, Dr. Songning Zhang via email at szhang@utk.edu .

For questions or concerns about your rights or to speak with someone other than the research team about the study, please contact:

Institutional Review Board
The University of Tennessee, Knoxville
Phone: 865-974-7697
Email: utkirb@utk.edu

STATEMENT OF PERMISSION

I have read this form and the research study has been explained to me. I have been given the chance to ask questions and my questions have been answered. If I have more questions, I have been told who to contact. By signing this document, I am giving permission for my child to be in this study. I will receive a copy of this document after I sign it.

Child's Name (printed) _____

Parent's Name (printed) _____

Parent's Signature _____ Date _____

Researcher Signature (to be completed at time of informed consent)

I have explained the study to the participant and answered all of his/her questions. I believe that he/she understands the information described in this consent form and freely consents to be in the study.

_____	_____	_____
Name of Research Team Member	Signature of Research Team Member	Date

Appendix H: Assent for Underage Participants

ASSENT TO PARTICIPATE IN RESEARCH

Are gait deviations associated with cycling deviations in children with cerebral palsy?

1. My name is Sean, and I am a researcher here at UTK.

2. We are asking you to take part in a research study because we are trying to learn more about how children with cerebral palsy ride a bike and walk differently compared to typically developing children.

3. If you agree to be in this study, I will put some reflective markers and muscle sensors on your body, and you will ride a stationary bike and walk in our lab. These markers and sensors will record your movement and muscle activities during your cycling and walking. It is the same technology that is used to make animated movies and video games.

4. The risks are very minimal as you will only ride a bike at moderate speeds and a moderate intensity and walk at your own speed. There may be discomfort with tape removal from your skin.

5. After you complete the study, you will be provided with a $40 gift card. You will help us better understand how children with cerebral palsy walk and ride a bike. This information may help with therapy in the future.

6. Please talk this over with your parents before you decide whether or not to participate. We will also ask your parents to give their permission for you to take part in this study. But even if your parents say "yes" you can still decide not to do this.

7. If you don't want to be in this study, you don't have to participate. Remember, being in this study is up to you and no one will be upset if you don't want to participate or even if you change your mind later and want to stop.

8. You can ask any questions that you have about the study. If you have a question later that you didn't think of now, you can call or email me. My phone number is: (865) 974 – 2091

9. Signing your name at the bottom means that you agree to be in this study. You and your parents will be given a copy of this form after you have signed it.

_____ _____

Name of Subject Date

IRB NUMBER: UTK IRB-23-07900-FB
IRB APPROVAL DATE: 02/05/2024
IRB EXPIRATION DATE: 02/04/2025

Appendix I: Recruitment Flyer for Typically Developing Individuals

Research Participants Needed

Are Gait Deviations Associated with Cycling Deviations in Children with Cerebral Palsy?

About the Research

- A team of researchers from the Department of Kinesiology Recreation and Sports Studies at UT
- The goal is to enhance our understanding of movement in individuals with cerebral palsy

Participation

- The study will last 1.5 – 2 hours
- The study will use 3D motion capture
- Participants will engage in cycling and walking
- Participants will receive compensation



Qualifications to Participate

- Between the age of 10 and 30
- Healthy
- No musculoskeletal injuries in the past 6 months
- No surgery on legs in the past 12 months
- Recreationally active

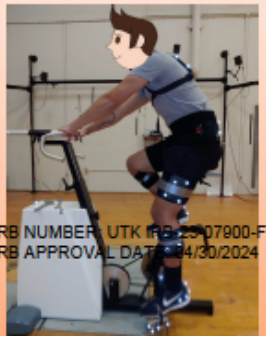
More Information

- For more information, please scan the code below
- Provide email and phone number
- A researcher will contact you with details about how to participate

Contact information

- Email: sbrow159@vols.utk.edu

THE UNIVERSITY OF TENNESSEE KNOXVILLE
BIOMECHANICS



UTK Biomechanics Research

Appendix J: Recruitment Flyer for Individuals with Cerebral Palsy

Research Participants Needed

Are Gait Deviations Associated with Cycling Deviations in Children with Cerebral Palsy?

About the Research

- A team of researchers from the Department of Kinesiology Recreation and Sports Studies at UT
- The goal is to enhance our understanding of movement in individuals with cerebral palsy

Participation

- The study will last 1.5 – 2 hours
- The study will use 3D motion capture
- Participants will engage in cycling and walking
- Participants will receive compensation



Qualifications to Participate

- Between the age of 10 and 30
- Diagnosis of unilateral cerebral palsy
- No surgery on legs in the past 12 months
- No musculoskeletal injuries in the past 6 months
- Able to walk independently

More Information

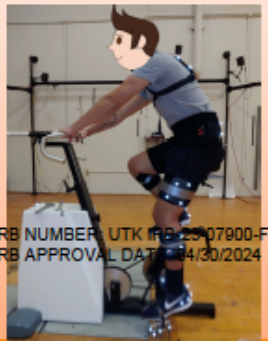
- For more information, please scan the code below
- Provide email and phone number
- A researcher will contact you with details about how to participate

Contact information

- Email: sbrow159@vols.utk.edu

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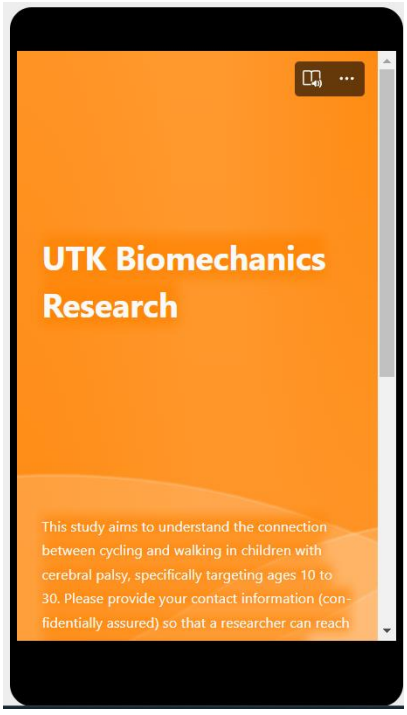
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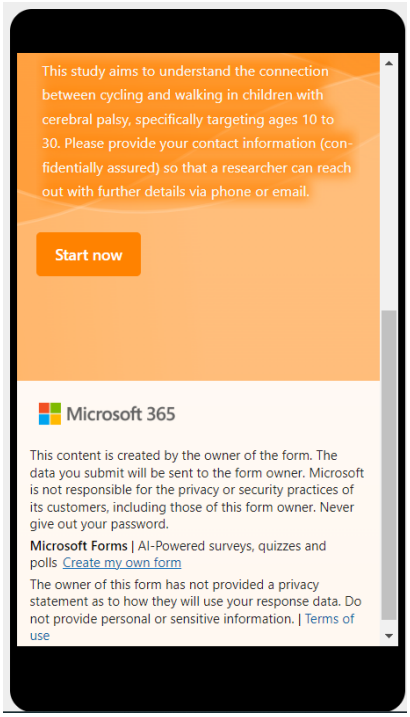


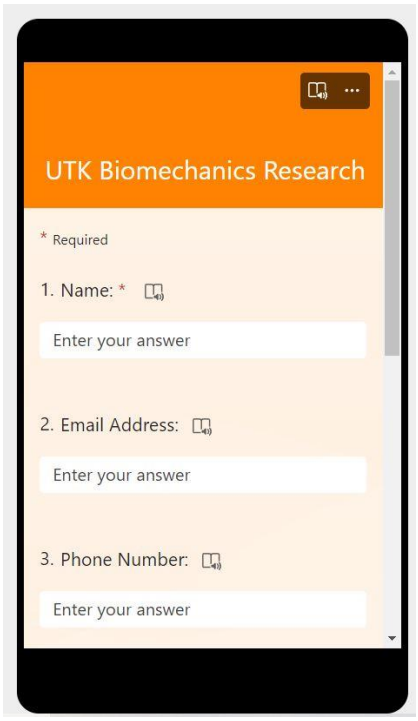
IRB NUMBER: UTK IRB-23-07900-FB
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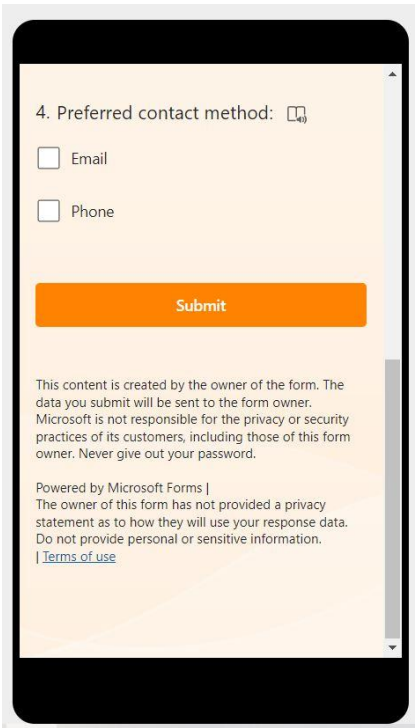
UTK Biomechanics CP Research

Appendix K: Recruitment Survey Screenshot









Appendix L: Physical Activity Readiness Questionnaire

2020 PAR-Q+

The Physical Activity Readiness Questionnaire for Everyone

The health benefits of regular physical activity are clear; more people should engage in physical activity every day of the week. Participating in physical activity is very safe for MOST people. This questionnaire will tell you whether it is necessary for you to seek further advice from your doctor OR a qualified exercise professional before becoming more physically active.

GENERAL HEALTH QUESTIONS

Please read the 7 questions below carefully and answer each one honestly: check YES or NO.	**YES**	**NO**
1) Has your doctor ever said that you have a heart condition ☐ **OR** high blood pressure ☐?	☐	☐
2) Do you feel pain in your chest at rest, during your daily activities of living, **OR** when you do physical activity?	☐	☐
3) Do you lose balance because of dizziness **OR** have you lost consciousness in the last 12 months? Please answer **NO** if your dizziness was associated with over-breathing (including during vigorous exercise).	☐	☐
4) Have you ever been diagnosed with another chronic medical condition (other than heart disease or high blood pressure)? **PLEASE LIST CONDITION(S) HERE:** _____	☐	☐
5) Are you currently taking prescribed medications for a chronic medical condition? **PLEASE LIST CONDITION(S) AND MEDICATIONS HERE:** _____	☐	☐
6) Do you currently have (or have had within the past 12 months) a bone, joint, or soft tissue (muscle, ligament, or tendon) problem that could be made worse by becoming more physically active? Please answer **NO** if you had a problem in the past, but it **does not limit your current ability** to be physically active. **PLEASE LIST CONDITION(S) HERE:** _____	☐	☐
7) Has your doctor ever said that you should only do medically supervised physical activity?	☐	☐

If you answered NO to all of the questions above, you are cleared for physical activity.
Please sign the PARTICIPANT DECLARATION. You do not need to complete Pages 2 and 3.

- Start becoming much more physically active – start slowly and build up gradually.
- Follow Global Physical Activity Guidelines for your age (https://apps.who.int/iris/handle/10665/44399).
- You may take part in a health and fitness appraisal.
- If you are over the age of 45 yr and NOT accustomed to regular vigorous to maximal effort exercise, consult a qualified exercise professional before engaging in this intensity of exercise.
- If you have any further questions, contact a qualified exercise professional.

PARTICIPANT DECLARATION

If you are less than the legal age required for consent or require the assent of a care provider, your parent, guardian or care provider must also sign this form.

I, the undersigned, have read, understood to my full satisfaction and completed this questionnaire. I acknowledge that this physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if my condition changes. I also acknowledge that the community/fitness center may retain a copy of this form for its records. In these instances, it will maintain the confidentiality of the same, complying with applicable law.

NAME _____ DATE _____

SIGNATURE _____ WITNESS _____

SIGNATURE OF PARENT/GUARDIAN/CARE PROVIDER _____

If you answered YES to one or more of the questions above, COMPLETE PAGES 2 AND 3.

Delay becoming more active if:

- You have a temporary illness such as a cold or fever; it is best to wait until you feel better.
- You are pregnant - talk to your health care practitioner, your physician, a qualified exercise professional, and/or complete the ePARmed-X+ at www.eparmedx.com before becoming more physically active.
- Your health changes - answer the questions on Pages 2 and 3 of this document and/or talk to your doctor or a qualified exercise professional before continuing with any physical activity programs.

PHYSICAL ACTIVITY PROGRAM: 23-07900-FB
IRB APPROVAL DATE: 02/05/2024

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FOLLOW-UP QUESTIONS ABOUT YOUR MEDICAL CONDITION(S)

1. Do you have Arthritis, Osteoporosis, or Back Problems?

If the above condition(s) is/are present, answer questions 1a-1c — If **NO** ☐ go to question 2

1a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer **NO** if you are not currently taking medications or other treatments)	YES ☐ NO ☐
1b.	Do you have joint problems causing pain, a recent fracture or fracture caused by osteoporosis or cancer, displaced vertebra (e.g., spondylolisthesis), and/or spondylolysis/pars defect (a crack in the bony ring on the back of the spinal column)?	YES ☐ NO ☐
1c.	Have you had steroid injections or taken steroid tablets regularly for more than 3 months?	YES ☐ NO ☐

2. Do you currently have Cancer of any kind?

If the above condition(s) is/are present, answer questions 2a-2b — If **NO** ☐ go to question 3

2a.	Does your cancer diagnosis include any of the following types: lung/bronchogenic, multiple myeloma (cancer of plasma cells), head, and/or neck?	YES ☐ NO ☐
2b.	Are you currently receiving cancer therapy (such as chemotheraphy or radiotherapy)?	YES ☐ NO ☐

3. Do you have a Heart or Cardiovascular Condition? This includes Coronary Artery Disease, Heart Failure, Diagnosed Abnormality of Heart Rhythm

If the above condition(s) is/are present, answer questions 3a-3d — If **NO** ☐ go to question 4

3a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer **NO** if you are not currently taking medications or other treatments)	YES ☐ NO ☐
3b.	Do you have an irregular heart beat that requires medical management? (e.g., atrial fibrillation, premature ventricular contraction)	YES ☐ NO ☐
3c.	Do you have chronic heart failure?	YES ☐ NO ☐
3d.	Do you have diagnosed coronary artery (cardiovascular) disease and have not participated in regular physical activity in the last 2 months?	YES ☐ NO ☐

4. Do you currently have High Blood Pressure?

If the above condition(s) is/are present, answer questions 4a-4b — If **NO** ☐ go to question 5

4a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer **NO** if you are not currently taking medications or other treatments)	YES ☐ NO ☐
4b.	Do you have a resting blood pressure equal to or greater than 160/90 mmHg with or without medication? (Answer **YES** if you do not know your resting blood pressure)	YES ☐ NO ☐

5. Do you have any Metabolic Conditions? This includes Type 1 Diabetes, Type 2 Diabetes, Pre-Diabetes

If the above condition(s) is/are present, answer questions 5a-5e — If **NO** ☐ go to question 6

5a.	Do you often have difficulty controlling your blood sugar levels with foods, medications, or other physician-prescribed therapies?	YES ☐ NO ☐
5b.	Do you often suffer from signs and symptoms of low blood sugar (hypoglycemia) following exercise and/or during activities of daily living? Signs of hypoglycemia may include shakiness, nervousness, unusual irritability, abnormal sweating, dizziness or light-headedness, mental confusion, difficulty speaking, weakness, or sleepiness.	YES ☐ NO ☐
5c.	Do you have any signs or symptoms of diabetes complications such as heart or vascular disease and/or complications affecting your eyes, kidneys, **OR** the sensation in your toes and feet?	YES ☐ NO ☐
5d.	Do you have other metabolic conditions (such as current pregnancy-related diabetes, chronic kidney disease, or liver problems)?	YES ☐ NO ☐
5e.	Are you planning to engage in what for you is unusually high (or vigorous) intensity exercise in the near future?	YES ☐ NO ☐

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IRB APPROVAL DATE: 02/05/2024

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11-01-2019

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6. Do you have any Mental Health Problems or Learning Difficulties? This includes Alzheimer's, Dementia, Depression, Anxiety Disorder, Eating Disorder, Psychotic Disorder, Intellectual Disability, Down Syndrome

If the above condition(s) is/are present, answer questions 6a-6b If **NO** ☐ go to question 7

6a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer **NO** if you are not currently taking medications or other treatments)	YES ☐ NO ☐
6b.	Do you have Down Syndrome **AND** back problems affecting nerves or muscles?	YES ☐ NO ☐

7. Do you have a Respiratory Disease? This includes Chronic Obstructive Pulmonary Disease, Asthma, Pulmonary High Blood Pressure

If the above condition(s) is/are present, answer questions 7a-7d If **NO** ☐ go to question 8

7a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer **NO** if you are not currently taking medications or other treatments)	YES ☐ NO ☐
7b.	Has your doctor ever said your blood oxygen level is low at rest or during exercise and/or that you require supplemental oxygen therapy?	YES ☐ NO ☐
7c.	If asthmatic, do you currently have symptoms of chest tightness, wheezing, laboured breathing, consistent cough (more than 2 days/week), or have you used your rescue medication more than twice in the last week?	YES ☐ NO ☐
7d.	Has your doctor ever said you have high blood pressure in the blood vessels of your lungs?	YES ☐ NO ☐

8. Do you have a Spinal Cord Injury? This includes Tetraplegia and Paraplegia

If the above condition(s) is/are present, answer questions 8a-8c If **NO** ☐ go to question 9

8a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer **NO** if you are not currently taking medications or other treatments)	YES ☐ NO ☐
8b.	Do you commonly exhibit low resting blood pressure significant enough to cause dizziness, light-headedness, and/or fainting?	YES ☐ NO ☐
8c.	Has your physician indicated that you exhibit sudden bouts of high blood pressure (known as Autonomic Dysreflexia)?	YES ☐ NO ☐

9. Have you had a Stroke? This includes Transient Ischemic Attack (TIA) or Cerebrovascular Event

If the above condition(s) is/are present, answer questions 9a-9c If **NO** ☐ go to question 10

9a.	Do you have difficulty controlling your condition with medications or other physician-prescribed therapies? (Answer **NO** if you are not currently taking medications or other treatments)	YES ☐ NO ☐
9b.	Do you have any impairment in walking or mobility?	YES ☐ NO ☐
9c.	Have you experienced a stroke or impairment in nerves or muscles in the past 6 months?	YES ☐ NO ☐

10. Do you have any other medical condition not listed above or do you have two or more medical conditions?

If you have other medical conditions, answer questions 10a-10c If **NO** ☐ read the Page 4 recommendations

10a.	Have you experienced a blackout, fainted, or lost consciousness as a result of a head injury within the last 12 months **OR** have you had a diagnosed concussion within the last 12 months?	YES ☐ NO ☐
10b.	Do you have a medical condition that is not listed (such as epilepsy, neurological conditions, kidney problems)?	YES ☐ NO ☐
10c.	Do you currently live with two or more medical conditions?	YES ☐ NO ☐

PLEASE LIST YOUR MEDICAL CONDITION(S) AND ANY RELATED MEDICATIONS HERE: _____

GO to Page 4 for recommendations about your current medical condition(s) and sign the PARTICIPANT DECLARATION.

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If you answered NO to all of the FOLLOW-UP questions (pgs. 2-3) about your medical condition, you are ready to become more physically active - sign the PARTICIPANT DECLARATION below:

- It is advised that you consult a qualified exercise professional to help you develop a safe and effective physical activity plan to meet your health needs.
- You are encouraged to start slowly and build up gradually - 20 to 60 minutes of low to moderate intensity exercise, 3-5 days per week including aerobic and muscle strengthening exercises.
- As you progress, you should aim to accumulate 150 minutes or more of moderate intensity physical activity per week.
- If you are over the age of 45 yr and **NOT** accustomed to regular vigorous to maximal effort exercise, consult a qualified exercise professional before engaging in this intensity of exercise.

If you answered **YES** to **one or more of the follow-up questions** about your medical condition:

You should seek further information before becoming more physically active or engaging in a fitness appraisal. You should complete the specially designed online screening and exercise recommendations program - the **ePARmed-X+ at www.eparmedx.com** and/or visit a qualified exercise professional to work through the ePARmed-X+ and for further information.

Delay becoming more active if:

- You have a temporary illness such as a cold or fever; it is best to wait until you feel better.
- You are pregnant - talk to your health care practitioner, your physician, a qualified exercise professional, and/or complete the ePARmed-X+ **at www.eparmedx.com** before becoming more physically active.
- Your health changes - talk to your doctor or qualified exercise professional before continuing with any physical activity program.

- You are encouraged to photocopy the PAR-Q+. You must use the entire questionnaire and NO changes are permitted.
- The authors, the PAR-Q+ Collaboration, partner organizations, and their agents assume no liability for persons who undertake physical activity and/or make use of the PAR-Q+ or ePARmed-X+. If in doubt after completing the questionnaire, consult your doctor prior to physical activity.

PARTICIPANT DECLARATION

- All persons who have completed the PAR-Q+ please read and sign the declaration below.
- If you are less than the legal age required for consent or require the assent of a care provider, your parent, guardian or care provider must also sign this form.

I, the undersigned, have read, understood to my full satisfaction and completed this questionnaire. I acknowledge that this physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if my condition changes. I also acknowledge that the community/fitness center may retain a copy of this form for records. In these instances, it will maintain the confidentiality of the same, complying with applicable law.

NAME _____ DATE _____

SIGNATURE _____ WITNESS _____

SIGNATURE OF PARENT/GUARDIAN/CARE PROVIDER _____

For more information, please contact
www.eparmedx.com
Email: eparmedx@gmail.com

Citation for PAR-Q+
Warburton DER, Jamnik VK, Bredin SSD, and Gledhill N on behalf of the PAR-Q+ Collaboration. The Physical Activity Readiness Questionnaire for Everyone (PAR-Q+) and Electronic Physical Activity Readiness Medical Examination (ePARmed-X+). Health & Fitness Journal of Canada 4(2):3-23, 2011.

The PAR-Q+ was created using the evidence-based AGREE process (1) by the PAR-Q+ Collaboration chaired by Dr. Darren E. R. Warburton with Dr. Norman Gledhill, Dr. Veronica Jamnik, and Dr. Donald C. McKenzie (2). Production of this document has been made possible through financial contributions from the Public Health Agency of Canada and the BC Ministry of Health Services. The views expressed herein do not necessarily represent the views of the Public Health Agency of Canada or the BC Ministry of Health Services.

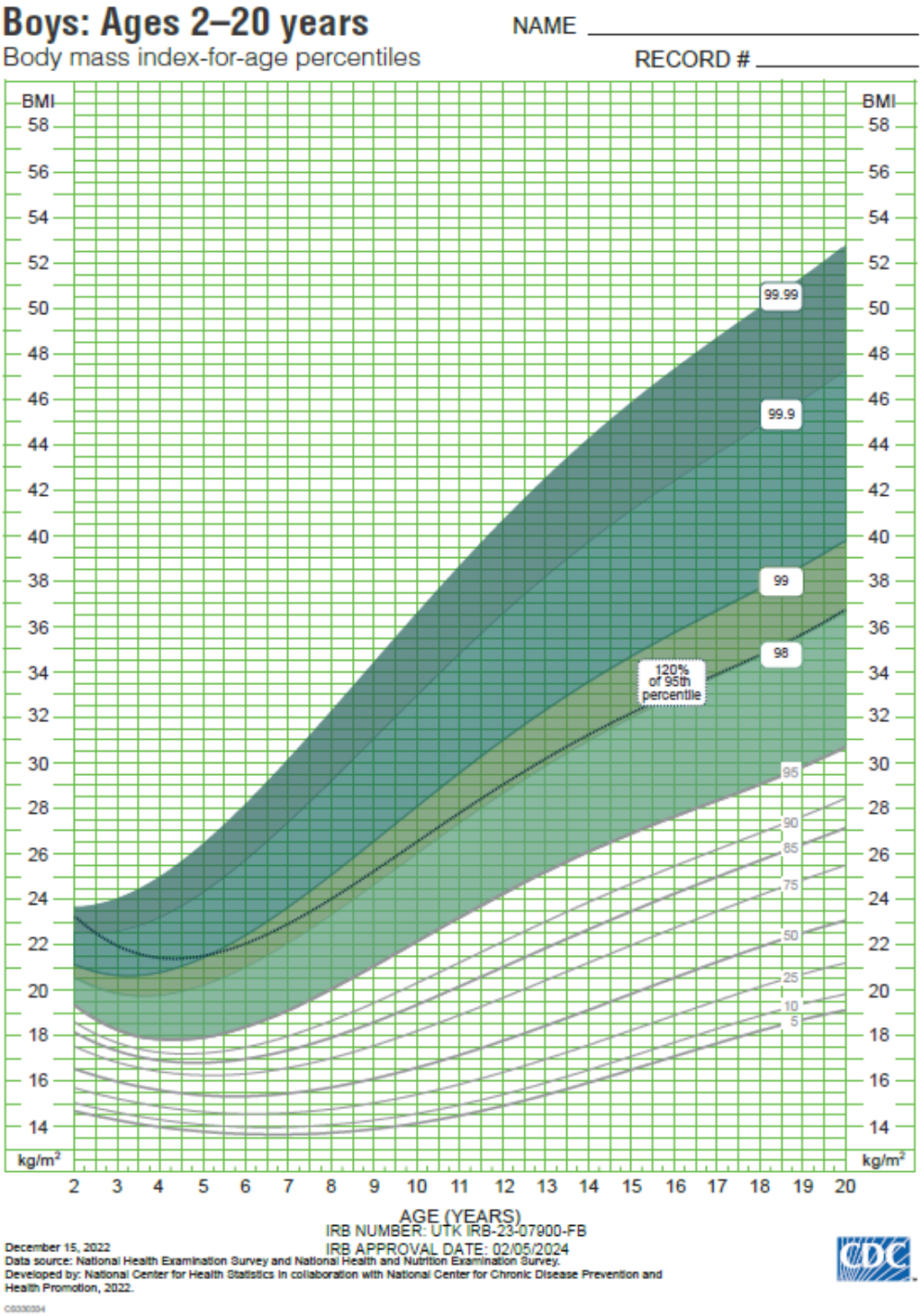
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1. Jamnik VK, Warburton DER, Makarski J, McKenzie DC, Shephard RJ, Stone J, and Gledhill N. Enhancing the effectiveness of clearance for physical activity participation: background and overall process. APNM 36(S1):S3-S13, 2011.
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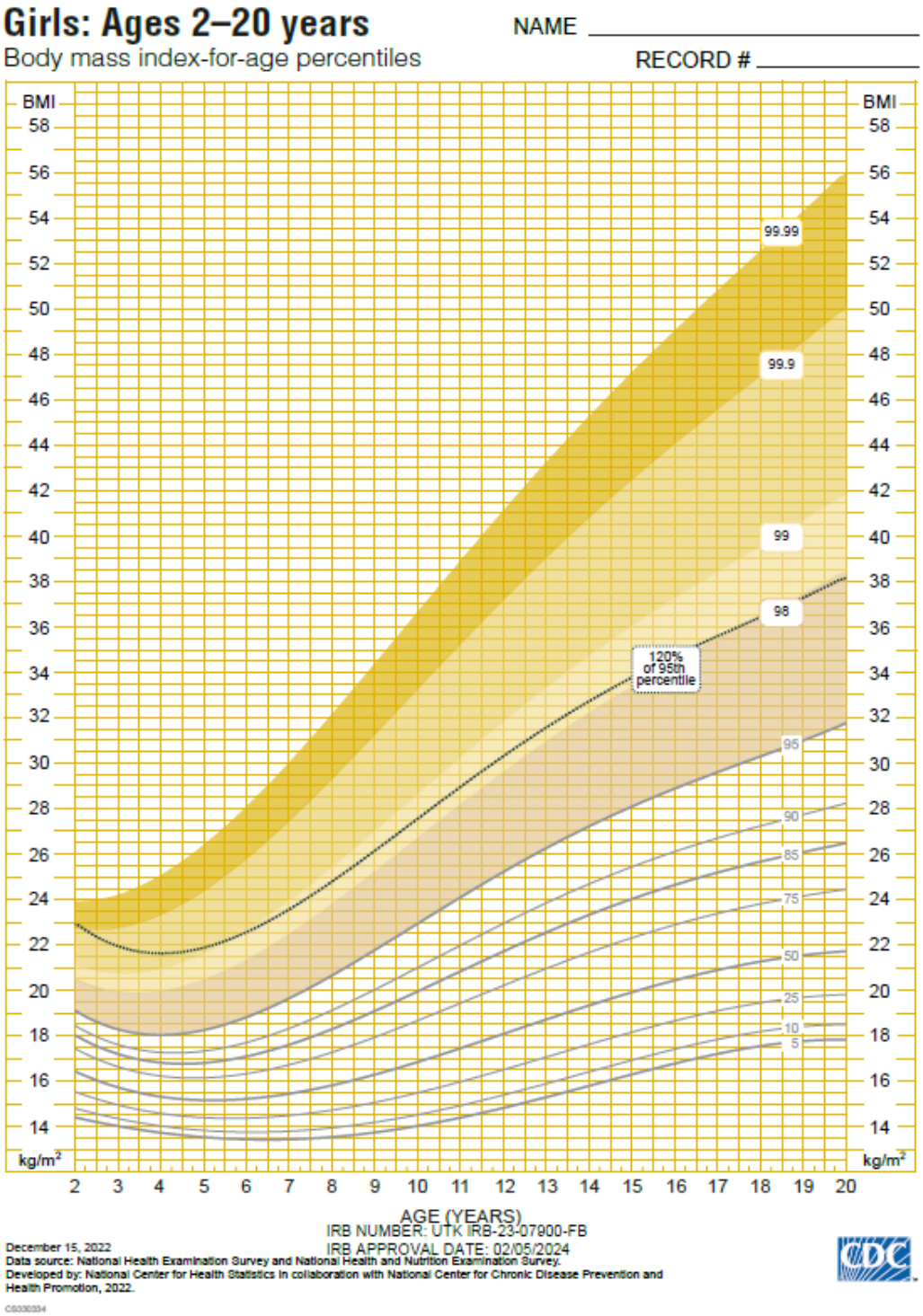
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Appendix M: Body Mass Index for age Percentiles - Male



Appendix N: Body Mass Index for age Percentiles - Female



Appendix O: Physician Recruitment Script

There is a group of researchers from the University of Tennessee that are conducting a study looking at the possible relationship between difficulties with cycling and walking in individuals with cerebral palsy. You may be a good candidate for the study. Your participation or non-participation in the study will not affect your care here. Here is a flyer with more information and contact information for the researchers.

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Appendix P: Gross Motor Classification System

CanChild Centre for Childhood Disability Research
Institute for Applied Health Sciences, McMaster University,
1400 Main Street West, Room 408, Hamilton, ON, Canada L8S 1C7
Tel: 905-525-9140 ext. 27850 Fax: 905-522-6095
E-mail: canchild@mcmaster.ca Website: www.canchild.ca

GMFCS – E & R
Gross Motor Function Classification System
Expanded and Revised

GMFCS - E & R © Robert Palisano, Peter Rosenbaum, Doreen Bartlett, Michael Livingston, 2007
CanChild Centre for Childhood Disability Research, McMaster University

GMFCS © Robert Palisano, Peter Rosenbaum, Stephen Walter, Dianne Russell, Ellen Wood, Barbara Galuppi, 1997
CanChild Centre for Childhood Disability Research, McMaster University
(Reference: Dev Med Child Neurol 1997;39:214-223)

INTRODUCTION & USER INSTRUCTIONS

The Gross Motor Function Classification System (GMFCS) for cerebral palsy is based on self-initiated movement, with emphasis on sitting, transfers, and mobility. When defining a five-level classification system, our primary criterion has been that the distinctions between levels must be meaningful in daily life. Distinctions are based on functional limitations, the need for hand-held mobility devices (such as walkers, crutches, or canes) or wheeled mobility, and to a much lesser extent, quality of movement. The distinctions between Levels I and II are not as pronounced as the distinctions between the other levels, particularly for infants less than 2 years of age.

The expanded GMFCS (2007) includes an age band for youth 12 to 18 years of age and emphasizes the concepts inherent in the World Health Organization's International Classification of Functioning, Disability and Health (ICF). We encourage users to be aware of the impact that **environmental** and **personal** factors may have on what children and youth are observed or reported to do. The focus of the GMFCS is on determining which level best represents the **child's or youth's present abilities and limitations in gross motor function**. Emphasis is on usual **performance** in home, school, and community settings (i.e., what they do), rather than what they are known to be able to do at their best (capability). It is therefore important to classify current performance in gross motor function and not to include judgments about the quality of movement or prognosis for improvement.

The title for each level is the method of mobility that is most characteristic of performance after 6 years of age. The descriptions of functional abilities and limitations for each age band are broad and are not intended to describe all aspects of the function of individual children/youth. For example, an infant with hemiplegia who is unable to crawl on his or her hands and knees, but otherwise fits the description of Level I (i.e., can pull to stand and walk), would be classified in Level I. The scale is ordinal, with no intent that the distances between levels be considered equal or that children and youth with cerebral palsy are equally distributed across the five levels. A summary of the distinctions between each pair of levels is provided to assist in determining the level that most closely resembles a child's/youth's current gross motor function.

We recognize that the manifestations of gross motor function are dependent on age, especially during infancy and early childhood. For each level, separate descriptions are provided in several age bands. Children below age 2 should be considered at their corrected age if they were premature. The descriptions for the 6 to 12 year and 12 to18 year age bands reflect the potential impact of environment factors (e.g., distances in school and community) and personal factors (e.g., energy demands and social preferences) on methods of mobility.

An effort has been made to emphasize abilities rather than limitations. Thus, as a general principle, the gross motor function of children and youth who are able to perform the functions described in any particular level will probably be classified at or above that level of function. In contrast, the gross motor function of children and youth who cannot perform the functions of a particular level should be classified below that level of function.

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OPERATIONAL DEFINITIONS

Body support walker – A mobility device that supports the pelvis and trunk. The child/youth is physically positioned in the walker by another person.

Hand-held mobility device – Canes, crutches, and anterior and posterior walkers that do not support the trunk during walking.

Physical assistance – Another person manually assists the child/youth to move.

Powered mobility – The child/youth actively controls the joystick or electrical switch that enables independent mobility. The mobility base may be a wheelchair, scooter or other type of powered mobility device.

Self-propels manual wheelchair – The child/youth actively uses arms and hands or feet to propel the wheels and move.

Transported – A person manually pushes a mobility device (e.g., wheelchair, stroller, or pram) to move the child/youth from one place to another.

Walks – Unless otherwise specified indicates no physical assistance from another person or any use of a hand-held mobility device. An orthosis (i.e., brace or splint) may be worn.

Wheeled mobility – Refers to any type of device with wheels that enables movement (e.g., stroller, manual wheelchair, or powered wheelchair).

GENERAL HEADINGS FOR EACH LEVEL

LEVEL I	-	Walks without Limitations
LEVEL II	-	Walks with Limitations
LEVEL III	-	Walks Using a Hand-Held Mobility Device
LEVEL IV	-	Self-Mobility with Limitations; May Use Powered Mobility
LEVEL V	-	Transported in a Manual Wheelchair

DISTINCTIONS BETWEEN LEVELS

Distinctions Between Levels I and II - Compared with children and youth in Level I, children and youth in Level II have limitations walking long distances and balancing; may need a hand-held mobility device when first learning to walk; may use wheeled mobility when traveling long distances outdoors and in the community; require the use of a railing to walk up and down stairs; and are not as capable of running and jumping.

Distinctions Between Levels II and III - Children and youth in Level II are capable of walking without a hand-held mobility device after age 4 (although they may choose to use one at times). Children and youth in Level III need a hand-held mobility device to walk indoors and use wheeled mobility outdoors and in the community.

Distinctions Between Levels III and IV - Children and youth in Level III sit on their own or require at most limited external support to sit, are more independent in standing transfers, and walk with a hand-held mobility device. Children and youth in Level IV function in sitting (usually supported) but self-mobility is limited. Children and youth in Level IV are more likely to be transported in a manual wheelchair or use powered mobility.

Distinctions Between Levels IV and V - Children and youth in Level V have severe limitations in head and trunk control and require extensive assisted technology and physical assistance. Self-mobility is achieved only if the child/youth can learn how to operate a powered wheelchair.

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Gross Motor Function Classification System – Expanded and Revised (GMFCS – E & R)

BEFORE 2ND BIRTHDAY

LEVEL I: Infants move in and out of sitting and floor sit with both hands free to manipulate objects. Infants crawl on hands and knees, pull to stand and take steps holding on to furniture. Infants walk between 18 months and 2 years of age without the need for any assistive mobility device.

LEVEL II: Infants maintain floor sitting but may need to use their hands for support to maintain balance. Infants creep on their stomach or crawl on hands and knees. Infants may pull to stand and take steps holding on to furniture.

LEVEL III: Infants maintain floor sitting when the low back is supported. Infants roll and creep forward on their stomachs.

LEVEL IV: Infants have head control but trunk support is required for floor sitting. Infants can roll to supine and may roll to prone.

LEVEL V: Physical impairments limit voluntary control of movement. Infants are unable to maintain antigravity head and trunk postures in prone and sitting. Infants require adult assistance to roll.

BETWEEN 2ND AND 4TH BIRTHDAY

LEVEL I: Children floor sit with both hands free to manipulate objects. Movements in and out of floor sitting and standing are performed without adult assistance. Children walk as the preferred method of mobility without the need for any assistive mobility device.

LEVEL II: Children floor sit but may have difficulty with balance when both hands are free to manipulate objects. Movements in and out of sitting are performed without adult assistance. Children pull to stand on a stable surface. Children crawl on hands and knees with a reciprocal pattern, cruise holding onto furniture and walk using an assistive mobility device as preferred methods of mobility.

LEVEL III: Children maintain floor sitting often by "W-sitting" (sitting between flexed and internally rotated hips and knees) and may require adult assistance to assume sitting. Children creep on their stomach or crawl on hands and knees (often without reciprocal leg movements) as their primary methods of self-mobility. Children may pull to stand on a stable surface and cruise short distances. Children may walk short distances indoors using a hand-held mobility device (walker) and adult assistance for steering and turning.

LEVEL IV: Children floor sit when placed, but are unable to maintain alignment and balance without use of their hands for support. Children frequently require adaptive equipment for sitting and standing. Self-mobility for short distances (within a room) is achieved through rolling, creeping on stomach, or crawling on hands and knees without reciprocal leg movement.

LEVEL V: Physical impairments restrict voluntary control of movement and the ability to maintain antigravity head and trunk postures. All areas of motor function are limited. Functional limitations in sitting and standing are not fully compensated for through the use of adaptive equipment and assistive technology. At Level V, children have no means of independent movement and are transported. Some children achieve self-mobility using a powered wheelchair with extensive adaptations.

BETWEEN 4TH AND 6TH BIRTHDAY

LEVEL I: Children get into and out of, and sit in, a chair without the need for hand support. Children move from the floor and from chair sitting to standing without the need for objects for support. Children walk indoors and outdoors, and climb stairs. Emerging ability to run and jump.

LEVEL II: Children sit in a chair with both hands free to manipulate objects. Children move from the floor to standing and from chair sitting to standing but often require a stable surface to push or pull up on with their arms. Children walk without the need for a hand-held mobility device indoors and for short distances on level surfaces outdoors. Children climb stairs holding onto a railing but are unable to run or jump.

LEVEL III: Children sit on a regular chair but may require pelvic or trunk support to maximize hand function. Children move in and out of chair sitting using a stable surface to push on or pull up with their arms. Children walk with a hand-held mobility device on level surfaces and climb stairs with assistance from an adult. Children frequently are transported when traveling for long distances or outdoors on uneven terrain.

LEVEL IV: Children sit on a chair but need adaptive seating for trunk control and to maximize hand function. Children move in and out of chair sitting with assistance from an adult or a stable surface to push or pull up on with their arms. Children may at best walk short distances with a walker and adult supervision but have difficulty turning and maintaining balance on uneven surfaces. Children are transported in the community. Children may achieve self-mobility using a powered wheelchair.

LEVEL V: Physical impairments restrict voluntary control of movement and the ability to maintain antigravity head and trunk postures. All areas of motor function are limited. Functional limitations in sitting and standing are not fully compensated for through the use of adaptive equipment and assistive technology. At Level V, children have no means of independent movement and are transported. Some children achieve self-mobility using a powered wheelchair with extensive adaptations.

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BETWEEN 6TH AND 12TH BIRTHDAY

Level I: Children walk at home, school, outdoors, and in the community. Children are able to walk up and down curbs without physical assistance and stairs without the use of a railing. Children perform gross motor skills such as running and jumping but speed, balance, and coordination are limited. Children may participate in physical activities and sports depending on personal choices and environmental factors.

Level II: Children walk in most settings. Children may experience difficulty walking long distances and balancing on uneven terrain, inclines, in crowded areas, confined spaces or when carrying objects. Children walk up and down stairs holding onto a railing or with physical assistance if there is no railing. Outdoors and in the community, children may walk with physical assistance, a hand-held mobility device, or use wheeled mobility when traveling long distances. Children have at best only minimal ability to perform gross motor skills such as running and jumping. Limitations in performance of gross motor skills may necessitate adaptations to enable participation in physical activities and sports.

Level III: Children walk using a hand-held mobility device in most indoor settings. When seated, children may require a seat belt for pelvic alignment and balance. Sit-to-stand and floor-to-stand transfers require physical assistance of a person or support surface. When traveling long distances, children use some form of wheeled mobility. Children may walk up and down stairs holding onto a railing with supervision or physical assistance. Limitations in walking may necessitate adaptations to enable participation in physical activities and sports including self-propelling a manual wheelchair or powered mobility.

Level IV: Children use methods of mobility that require physical assistance or powered mobility in most settings. Children require adaptive seating for trunk and pelvic control and physical assistance for most transfers. At home, children use floor mobility (roll, creep, or crawl), walk short distances with physical assistance, or use powered mobility. When positioned, children may use a body support walker at home or school. At school, outdoors, and in the community, children are transported in a manual wheelchair or use powered mobility. Limitations in mobility necessitate adaptations to enable participation in physical activities and sports, including physical assistance and/or powered mobility.

Level V: Children are transported in a manual wheelchair in all settings. Children are limited in their ability to maintain antigravity head and trunk postures and control arm and leg movements. Assistive technology is used to improve head alignment, seating, standing, and and/or mobility but limitations are not fully compensated by equipment. Transfers require complete physical assistance of an adult. At home, children may move short distances on the floor or may be carried by an adult. Children may achieve self-mobility using powered mobility with extensive adaptations for seating and control access. Limitations in mobility necessitate adaptations to enable participation in physical activities and sports including physical assistance and using powered mobility.

BETWEEN 12TH AND 18TH BIRTHDAY

Level I: Youth walk at home, school, outdoors, and in the community. Youth are able to walk up and down curbs without physical assistance and stairs without the use of a railing. Youth perform gross motor skills such as running and jumping but speed, balance, and coordination are limited. Youth may participate in physical activities and sports depending on personal choices and environmental factors.

Level II: Youth walk in most settings. Environmental factors (such as uneven terrain, inclines, long distances, time demands, weather, and peer acceptability) and personal preference influence mobility choices. At school or work, youth may walk using a hand-held mobility device for safety. Outdoors and in the community, youth may use wheeled mobility when traveling long distances. Youth walk up and down stairs holding a railing or with physical assistance if there is no railing. Limitations in performance of gross motor skills may necessitate adaptations to enable participation in physical activities and sports.

Level III: Youth are capable of walking using a hand-held mobility device. Compared to individuals in other levels, youth in Level III demonstrate more variability in methods of mobility depending on physical ability and environmental and personal factors. When seated, youth may require a seat belt for pelvic alignment and balance. Sit-to-stand and floor-to-stand transfers require physical assistance from a person or support surface. At school, youth may self-propel a manual wheelchair or use powered mobility. Outdoors and in the community, youth are transported in a wheelchair or use powered mobility. Youth may walk up and down stairs holding onto a railing with supervision or physical assistance. Limitations in walking may necessitate adaptations to enable participation in physical activities and sports including self-propelling a manual wheelchair or powered mobility.

Level IV: Youth use wheeled mobility in most settings. Youth require adaptive seating for pelvic and trunk control. Physical assistance from 1 or 2 persons is required for transfers. Youth may support weight with their legs to assist with standing transfers. Indoors, youth may walk short distances with physical assistance, use wheeled mobility, or, when positioned, use a body support walker. Youth are physically capable of operating a powered wheelchair. When a powered wheelchair is not feasible or available, youth are transported in a manual wheelchair. Limitations in mobility necessitate adaptations to enable participation in physical activities and sports, including physical assistance and/or powered mobility.

Level V: Youth are transported in a manual wheelchair in all settings. Youth are limited in their ability to maintain antigravity head and trunk postures and control arm and leg movements. Assistive technology is used to improve head alignment, seating, standing, and mobility but limitations are not fully compensated by equipment. Physical assistance from 1 or 2 persons or a mechanical lift is required for transfers. Youth may achieve self-mobility using powered mobility with extensive adaptations for seating and control access. Limitations in mobility necessitate adaptations to enable participation in physical activities and sports including physical assistance and using powered mobility.

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Appendix Q: Recruitment E-Mail for Individuals with Cerebral Palsy

Hello,
My name is Sean, and I am a PhD candidate in Biomechanics in The Department of kinesiology, Recreation, and Sports Studies at The University of Tennessee. I am working with Dr. Songning Zhang on a study aimed at understanding the effects that changes to the length of one crankarm will have on cycling mobility and efficiency of individuals with cerebral palsy. We are reaching out to people within the cerebral palsy community to invite them to participate in the research study. We are seeking both typically developing individuals and individuals with cerebral palsy for a study looking at the possible relationship between difficulties with cycling and walking.
We are specifically seeking participants aged 10-30 with unilateral cerebral palsy to partake in a study that will examine walking and the effects of asymmetric cycling utilizing 3D motion capture.
Here's what participants can expect from the study:

- The study will last between 1.5 and 2 hours.
- Participants will engage in supervised cycling and walking.
- Participation will take place in our cutting-edge biomechanics laboratory.

To show our gratitude for your time and participation, you will receive a $40 gift card upon completion of the study session.
We are reaching out to see if you or someone you know might qualify for and be interested in participating in this study. Your support in spreading the word about our research would be invaluable.
If you are interested in participating or would like more information, please feel free to contact me at sbrow159@vols.utk.edu. We are happy to answer any questions you might have about the study, participation criteria, and scheduling.
Thank you for considering this opportunity to contribute to valuable research in the field of cerebral palsy.

Best regards,
Sean Brown
PhD Candidate
Department of Kinesiology, Recreation, and Sports Studies
University of Tennessee – Knoxville
Sbrow159@vols.utk.edu

Appendix R: Recruitment E-Mail for Typically Developing Individuals

Hello,
My name is Sean, and I am a PhD candidate in Biomechanics in The Department of kinesiology, Recreation, and Sports Studies at The University of Tennessee. I am working with Dr. Songning Zhang on a study aimed at understanding the effects that changes to the length of one crankarm will have on cycling mobility and efficiency of individuals with cerebral palsy. We require the help of typically developing individuals, aged 10-30, to serve as control participants. We are seeking both typically developing individuals and individuals with cerebral palsy for a study looking at the possible relationship between difficulties with cycling and walking.
This study provides an excellent opportunity for you to contribute to scientific research that could lead to a better understanding of movement patterns for individuals with cerebral palsy. By participating, you will help us establish important comparative data that is crucial for our analyses.
Here are some key points about the study:

- The study will last between 1.5 and 2 hours.
- Participants will engage in supervised cycling and walking.
- Participation will take place in our cutting-edge biomechanics laboratory.

To show our gratitude for your time and participation, you will receive a $40 gift card upon completion of the study session.
Your participation would be incredibly valuable to us, and we hope you consider joining. If you are interested in participating or know someone who fits the criteria and may be interested, please reach out to me at sbrow159@vols.utk.edu. We are more than happy to provide additional details about the study and address any questions or concerns you may have.
Thank you for your time and for considering being a part of this significant research endeavor. We look forward to the possibility of your participation.

Best regards,
Sean Brown
PhD Candidate
Department of Kinesiology, Recreation, and Sports Studies
University of Tennessee – Knoxville
Sbrow159@vols.utk.edu

Appendix S: Inclusion Criteria for Individuals with Cerebral Palsy

Subject: Invitation to Participate in a Research Study on Cycling Mobility and Efficiency

Dear [Participant's Name],

Thank you for expressing interest in our research study focused on understanding the effects of cycling mobility and efficiency in individuals with cerebral palsy. Your participation could provide valuable insights into this important area of study.

Before we proceed, it is essential for us to conduct a brief screening to ensure the safety and relevance of the study for each participant. We assure you that all your responses will be kept confidential. Below are a series of questions that form part of our inclusion and exclusion criteria for the study:

Important Notice for Participants Under 18:

If you are under the age of 18, it is necessary for you to discuss your participation in this study with a parent or guardian. Please ensure that you have their consent before proceeding with the following screening questions.

Inclusion Criteria Questions:

1. Age: May we know your age? We are looking for participants aged 10 to 30.
2. Diagnosis: Do you have a diagnosis of cerebral palsy?
3. Mobility: Are you able to walk without assistive devices?
4. Stair Mobility: Are you able to walk up a flight of stairs without using a handrail?

Exclusion Criteria Questions:

1. Could you please provide your approximate weight and height?
2. Orthopedic Surgery: Have you undergone orthopedic surgery on your legs in the past 12 months?
3. Recent Injuries: Have you had any injuries to your legs in the past 6 months?
4. Medications: Have you taken baclofen in the past 10 weeks?
5. Botox Injections: Have you had Botox injections in your legs in the past 10 weeks?
6. Health Conditions: Do you have any neurological or cardiovascular conditions that prevent walking or cycling?
7. Pregnancy/Nursing Status: Are you currently pregnant or nursing?

Please fill out the attached PAR-Q+ form to assess physical activity readiness.

We appreciate you taking the time to answer these questions. Feel free to reach out if you have any questions or need further clarification.

Based on your responses, we will either proceed with scheduling the next steps of your participation or inform you if unfortunately, you do not meet our criteria for this study. Your time and interest in our research are highly valued.

Thank you once again for considering participation in our study. We look forward to your response.

Best regards,

Sean Brown
PhD Candidate
Department of Kinesiology, Recreation, and Sports Studies

Appendix T: Inclusion Criteria for Typically Developing Individuals

Subject: Invitation to Participate in a Research Study on Cycling Mobility and Efficiency
Dear [Participant's Name],
Thank you for expressing interest in our research study focused on understanding the effects of cycling mobility and efficiency in individuals with cerebral palsy. Your participation could provide valuable insights into this important area of study.
Before we proceed, it is essential for us to conduct a brief screening to ensure the safety and relevance of the study for each participant. We assure you that all your responses will be kept confidential. Below are a series of questions that form part of our inclusion and exclusion criteria for the study:
Important Notice for Participants Under 18:
If you are under the age of 18, it is necessary for you to discuss your participation in this study with a parent or guardian. Please ensure that you have their consent before proceeding with the following screening questions.
Inclusion Criteria Questions:

1. Age: May we know your age? We are looking for participants aged 10 to 30.
2. Physical Activity: Would you describe yourself as recreationally active, engaging in at least 30 minutes of exercise at least two days a week?

Exclusion Criteria Questions:

1. Could you please provide your approximate weight and height?
2. Orthopedic Surgery: Have you undergone orthopedic surgery on your legs in the past 12 months?
3. Recent Injuries: Have you had any injuries to your legs in the past 6 months?
4. Health Conditions: Do you have any neurological or cardiovascular conditions that prevent walking or cycling?
5. Pregnancy/Nursing Status: Are you currently pregnant or nursing?

Please fill out the attached PAR-Q+ form to assess physical activity readiness.
We appreciate you taking the time to answer these questions. Feel free to reach out if you have any questions or need further clarification.
Based on your responses, we will either proceed with scheduling the next steps of your participation or inform you if unfortunately, you do not meet our criteria for this study.
Your time and interest in our research are highly valued.
Thank you once again for considering participation in our study. We look forward to your response.

Best regards,
Sean Brown
PhD Candidate
Department of Kinesiology, Recreation, and Sports Studies
University of Tennessee – Knoxville

Appendix U: Inclusion Criteria Phone Script for Individuals with Cerebral Palsy

Script for Individuals with Cerebral Palsy (CP)

Introduction:
"Hello, thank you for your interest in our study on cycling mobility and efficiency in individuals with cerebral palsy. To ensure participant safety and relevance, we have a few screening questions. Your responses will remain confidential. Before we continue, if you are under 18 years of age, please have a parent or guardian present during this call, or ensure you have their permission to proceed."

Inclusion Criteria Questions:
"May I ask your age? (We are looking for participants aged 10 to 30.)"
"Do you have a diagnosis of cerebral palsy?"
"Are you able to walk without assistive devices? (Unable to walk without assistive devices indicates they are a GMFCS level III and do not meet the criteria for the study.)"
"Are you able to walk up a flight of stairs without using a handrail? (If yes, they are likely a GMCS level I. If no, they are likely a GMFCS level II.)"

Exclusion Criteria Questions:
"What is your approximate weight? What is your approximate height? (Calculate BMI. If greater than 30, they are excluded.)"
If yes to any of the following they are excluded:
"Have you undergone orthopedic surgery on your legs in the past 12 months?"
"Have you had any injuries to your legs in the past 6 months?"
"Have you taken baclofen in the past 10 weeks?"
"Have you had Botox injections in your legs in the past 10 weeks?"
"Do you have any neurological or cardiovascular conditions that prevent walking or cycling?"
"Are you currently pregnant or nursing?"

Physical activity readiness:
Ask questions on the PAR-Q+

Closure:
"Thank you for your responses. Do you have any questions for me?”
“Based on your answers, [we will proceed with scheduling if you are interested / unfortunately, you do not meet our criteria for this study]. We appreciate your time."

Appendix V: Inclusion Criteria Phone Script for Typically Developing Individuals

Script for Typically Developing Healthy Individuals (TD)

Introduction:
"Hello, thank you for your interest in our study on cycling mobility and efficiency in individuals with cerebral palsy. To ensure participant safety and relevance, we have a few screening questions. Your responses will remain confidential. Before we continue, if you are under 18 years of age, please have a parent or guardian present during this call, or ensure you have their permission to proceed."

Inclusion Criteria Questions:
"May I ask your age? (We are looking for participants aged 10 to 30.)"
"Would you describe yourself as recreationally active, such as engaging in at least 30 minutes of exercise at least two days a week?"

Exclusion Criteria Questions:
"What is your approximate weight? What is your approximate height? (Calculate BMI. If greater than 30, they are excluded.)"
If yes to any of the following they are excluded:
"Have you undergone orthopedic surgery on your legs in the past 12 months?"
"Have you had any injuries to your legs in the past 6 months?"
"Do you have any neurological or cardiovascular conditions that prevent walking or cycling?"
"Are you currently pregnant or nursing?"

Physical activity readiness:
Ask questions on the PAR-Q+

Closure:
"Thank you for your responses. Do you have any questions for me?"
"Based on your answers, [we will proceed with scheduling if you are interested / unfortunately, you do not meet our criteria for this study]. We appreciate your time."

Appendix W: Gillette Functional Assessment Questionnaire

Choose the **one** answer below that best describes your (or your child's) typical walking ability

(with the use of any needed assistive devices)

____ 1. Cannot take any steps at all.
____ 2. Can do some stepping on your (their) own with the help of another person. Does not take full weight on feet; does not walk on a routine basis.
____ 3. Walks for exercise in therapy and less than typical household distances. Usually requires assistance from another person.
____ 4. Walks for household distances but makes slow progress. Does not use walking at home as preferred mobility (primarily walks in therapy)
____ 5. Walks more than 15-50 feet but only inside at home or school (walks for household distances)
____ 6. Walks more than 15-50 feet but only outside the home, but usually uses a wheelchair or stroller for community distances or in congested areas.
____ 7. Walks outside the home for community distances, but only on level surfaces (cannot perform curbs, uneven terrain, or stairs without assistance from another person.
____ 8. Walks outside the home for community distances, is able to perform curbs and uneven terrain in addition to level surfaces, but usually requires minimal assistance or supervision for safety.
____ 9. Walks outside the home for community distances, easily gets around on level ground, curbs, and uneven terrain, but has difficulty or requires minimal assistance with running, climbing, and/or stairs.
____ 10. Walks, runs, and climbs on level and uneven terrain without difficulty or assistance.

Appendix X: Participant Demographics

Typically Developing Participant Demographics

Participant	Sex	Age (years)	Height (cm)	Mass (kg)	BMI (kg/m^2)
S101	F	19	164.5	49.5	18.3
S102	F	20	175.9	81.4	26.3
S103	F	11	164.5	49.5	18.3
S104	F	25	165.1	49.2	18.0
S105	F	21	163.8	71.5	26.6
S106	F	20	177.8	54.2	17.1
S107	F	16	166.4	58.7	21.2
S108	M	16	168.9	56.4	19.8
S109	F	16	162.6	51.1	19.3
S110	M	16	179.7	80.2	24.8
S111	F	15	167.0	60.9	21.8
S112	F	18	167.6	71.2	25.3
S113	F	21	163.8	77.8	29.0

Participants with Cerebral Palsy Demographics

Participant	Sex	Age (years)	Height (cm)	Mass (kg)	BMI (kg/m^2)	Affected Limb	GMFCS	FAQ	FMS 5	FMS 50	FMS 500
S201	F	21	164.5	58.4	21.6	R	I	10	6	6	6
S202	F	23	165.1	74.1	27.2	L	I	10	6	6	6

Appendix Y: Clinical Exam for Participant with Cerebral Palsy 1

Trunk						
Abdominal Strength		5				
HIP				Selective Control (SCALE)		
		Left	Right		Left	Right
ROM	Flexion	140	145	Hip	2	2
	Extension	0	0	Knee	2	2
	Abduction	35	35	Ankle	2	2
	Adduction	30	30	Subtalar	2	2
	Internal Rotation	40	40	Toes	2	0
	External Rotation	45	30	Total	10	8
Rotation	Femoral Anteversion	0	0			
Strength	Flexion	5	5			
	Extension	5	5			
	Abduction	5	5			
	Adduction	5	5			
Knee						
		Left	Right			
ROM	Flexion	140	145			
	Flexion (R1)	-	-			
	Flexion (R2)	-	-			
	Extension	10	0			
	Extensor Lag	0	0			
	Straight Leg Raise	75	70			
	Popliteal Angle	20	45			
Strength	Flexion	5	5			
	Extension	5	5			
Ankle						
		Left	Right			
ROM	Plantarflexion	40	45			
	Dorsiflexion w/ Ext	20	-5			
	Dorsiflexion w/ Flex	25	5			
Strength	Plantarflexion	5	3			
	Dorsiflexion	5	4			
	Inversion	5	4			
	Eversion	5	3			

Appendix Z: Clinical Exam for Participant with Cerebral Palsy 2

Trunk						
Abdominal Strength		5				
HIP				Selective Control (SCALE)		
		Left	Right		Left	Right
ROM	Flexion	140	145	Hip	2	2
	Extension	0	0	Knee	2	2
	Abduction	35	35	Ankle	1	2
	Adduction	25	30	Subtalar	1	2
	Internal Rotation	50	40	Toes	1	2
	External Rotation	30	35	Total	7	10
Rotation	Femoral Anteversion	0	0			
Strength	Flexion	4	5			
	Extension	5	5			
	Abduction	5	5			
	Adduction	5	5			
Knee						
		Left	Right			
ROM	Flexion	150	145			
	Flexion (R1)	-	-			
	Flexion (R2)	-	-			
	Extension	0	10			
	Extensor Lag	10	0			
	Straight Leg Raise	60	75			
	Popliteal Angle	40	20			
Strength	Flexion	5	5			
	Extension	5	5			
Ankle						
		Left	Right			
ROM	Plantarflexion	40	35			
	Dorsiflexion w/ Ext	-10	10			
	Dorsiflexion w/ Flex	-5	25			
Strength	Plantarflexion	3	5			
	Dorsiflexion	5	5			
	Inversion	4	5			
	Eversion	2	5			

Appendix AA: Representative Trial: Self-Selected Slow Walk

Root mean square difference from the average of all trials: Right (°)

Subject	Trial_1	Trial_2	Trial_3	Trial_4	Trial_5	Best_Trial
S101	2.0318	1.6687	1.6156	1.5643	1.0883	5
S102	1.3792	0.9954	1.1419	1.0745	1.3894	2
S103	2.0485	1.5479	1.5784	1.5793	1.7573	2
S104	1.6129	1.2951	1.0690	1.1259	1.0637	5
S105	2.7757	1.0125	2.0322	1.3804	1.6480	2
S106	1.8212	1.6912	1.1675	1.4070	1.4697	3
S107	1.1184	1.2834	2.2300	1.1720	1.5504	1
S108	1.8684	2.5822	1.5799	1.3769	2.1013	4
S109	2.7446	2.3390	2.6957	2.7783	2.8532	2
S110	2.1106	1.7243	1.4834	1.3285	1.2939	5
S111	1.3251	1.4016	0.9989	1.0611	1.2184	3
S112	1.5329	1.1550	1.1815	1.4039	1.2264	2
S113	1.5290	1.1514	1.1375	1.1986	0.9506	5
S201	1.5174	1.8935	1.5145	1.5366	1.5767	3
S202	1.6194	1.2676	1.8335	1.2731	1.1101	5

Root mean square difference from the average of all trials: Left (°)

Subject	Trial_1	Trial_2	Trial_3	Trial_4	Trial_5	Best_Trial
S101	1.6657	1.2498	1.0139	1.3839	0.9780	5
S102	1.5600	1.2266	0.7744	1.3998	1.1695	3
S103	1.9348	1.6759	1.6564	1.4823	1.3834	5
S104	1.2876	1.2421	1.2599	1.1383	0.9148	5
S105	2.1686	1.0238	1.3033	1.6126	1.9550	2
S106	1.5486	1.4609	1.4676	1.1775	1.3267	4
S107	1.4210	1.1667	1.5297	1.0527	1.4706	4
S108	1.7356	1.5559	1.9332	2.3492	1.7495	2
S109	2.0571	1.9936	2.1805	1.8149	2.4208	4
S110	1.7657	1.4829	1.3633	1.2880	1.3515	4
S111	1.3023	1.1824	1.4459	1.8383	1.3057	2
S112	1.4526	1.1333	0.9996	1.6502	0.9434	5
S113	1.6662	1.3549	1.3416	1.4693	1.0412	5
S201	1.6890	1.6754	1.5588	1.7418	1.4442	5
S202	1.4433	1.8560	1.3173	0.9511	1.4237	4

Appendix BB: Representative Trial: Self-Selected Fast Walk

Root mean square difference from the average of all trials: Right (°)

Subject	Trial_1	Trial_2	Trial_3	Trial_4	Trial_5	Best_Trial
S101	1.6449	1.3527	1.2211	1.3133	1.5081	3
S102	2.0866	2.2530	2.0051	1.8994	1.8368	5
S103	2.7288	4.5264	3.5312	3.2676	5.2012	1
S104	1.8491	1.4679	1.6921	1.6896	1.8687	2
S105	1.2774	1.4893	1.4404	2.4275	1.7515	1
S106	1.6648	2.5765	1.5920	1.5204	1.6254	4
S107	1.1663	1.6267	1.0425	1.5854	2.2049	3
S108	1.7472	2.2259	1.6250	1.8728	2.0878	3
S109	1.5468	1.3085	1.4780	1.8825	1.3988	2
S110	1.8796	1.7230	2.1170	-	2.4448	2
S111	1.8095	1.5048	1.6170	1.4785	1.4793	4
S112	1.6521	1.8068	1.6502	1.6770	1.4303	5
S113	1.6141	1.3098	1.1647	1.2840	1.5144	3
S201	1.9950	1.6057	1.1554	2.2647	2.3426	3
S202	1.7359	1.5093	1.4721	1.1855	1.5704	4

Root mean square difference from the average of all trials: Left (°)

Subject	Trial_1	Trial_2	Trial_3	Trial_4	Trial_5	Best_Trial
S101	1.4912	1.5559	1.1148	1.1325	1.3759	3
S102	2.3234	2.0653	2.4156	2.8479	2.4322	2
S103	2.5072	4.8907	2.5167	3.2140	5.9309	1
S104	1.8632	1.8051	1.9422	1.6563	1.7099	4
S105	1.2064	1.5574	1.4515	2.7537	1.4857	1
S106	1.4624	1.7758	1.4487	1.9066	1.3374	5
S107	1.3030	1.5798	1.1065	1.5757	2.2155	3
S108	2.5348	2.0278	1.7659	1.7792	1.4872	5
S109	1.7788	1.8455	1.3908	1.8191	1.4255	3
S110	1.9947	2.4574	1.5827	-	1.4484	5
S111	1.7147	1.6481	1.5166	1.6681	1.4548	5
S112	1.5954	2.1069	1.4327	1.1924	1.2387	4
S113	1.2911	1.4866	1.2663	1.8341	1.5738	3
S201	1.9630	1.1371	1.2663	2.1706	1.7928	2
S202	1.2190	1.6313	1.2642	1.0378	1.6649	4

Appendix CC: Representative Trial: Self-Selected Slow Cycle: Both 170mm Crank Arms

Root mean square difference from the average of all trials: Unchanged length side (°)

Subject	Trial_1	Trial_2	Trial_3	Trial_4	Trial_5	Best_Trial
S101	0.9528	0.7998	0.6147	0.8241	1.5069	3
S102	0.6633	0.7670	1.0652	0.9091	1.2642	1
S103	4.9368	3.4680	5.3136	4.7665	12.0164	2
S104	1.4282	1.3607	1.3714	1.1997	1.2962	4
S105	1.3223	1.1495	1.0531	1.0216	1.1902	4
S106	1.3444	1.3026	0.8042	1.5414	1.1973	3
S107	0.9629	1.7430	2.9349	1.5332	1.4137	1
S108	2.6856	1.5384	2.1996	2.0831	2.0060	2
S109	1.9494	1.4126	1.5141	1.6915	3.2918	2
S110	1.2856	1.4661	0.9692	0.9556	0.8520	5
S111	0.5870	1.3176	1.3578	1.4479	1.0666	1
S112	0.7271	1.1623	0.9811	0.9513	-	1
S113	1.7163	1.4086	1.3718	1.4183	3.0688	3
S201	1.6569	1.0295	1.5281	1.5820	-	2
S202	1.8443	1.5302	1.4863	0.8255	1.2227	4

Root mean square difference from the average of all trials: Changed length side (°)

Subject	Trial_1	Trial_2	Trial_3	Trial_4	Trial_5	Best_Trial
S101	0.8964	0.8194	1.0554	0.5522	1.1458	4
S102	0.8315	0.4706	0.6996	0.5031	0.7873	2
S103	5.2265	5.9086	7.4404	7.0327	11.7289	1
S104	1.4065	1.2088	1.2226	1.4781	1.2591	2
S105	1.3483	1.0583	0.9085	0.7058	1.1474	4
S106	1.1099	1.4545	0.7631	1.3014	1.9151	3
S107	1.3838	1.4387	1.5191	2.0713	1.4228	1
S108	2.5359	1.8355	1.2739	2.2935	2.5243	3
S109	1.6211	1.3545	1.1283	1.5274	2.5928	3
S110	0.9654	1.3248	1.2710	1.1766	0.6563	5
S111	0.8124	0.9718	1.3429	1.2406	1.6639	1
S112	1.2146	0.9354	0.7906	0.9676	0.9847	3
S113	1.5272	1.4302	1.5483	1.0226	2.9741	4
S201	1.3151	1.4770	1.1766	1.2677	1.7693	3
S202	0.8598	1.4620	0.9058	1.1183	1.0282	1

Appendix DD: Representative Trial: Self-Selected Fast Cycle: Both 170mm Crank Arms

Root mean square difference from the average of all trials: Unchanged length side (°)

Subject	Trial_1	Trial_2	Trial_3	Trial_4	Trial_5	Best_Trial
S101	0.8400	1.0288	0.8804	0.7131	0.9654	4
S102	1.3676	1.0479	0.8283	1.2176	1.4592	3
S103	3.5051	2.5051	2.3406	2.2325	3.2662	4
S104	0.8643	0.4737	0.5230	0.8361	0.6704	2
S105	0.5865	0.7395	0.8826	0.7204	0.7062	1
S106	0.7100	0.6355	0.7889	0.7488	0.6977	2
S107	0.8963	0.6657	0.9145	1.2095	1.0317	2
S108	1.4569	1.6426	0.9080	1.4371	2.1907	3
S109	1.0807	0.7853	0.7358	0.8707	0.9655	3
S110	2.8779	1.7305	2.4433	1.4455	1.6321	4
S111	1.5694	0.8894	1.0476	1.4585	1.2391	2
S112	0.8334	1.0338	0.8483	0.8614	1.0672	1
S113	0.8660	0.6043	0.4983	0.7283	0.8940	3
S201	1.3687	1.0343	1.0051	0.9481	1.2102	4
S202	0.5216	0.5317	0.6540	0.7134	0.7663	1

Root mean square difference from the average of all trials: Changed length side (°)

Subject	Trial_1	Trial_2	Trial_3	Trial_4	Trial_5	Best_Trial
S101	1.3162	1.0106	0.8768	1.0602	1.1187	3
S102	1.0657	1.3198	0.6514	0.9999	1.0771	3
S103	1.8958	3.1878	2.1500	2.3026	1.7808	5
S104	0.5108	0.6323	0.6178	0.6521	0.5287	1
S105	0.6641	0.8367	0.7046	0.5175	0.6871	4
S106	0.8122	0.7371	0.6414	0.8949	0.7917	3
S107	0.9369	0.7232	0.9567	1.3513	1.8807	2
S108	1.6787	1.4584	0.9158	1.2004	2.0976	3
S109	1.3815	0.6412	0.8826	0.7035	1.4488	2
S110	2.1718	2.4139	2.1515	2.0558	1.3943	5
S111	1.6912	0.7891	0.7789	1.2482	1.3113	3
S112	1.0516	0.6959	0.9284	0.6777	1.3114	4
S113	0.8469	0.7319	0.5317	0.7569	0.9933	3
S201	0.9623	1.0474	0.8920	0.8726	1.1585	4
S202	0.5386	0.4430	0.7124	0.5532	0.7948	2

Appendix EE: Representative Trial: Self-Selected Slow Cycle: 170mm and 150mm Crank Arms

Root mean square difference from the average of all trials: 170 mm Side (°)

Subject	Trial_1	Trial_2	Trial_3	Trial_4	Trial_5	Best_Trial
S101	1.8088	0.7885	1.2880	1.2362	1.2514	2
S102	0.8308	0.7002	0.8409	1.0219	0.7271	2
S103	2.6798	2.1703	2.4028	2.4715	2.2098	2
S104	1.1721	0.8557	0.7781	0.9921	0.9958	3
S105	1.0565	0.9174	0.9854	0.6252	0.9033	4
S106	1.0117	0.7759	1.0456	0.9942	1.4081	2
S107	1.7336	3.2070	6.0138	3.3657	1.8786	1
S108	1.9756	1.0956	1.8615	2.0360	2.1476	2
S109	1.7114	1.9187	1.7785	2.0240	1.7982	1
S110	1.6855	1.3490	1.0008	1.0933	1.2005	3
S111	1.6125	2.2698	2.1791	2.3366	1.3499	5
S112	1.1328	0.6744	1.0349	0.7165	0.8522	2
S113	1.3656	1.2675	0.7988	1.5265	1.3132	3
S201	3.3229	2.2076	2.4530	1.9568	2.0770	4
S202	1.1071	0.9257	1.3859	1.2926	1.2348	2

Root mean square difference from the average of all trials: 150 mm Side (°)

Subject	Trial_1	Trial_2	Trial_3	Trial_4	Trial_5	Best_Trial
S101	1.9435	0.9207	1.0339	1.1818	0.9825	2
S102	0.6534	0.7678	0.8430	0.6557	0.8766	1
S103	3.9585	2.4345	3.9276	3.7707	3.1804	2
S104	0.9778	0.8628	0.8388	0.8632	0.8673	3
S105	1.1300	1.1216	0.6907	0.9530	1.0476	3
S106	1.0489	0.8019	0.6457	0.9022	1.1643	3
S107	4.3138	3.8546	3.7627	3.5862	5.6327	4
S108	2.4510	1.1968	1.5452	1.9382	1.8955	2
S109	2.5097	1.5006	1.7916	2.2036	1.9458	2
S110	1.7184	1.3484	1.6094	1.0353	1.1429	4
S111	2.0293	1.8219	2.0480	1.4672	1.3789	5
S112	0.7977	0.7265	0.6390	0.8021	1.1814	3
S113	1.3632	2.5283	0.9024	1.7757	2.0043	3
S201	3.5749	2.2726	1.7106	2.5865	1.8508	3
S202	0.7889	0.8290	1.0645	1.0391	0.7473	5

Appendix FF: Representative Trial: Self-Selected Fast Cycle: 170mm and 150mm Crank Arms

Root mean square difference from the average of all trials: 170 mm Side (°)

Subject	Trial_1	Trial_2	Trial_3	Trial_4	Trial_5	Best_Trial
S101	0.8465	0.5721	0.5800	0.9377	0.8173	2
S102	0.7652	0.8299	0.7149	0.8740	1.1276	3
S103	1.9082	1.9883	1.3105	1.4592	2.1136	3
S104	0.7017	0.9860	0.8934	1.0424	0.6570	5
S105	0.8525	1.2281	1.2390	1.0865	0.9196	1
S106	1.1426	0.8264	0.9485	0.8096	0.9235	4
S107	2.3983	1.7050	1.1949	1.8704	1.4755	3
S108	1.7305	2.2337	1.9441	1.7366	2.7692	1
S109	1.6009	1.4909	0.9854	1.2017	1.3042	3
S110	1.1132	1.4666	1.1606	1.1870	1.5640	1
S111	1.3890	1.2467	0.7790	1.3838	1.4518	3
S112	1.0204	1.0246	0.6200	0.6554	1.0219	3
S113	0.5808	0.9450	0.6961	0.8396	1.2636	1
S201	2.3137	3.6471	2.3888	1.8541	1.5437	5
S202	0.8929	0.7730	0.7554	0.7988	0.8165	3

Root mean square difference from the average of all trials: 150 mm Side (°)

Subject	Trial_1	Trial_2	Trial_3	Trial_4	Trial_5	Best_Trial
S101	0.9666	0.7854	0.6494	0.8437	0.9742	3
S102	0.8281	0.6471	0.6056	0.8631	0.7996	3
S103	2.2314	2.5603	1.4653	1.6056	1.9428	3
S104	0.7605	0.8984	1.1571	1.1218	1.0004	1
S105	1.0682	1.1993	0.9425	1.4448	1.1336	3
S106	1.1358	1.0005	0.8402	1.0267	0.8860	3
S107	3.1193	2.2669	1.7778	2.5669	1.7973	3
S108	1.6621	1.9092	1.9868	1.3242	2.2794	4
S109	1.3668	1.4519	0.8336	1.1308	1.3251	3
S110	1.0861	1.1347	1.3075	1.2676	1.6440	1
S111	1.2750	1.1202	1.0590	1.6232	1.4523	3
S112	0.6893	0.7724	0.8199	0.7854	0.7258	1
S113	0.7472	0.8059	0.8024	0.7525	1.5620	1
S201	3.0563	2.8839	2.3687	1.5642	3.1203	4
S202	0.8356	0.6838	0.6667	0.6742	0.7431	3

Appendix GG: Representative Trial: Self-Selected Slow Cycle: 170mm and 130mm Crank Arms

Root mean square difference from the average of all trials: 170 mm Side (°)

Subject	Trial_1	Trial_2	Trial_3	Trial_4	Trial_5	Best_Trial
S101	1.9335	1.6644	1.4512	1.4140	1.6327	4
S102	1.3835	1.6851	2.2904	1.0248	2.3239	4
S103	2.1219	5.3638	2.8637	3.2750	4.1893	1
S104	1.0179	1.3332	1.2300	1.5421	1.4206	1
S105	1.3646	0.9541	1.1552	1.1517	1.4426	2
S106	1.1012	1.2926	0.9666	1.0165	0.9766	3
S107	2.9419	2.0054	1.9411	3.3373	3.0218	3
S108	2.1859	1.7526	1.0214	1.9114	1.4507	3
S109	2.1510	1.9997	1.3397	2.1682	1.6453	3
S110	1.4288	1.1452	0.8616	1.5121	1.4088	3
S111	1.5600	1.2637	1.6596	1.7932	1.5971	2
S112	1.2796	1.0206	1.0165	0.9518	1.1800	4
S113	1.4050	1.3864	2.2949	1.6995	1.7858	2
S201	1.1015	1.0706	1.2503	1.1280	1.4310	2
S202	0.8371	0.7078	1.1283	0.7508	0.7122	2

Root mean square difference from the average of all trials: 130 mm Side (°)

Subject	Trial_1	Trial_2	Trial_3	Trial_4	Trial_5	Best_Trial
S101	1.7910	1.8101	1.6573	1.6466	1.4803	5
S102	0.9605	1.4823	1.5500	1.4413	1.2102	1
S103	4.0781	5.5061	2.0810	3.4747	5.6001	3
S104	1.1586	0.7963	0.8666	0.9310	1.5099	2
S105	0.9297	1.4743	0.7835	1.2751	1.1326	3
S106	1.4201	1.1854	0.8171	1.0731	1.0599	3
S107	1.8919	2.4303	3.0788	2.2821	2.1555	1
S108	2.8965	2.1848	1.4328	2.0693	2.5442	3
S109	2.3470	2.4519	1.8536	1.7449	3.2359	4
S110	1.8224	1.0417	1.1135	1.6427	1.7250	2
S111	1.5989	1.4146	1.0560	2.1286	1.6546	3
S112	1.4269	1.7929	1.4846	1.2843	1.9681	4
S113	1.8961	1.3796	1.4453	1.3751	2.4218	4
S201	0.9804	1.2820	1.0232	0.9864	0.9778	5
S202	0.8736	0.5450	0.6997	0.7290	0.7248	2

Appendix HH: Representative Trial: Self-Selected Fast Cycle: 170mm and 130mm Crank Arms

Root mean square difference from the average of all trials: 170 mm Side (°)

Subject	Trial_1	Trial_2	Trial_3	Trial_4	Trial_5	Best_Trial
S101	1.7297	1.8780	1.4985	2.1815	1.9903	3
S102	0.9807	1.2529	1.3524	1.6122	1.2467	1
S103	3.9145	3.2734	2.0465	2.5516	3.0433	3
S104	0.9257	0.7927	0.7823	1.2781	0.8615	3
S105	1.0975	1.1423	1.3294	1.0422	2.0324	4
S106	1.2419	1.1616	0.9494	1.1134	1.0776	3
S107	1.8893	2.9769	3.2277	2.0227	2.4390	1
S108	2.1845	1.3517	2.3237	1.5265	1.8406	2
S109	0.9403	1.2042	1.6579	1.3676	1.3498	1
S110	1.2457	0.9658	1.1118	1.3121	0.8660	5
S111	1.4978	1.7391	1.6236	1.4931	1.4562	5
S112	1.4233	1.4177	1.1219	1.0959	1.5040	4
S113	0.9278	0.8205	0.7844	0.8832	1.7315	3
S201	1.0926	1.1660	1.2649	1.1001	1.8454	1
S202	1.0267	0.6836	0.4344	0.5422	1.1916	3

Root mean square difference from the average of all trials: 130 mm Side (°)

Subject	Trial_1	Trial_2	Trial_3	Trial_4	Trial_5	Best_Trial
S101	2.2770	2.1332	1.9160	1.8763	2.6166	4
S102	0.9831	1.1931	1.1853	1.1907	1.5766	1
S103	3.7756	3.0639	1.9098	2.5566	2.3372	3
S104	1.4035	0.8081	0.7166	1.1225	1.4658	3
S105	1.4657	0.9690	0.6943	1.1482	0.9511	3
S106	1.8466	1.2371	1.1159	1.1349	1.1989	3
S107	2.3524	1.8505	3.9297	2.2673	1.8253	5
S108	3.5692	1.5676	1.6991	2.9037	2.6123	2
S109	1.3441	1.2821	1.5898	1.9200	1.5160	2
S110	1.8074	0.8625	1.0939	1.2454	1.0991	2
S111	1.0945	0.9478	1.2852	1.5292	1.2177	2
S112	1.2260	1.1769	1.2007	0.9189	1.1142	4
S113	1.3363	0.9467	0.6356	0.8891	1.2241	3
S201	0.7846	1.2039	0.7323	0.8917	1.3240	3
S202	0.6580	0.6876	0.3914	0.4002	0.7454	3

Appendix II: GPS/GVS Scores: Right Self-Selected Slow Walk

subject	GPS_Overall	trunk_tilt	trunk_lat	trunk_rot	pel_tilt	pel_obl	pel_rot	hip_flex	hip_abd	hip_rot	knee_flex	ank_dors	foot_prg
S101	2.88 ± 0.35	3.32 ± 2.14	1.62 ± 0.59	5.0 ± 0.64	2.06 ± 0.58	1.4 ± 0.14	3.38 ± 0.95	3.02 ± 1.19	1.56 ± 0.3	3.46 ± 0.62	3.62 ± 1.61	3.86 ± 0.44	2.42 ± 0.9
S102	3.9 ± 0.14	2.64 ± 1.48	2.3 ± 0.53	2.5 ± 0.37	4.1 ± 0.52	1.44 ± 0.15	4.28 ± 0.72	6.6 ± 0.63	4.9 ± 0.62	9.14 ± 0.4	3.04 ± 0.44	3.0 ± 0.33	2.78 ± 0.56
S103	2.74 ± 0.21	2.38 ± 1.4	3.46 ± 0.37	2.82 ± 1.01	2.1 ± 0.82	2.86 ± 0.61	2.46 ± 1.06	3.2 ± 1.13	1.94 ± 0.4	3.34 ± 0.49	2.86 ± 0.44	2.18 ± 0.16	3.1 ± 0.67
S104	3.08 ± 0.23	1.86 ± 0.84	1.34 ± 0.44	3.1 ± 1.11	2.42 ± 1.07	4.68 ± 0.66	2.56 ± 0.81	5.84 ± 1.35	2.08 ± 0.76	3.28 ± 0.38	5.34 ± 0.45	1.38 ± 0.28	2.9 ± 0.59
S105	3.16 ± 0.36	1.6 ± 0.46	1.1 ± 0.37	3.14 ± 0.21	4.4 ± 0.84	2.28 ± 0.38	2.74 ± 0.5	7.42 ± 3.01	3.06 ± 0.32	2.78 ± 0.29	4.74 ± 2.22	2.68 ± 0.36	2.04 ± 0.82
S106	3.32 ± 0.29	3.16 ± 0.91	1.1 ± 0.25	3.24 ± 1.23	2.22 ± 0.4	1.5 ± 0.24	3.8 ± 0.95	3.16 ± 0.84	2.84 ± 0.5	7.14 ± 0.99	4.26 ± 1.03	2.9 ± 0.58	4.28 ± 0.96
S107	3.22 ± 0.35	5.12 ± 1.89	2.92 ± 0.75	2.94 ± 0.98	1.46 ± 0.38	1.16 ± 0.21	3.02 ± 0.64	2.64 ± 0.64	1.72 ± 0.23	3.52 ± 0.66	4.48 ± 0.55	4.74 ± 0.85	4.66 ± 0.78
S108	3.98 ± 0.7	2.4 ± 0.97	1.02 ± 0.33	2.94 ± 1.45	1.96 ± 0.8	5.02 ± 0.31	6.62 ± 1.15	2.72 ± 0.8	8.36 ± 0.46	6.44 ± 1.63	3.26 ± 1.47	2.98 ± 1.35	3.96 ± 1.76
S109	5.06 ± 0.86	2.3 ± 1.35	2.06 ± 0.78	6.58 ± 2.53	7.26 ± 2.55	1.8 ± 0.66	5.64 ± 1.84	8.88 ± 3.09	3.32 ± 0.73	8.5 ± 1.33	6.66 ± 2.45	4.58 ± 1.15	3.22 ± 1.54
S110	4.08 ± 0.37	3.92 ± 0.66	2.52 ± 0.43	3.38 ± 0.53	1.94 ± 0.69	2.08 ± 0.33	2.7 ± 0.58	4.14 ± 1.78	2.32 ± 0.44	10.56 ± 0.89	7.26 ± 1.87	4.56 ± 0.84	3.46 ± 1.59
S111	4.34 ± 0.15	2.82 ± 0.96	1.04 ± 0.36	2.06 ± 1.04	10.34 ± 0.63	2.0 ± 0.42	4.12 ± 0.88	10.94 ± 0.67	1.24 ± 0.23	6.0 ± 0.6	2.60 ± 0.4	5.28 ± 0.26	3.62 ± 0.77
S112	3.52 ± 0.24	2.74 ± 1.83	1.04 ± 0.51	1.28 ± 0.55	5.22 ± 0.84	2.72 ± 0.13	2.74 ± 0.38	3.74 ± 0.68	1.22 ± 0.37	4.02 ± 0.27	4.2 ± 0.82	7.96 ± 0.63	5.14 ± 1.1
S113	4.48 ± 0.18	2.44 ± 1.1	1.36 ± 0.11	2.18 ± 0.57	2.84 ± 0.3	2.92 ± 0.26	3.24 ± 0.8	4.88 ± 0.47	4.72 ± 0.48	12.22 ± 0.51	9.24 ± 1.02	3.44 ± 0.36	4.14 ± 0.74
S201	4.26 ± 0.23	3.1 ± 0.92	6.12 ± 0.92	3.02 ± 0.77	4.8 ± 0.69	2.28 ± 0.75	3.12 ± 1.51	5.64 ± 0.65	2.12 ± 0.51	4.74 ± 0.71	6.24 ± 0.57	6.6 ± 0.55	3.08 ± 1.14
S202	4.64 ± 0.25	2.6 ± 0.41	1.1 ± 0.37	3.86 ± 0.8	2.58 ± 0.55	6.94 ± 0.49	3.94 ± 0.97	5.56 ± 0.92	6.9 ± 0.56	4.56 ± 0.33	4.78 ± 0.61	5.08 ± 0.28	7.92 ± 1.07

Appendix JJ: GPS/GVS Scores: Left Self-Selected Slow Walk

subject	GPS_Overall	trunk_tilt	trunk_lat	trunk_rot	pel_tilt	pel_obl	pel_rot	hip_flex	hip_abd	hip_rot	knee_flex	ank_dors	foot_prg
S101	3.5 ± 0.2	3.6 ± 1.44	1.74 ± 0.47	4.98 ± 0.48	2.24 ± 0.68	1.42 ± 0.13	2.8 ± 0.28	2.58 ± 0.54	2.44 ± 0.24	8.76 ± 0.43	4.12 ± 0.54	4.44 ± 0.43	2.6 ± 0.83
S102	3.16 ± 0.22	2.06 ± 1.06	2.24 ± 0.38	2.28 ± 0.71	4.22 ± 1.36	1.44 ± 0.18	4.32 ± 0.7	5.0 ± 1.02	2.58 ± 0.19	2.48 ± 0.46	2.94 ± 0.66	4.82 ± 0.49	3.7 ± 0.64
S103	3.22 ± 0.19	2.16 ± 1.43	2.68 ± 0.59	2.76 ± 0.11	2.16 ± 0.8	2.64 ± 0.43	1.94 ± 0.77	6.02 ± 0.63	2.2 ± 0.6	3.28 ± 0.62	7.62 ± 0.4	2.4 ± 0.21	2.36 ± 0.69
S104	3.18 ± 0.16	1.58 ± 0.43	1.26 ± 0.25	3.28 ± 1.14	2.08 ± 0.67	4.52 ± 0.66	2.9 ± 0.61	4.04 ± 0.71	6.7 ± 0.41	4.4 ± 0.37	4.34 ± 0.32	1.26 ± 0.21	1.76 ± 0.33
S105	3.2 ± 0.32	1.86 ± 0.36	1.14 ± 0.44	2.96 ± 0.53	4.26 ± 1.35	2.14 ± 0.36	2.8 ± 0.33	5.04 ± 1.71	2.58 ± 0.11	2.78 ± 0.35	3.28 ± 1.6	6.96 ± 0.48	2.38 ± 0.41
S106	3.2 ± 0.16	2.9 ± 0.67	1.32 ± 0.41	2.54 ± 1.44	1.72 ± 0.58	1.66 ± 0.26	3.48 ± 0.83	4.18 ± 0.18	1.94 ± 0.3	5.42 ± 0.59	6.7 ± 0.51	3.34 ± 0.36	3.3 ± 0.45
S107	2.74 ± 0.15	4.48 ± 0.44	2.9 ± 0.32	2.4 ± 0.89	1.44 ± 0.25	1.04 ± 0.18	2.66 ± 0.61	2.18 ± 0.64	1.56 ± 0.15	3.64 ± 0.05	2.52 ± 1.46	3.16 ± 0.26	4.82 ± 0.93
S108	4.36 ± 0.42	2.46 ± 1.34	0.8 ± 0.37	3.4 ± 1.33	2.08 ± 0.44	5.02 ± 0.2	6.2 ± 1.56	5.2 ± 0.64	5.98 ± 0.59	3.46 ± 0.42	7.0 ± 1.57	3.26 ± 0.56	7.34 ± 0.55
S109	4.32 ± 0.48	3.5 ± 1.15	2.22 ± 0.95	6.5 ± 1.77	7.22 ± 2.56	1.52 ± 0.66	5.36 ± 1.86	7.2 ± 2.44	2.86 ± 1.02	2.74 ± 0.4	6.14 ± 2.02	4.72 ± 0.68	2.16 ± 0.53
S110	3.04 ± 0.23	3.72 ± 0.76	2.54 ± 0.48	3.02 ± 0.65	2.12 ± 0.55	2.04 ± 0.29	2.56 ± 0.52	3.5 ± 1.81	3.1 ± 0.31	3.7 ± 0.66	4.56 ± 2.02	3.2 ± 0.78	2.46 ± 0.71
S111	4.38 ± 0.26	2.8 ± 1.17	1.32 ± 0.43	1.74 ± 0.65	9.48 ± 0.54	2.08 ± 0.48	3.94 ± 1.03	11.46 ± 1.5	2.22 ± 0.16	5.34 ± 0.57	2.66 ± 1.4	6.34 ± 0.3	3.18 ± 0.71
S112	3.92 ± 0.16	2.88 ± 1.79	0.92 ± 0.26	1.1 ± 0.32	5.12 ± 0.56	2.96 ± 0.19	3.16 ± 0.51	7.9 ± 1.19	4.3 ± 0.21	4.02 ± 0.13	4.88 ± 0.51	5.42 ± 0.43	4.12 ± 0.92
S113	3.36 ± 0.29	2.82 ± 1.22	1.58 ± 0.18	1.84 ± 0.67	2.62 ± 0.27	2.76 ± 0.49	2.9 ± 0.79	3.84 ± 0.58	4.08 ± 0.35	6.6 ± 0.61	3.4 ± 1.22	2.6 ± 0.07	5.02 ± 1.2
S201	5.9 ± 0.23	3.78 ± 1.45	5.48 ± 1.54	3.04 ± 0.68	4.96 ± 1.09	2.7 ± 0.57	2.76 ± 0.84	11.2 ± 1.06	3.52 ± 0.65	8.56 ± 0.61	9.62 ± 1.03	7.04 ± 0.19	8.36 ± 1.04
S202	5.68 ± 0.11	3.18 ± 0.91	1.62 ± 0.25	3.92 ± 0.85	2.68 ± 0.66	6.72 ± 0.29	3.98 ± 0.91	8.68 ± 0.65	5.82 ± 0.31	12.4 ± 0.45	8.58 ± 0.94	6.08 ± 0.31	4.64 ± 0.93

Appendix KK: GPS/GVS Scores: Right Self-Selected Fast Walk

subject	GPS_Overall	trunk_tilt	trunk_lat	trunk_rot	pel_tilt	pel_obl	pel_rot	hip_flex	hip_abd	hip_rot	knee_flex	ank_dors	foot_prg
S101	3.62 ± 0.29	2.54 ± 0.94	1.56 ± 0.11	5.88 ± 0.68	5.06 ± 0.82	1.72 ± 0.42	3.76 ± 0.76	6.44 ± 0.97	2.36 ± 0.23	3.42 ± 0.59	4.16 ± 1.09	3.94 ± 1.16	2.58 ± 0.65
S102	4.48 ± 0.48	2.46 ± 0.68	3.82 ± 0.65	4.5 ± 1.54	3.88 ± 1.39	3.16 ± 0.6	8.62 ± 0.89	2.78 ± 0.98	4.46 ± 0.81	11.62 ± 0.78	2.82 ± 1.15	2.74 ± 0.61	2.74 ± 1.15
S103	5.52 ± 0.51	4.0 ± 1.24	4.98 ± 1.7	7.38 ± 5.74	3.68 ± 1.34	4.32 ± 1.36	6.6 ± 1.28	7.84 ± 1.97	5.66 ± 1.84	4.48 ± 0.95	7.68 ± 2.17	6.18 ± 0.78	3.6 ± 0.86
S104	3.26 ± 0.27	1.34 ± 0.71	1.36 ± 0.29	4.96 ± 2.08	2.42 ± 0.51	4.0 ± 0.12	2.24 ± 0.69	5.62 ± 1.05	2.0 ± 0.51	4.6 ± 0.7	4.68 ± 0.53	2.86 ± 0.76	3.12 ± 0.99
S105	3.28 ± 0.48	2.7 ± 1.49	1.6 ± 0.7	4.18 ± 1.05	3.62 ± 1.38	2.62 ± 0.39	2.04 ± 0.38	6.32 ± 2.37	2.9 ± 0.76	3.4 ± 0.83	3.82 ± 0.96	3.56 ± 0.71	2.26 ± 0.59
S106	4.04 ± 0.6	4.9 ± 0.41	1.44 ± 0.4	4.92 ± 1.19	2.04 ± 0.67	1.62 ± 0.59	6.28 ± 1.2	3.54 ± 1.14	3.16 ± 0.78	7.66 ± 0.84	4.78 ± 2.7	4.04 ± 1.41	4.24 ± 1.11
S107	2.96 ± 0.24	2.26 ± 0.95	2.52 ± 0.86	2.94 ± 1.52	2.6 ± 0.6	1.16 ± 0.36	2.88 ± 0.87	3.38 ± 0.47	1.6 ± 0.42	4.42 ± 0.26	4.10 ± 0.50	4.58 ± 0.82	3.06 ± 0.57
S108	4.14 ± 0.52	2.52 ± 0.76	0.96 ± 0.23	3.9 ± 1.48	3.18 ± 0.88	4.98 ± 0.33	4.92 ± 2.1	4.6 ± 1.48	8.28 ± 0.89	6.34 ± 0.8	3.14 ± 0.98	3.28 ± 0.75	3.48 ± 0.64
S109	4.26 ± 0.17	3.28 ± 1.77	2.58 ± 0.41	5.54 ± 1.54	3.12 ± 0.83	1.54 ± 0.4	5.94 ± 0.64	6.2 ± 0.51	3.08 ± 0.79	8.68 ± 0.35	2.78 ± 0.85	3.42 ± 0.45	4.96 ± 1.1
S110	4.85 ± 0.53	2.22 ± 0.5	2.8 ± 1.33	5.52 ± 0.71	7.98 ± 1.51	2.7 ± 0.37	3.58 ± 0.92	8.85 ± 1.5	3.1 ± 0.58	9.75 ± 0.53	4.47 ± 1.98	3.62 ± 1.2	3.75 ± 0.66
S111	4.8 ± 0.29	2.04 ± 0.76	2.08 ± 1.25	1.7 ± 0.89	13.08 ± 0.67	2.3 ± 0.64	4.38 ± 0.97	13.36 ± 1.07	1.94 ± 0.5	6.82 ± 0.41	3.22 ± 1.32	4.16 ± 0.52	2.46 ± 1.0
S112	4.88 ± 0.29	4.16 ± 0.9	1.56 ± 0.29	3.0 ± 1.16	8.12 ± 1.59	3.5 ± 0.44	3.62 ± 0.53	8.42 ± 0.94	2.46 ± 0.5	5.54 ± 0.3	3.9 ± 1.66	9.14 ± 0.87	5.02 ± 0.62
S113	5.02 ± 0.26	2.98 ± 1.35	2.58 ± 0.48	2.96 ± 0.72	3.26 ± 0.52	3.08 ± 0.38	2.48 ± 0.28	6.18 ± 0.56	5.1 ± 0.35	13.76 ± 0.65	9.5 ± 0.86	3.56 ± 0.49	4.76 ± 0.71
S201	4.94 ± 0.34	3.84 ± 2.65	4.66 ± 1.12	4.98 ± 1.57	4.22 ± 1.07	2.86 ± 0.25	3.56 ± 1.15	6.5 ± 0.94	3.64 ± 0.51	4.58 ± 0.45	6.56 ± 0.87	9.66 ± 0.23	3.88 ± 0.61
S202	4.98 ± 0.31	2.74 ± 1.08	1.16 ± 0.44	4.86 ± 1.08	2.7 ± 0.07	5.88 ± 0.25	4.96 ± 0.43	3.78 ± 0.5	6.96 ± 0.56	4.5 ± 0.19	6.46 ± 1.04	6.34 ± 0.83	9.5 ± 0.82

Appendix LL: GPS/GVS Scores: Left Self-Selected Fast Walk

subject	GPS_Overall	trunk_tilt	trunk_lat	trunk_rot	pel_tilt	pel_obl	pel_rot	hip_flex	hip_abd	hip_rot	knee_flex	ank_dors	foot_prg
S101	3.7 ± 0.32	2.76 ± 1.01	1.7 ± 0.32	5.76 ± 0.73	3.94 ± 0.8	2.14 ± 0.15	4.28 ± 0.59	2.86 ± 0.45	3.58 ± 0.62	8.22 ± 0.36	3.66 ± 1.64	3.16 ± 0.37	2.34 ± 0.54
S102	4.7 ± 0.64	2.74 ± 1.24	3.44 ± 0.76	4.58 ± 1.95	4.42 ± 0.83	3.38 ± 0.41	8.78 ± 1.15	5.8 ± 1.54	4.12 ± 0.73	4.58 ± 1.01	3.54 ± 2.39	4.84 ± 1.01	6.06 ± 0.97
S103	5.62 ± 0.82	4.18 ± 0.96	5.6 ± 1.96	8.68 ± 5.27	3.94 ± 1.16	3.8 ± 0.42	7.06 ± 2.5	5.5 ± 1.52	5.42 ± 1.39	4.7 ± 1.47	6.48 ± 1.29	7.88 ± 1.14	3.94 ± 0.48
S104	3.46 ± 0.3	1.26 ± 0.42	1.78 ± 0.9	5.28 ± 2.13	2.16 ± 0.63	3.7 ± 0.65	2.14 ± 0.55	4.62 ± 0.64	6.04 ± 0.97	6.1 ± 0.48	4.48 ± 0.82	2.04 ± 0.52	1.88 ± 0.39
S105	3.66 ± 0.27	3.0 ± 1.42	1.92 ± 0.61	4.4 ± 0.65	3.86 ± 1.32	2.58 ± 0.36	2.18 ± 0.55	4.62 ± 1.21	2.88 ± 0.56	3.5 ± 0.19	3.64 ± 1.0	7.98 ± 0.75	3.12 ± 0.24
S106	4.1 ± 0.51	3.28 ± 0.77	1.34 ± 0.34	4.6 ± 1.26	2.48 ± 0.9	1.82 ± 0.34	6.76 ± 1.03	5.46 ± 1.52	2.74 ± 0.47	5.72 ± 0.64	8.5 ± 1.53	3.44 ± 0.65	3.0 ± 0.72
S107	3.0 ± 0.17	2.36 ± 1.02	2.34 ± 1.21	2.54 ± 1.01	2.52 ± 0.68	1.42 ± 0.33	2.7 ± 1.17	3.6 ± 0.29	2.04 ± 0.71	5.1 ± 0.49	4.68 ± 0.82	3.3 ± 0.56	3.6 ± 0.78
S108	3.92 ± 0.16	2.02 ± 0.57	1.14 ± 0.25	2.74 ± 1.2	2.84 ± 0.38	4.98 ± 0.11	3.66 ± 1.97	3.74 ± 1.18	4.66 ± 0.76	3.38 ± 0.43	5.36 ± 2.52	3.18 ± 0.47	9.26 ± 0.99
S109	3.42 ± 0.18	2.82 ± 1.34	2.48 ± 0.68	5.12 ± 0.91	3.42 ± 0.48	1.68 ± 0.5	6.16 ± 0.66	4.08 ± 0.48	3.06 ± 0.38	2.84 ± 0.15	3.82 ± 0.5	3.88 ± 0.48	1.98 ± 0.54
S110	4.25 ± 0.51	2.38 ± 0.79	2.33 ± 1.34	5.3 ± 1.19	8.78 ± 1.55	2.5 ± 0.47	3.55 ± 0.25	7.57 ± 2.53	2.88 ± 0.95	4.2 ± 0.36	2.95 ± 0.79	4.7 ± 1.17	3.58 ± 0.26
S111	5.16 ± 0.29	2.7 ± 0.98	2.14 ± 1.43	2.06 ± 0.79	12.88 ± 0.68	2.68 ± 0.52	4.98 ± 1.03	15.78 ± 0.93	2.98 ± 0.79	4.44 ± 0.63	3.56 ± 1.77	5.24 ± 0.74	2.46 ± 0.55
S112	5.06 ± 0.36	3.52 ± 1.08	1.26 ± 0.25	3.5 ± 1.01	7.68 ± 1.63	3.52 ± 0.3	3.94 ± 0.63	11.62 ± 2.04	5.82 ± 0.23	4.34 ± 0.51	6.78 ± 0.88	6.44 ± 0.64	2.32 ± 0.43
S113	3.68 ± 0.28	2.06 ± 0.67	2.74 ± 0.91	3.38 ± 0.81	3.38 ± 0.58	2.78 ± 0.24	2.0 ± 0.49	4.38 ± 0.54	3.06 ± 0.3	7.54 ± 0.81	3.98 ± 1.34	3.62 ± 0.54	5.5 ± 1.24
S201	5.52 ± 0.41	3.28 ± 2.89	4.82 ± 1.12	4.74 ± 1.54	4.24 ± 1.15	2.86 ± 0.17	2.66 ± 1.15	9.56 ± 1.26	3.48 ± 0.54	8.86 ± 0.88	7.06 ± 0.34	5.68 ± 0.33	8.84 ± 0.77
S202	5.4 ± 0.21	3.04 ± 1.3	1.34 ± 0.21	5.2 ± 0.85	2.48 ± 0.22	5.34 ± 0.4	2.92 ± 1.11	6.48 ± 0.36	4.64 ± 0.43	11.52 ± 0.61	6.3 ± 0.98	9.3 ± 0.14	6.42 ± 0.41

Appendix MM: CPS/CVS Scores: Self-Selected Slow Cycle: Both 170mm Crank Arms: Shortened Side

subject	GPS_Overall	trunk_tilt	trunk_obl	trunk_rot	pel_tilt	pel_obl	pel_rot	hip_flex	hip_abd	hip_rot	knee_flex	ank_dors	foot_prg
S101	5.52 ± 0.18	6.66 ± 0.75	2.64 ± 0.74	2.82 ± 0.53	12.78 ± 0.51	2.26 ± 0.05	2.24 ± 0.19	10.32 ± 0.43	1.76 ± 0.38	2.56 ± 0.25	12.76 ± 0.17	8.76 ± 0.68	0.9 ± 0.07
S102	3.64 ± 0.13	9.36 ± 0.24	0.92 ± 0.23	0.68 ± 0.08	5.02 ± 0.37	0.78 ± 0.26	2.32 ± 0.28	5.92 ± 0.3	4.46 ± 0.41	3.34 ± 0.18	3.64 ± 0.13	6.18 ± 1.03	0.98 ± 0.08
S103	6.9 ± 3.33	4.8 ± 3.27	6.76 ± 4.77	18.76 ± 19.2	4.68 ± 4.42	2.6 ± 1.41	7.04 ± 4.2	6.24 ± 4.86	7.96 ± 4.21	3.28 ± 0.55	3.92 ± 2.58	11.72 ± 6.08	4.84 ± 0.57
S104	5.44 ± 0.26	4.92 ± 3.6	1.66 ± 0.48	5.48 ± 0.98	11.88 ± 0.78	0.88 ± 0.41	1.12 ± 0.58	14.42 ± 0.8	2.02 ± 0.45	8.92 ± 0.96	4.72 ± 0.18	6.78 ± 0.54	2.6 ± 0.23
S105	4.34 ± 0.17	7.84 ± 1.21	2.06 ± 0.59	1.42 ± 0.34	9.36 ± 0.38	3.24 ± 0.46	1.08 ± 0.8	6.66 ± 0.38	2.54 ± 1.05	7.94 ± 0.58	2.1 ± 0.56	6.28 ± 0.81	1.56 ± 0.57
S106	2.82 ± 0.16	6.56 ± 2.59	1.34 ± 0.18	0.62 ± 0.44	1.76 ± 0.71	0.82 ± 0.13	1.8 ± 0.26	1.88 ± 0.83	1.6 ± 0.48	9.96 ± 0.39	2.46 ± 0.27	4.64 ± 1.5	0.58 ± 0.15
S107	6.28 ± 0.19	7.82 ± 0.97	1.66 ± 0.57	0.82 ± 0.15	15.38 ± 0.26	2.16 ± 0.9	1.16 ± 0.36	15.2 ± 0.47	2.66 ± 1.05	5.22 ± 0.94	5.26 ± 1.03	14.62 ± 2.46	3.78 ± 0.52
S108	5.42 ± 0.38	4.5 ± 2.41	2.6 ± 0.45	3.86 ± 0.38	9.24 ± 2.71	6.06 ± 0.66	2.84 ± 0.84	12.88 ± 1.74	4.26 ± 0.74	7.06 ± 0.68	1.8 ± 0.19	7.36 ± 1.9	2.66 ± 0.6
S109	3.1 ± 0.25	5.98 ± 1.4	1.88 ± 1.13	1.72 ± 0.72	2.08 ± 0.55	1.6 ± 0.29	2.48 ± 0.65	3.78 ± 1.45	2.4 ± 0.41	4.24 ± 0.86	4.34 ± 1.14	3.88 ± 0.8	2.76 ± 0.19
S110	6.7 ± 0.31	0.98 ± 0.88	2.32 ± 0.56	4.52 ± 0.87	19.92 ± 0.66	2.3 ± 0.45	2.9 ± 0.35	10.14 ± 0.55	4.46 ± 0.5	9.6 ± 0.62	13.36 ± 0.57	5.38 ± 0.38	4.72 ± 0.33
S111	5.5 ± 0.1	16.94 ± 1.01	1.92 ± 0.55	1.8 ± 0.94	11.04 ± 0.76	1.12 ± 0.53	1.62 ± 0.22	8.5 ± 0.64	2.24 ± 0.52	3.96 ± 0.3	7.32 ± 0.4	8.9 ± 1.08	0.62 ± 0.24
S112	4.54 ± 0.23	3.48 ± 0.72	1.3 ± 0.53	3.16 ± 0.15	7.78 ± 0.4	1.0 ± 0.21	2.92 ± 0.22	9.0 ± 0.51	1.66 ± 0.19	1.98 ± 0.19	6.38 ± 0.74	9.08 ± 1.42	6.62 ± 0.04
S113	4.52 ± 0.15	4.1 ± 1.56	1.78 ± 0.67	0.8 ± 0.23	3.9 ± 0.36	2.38 ± 0.54	3.02 ± 0.51	2.28 ± 0.51	3.64 ± 0.65	14.72 ± 0.54	4.66 ± 0.9	11.92 ± 3.98	0.96 ± 0.11
S201	5.32 ± 0.26	7.76 ± 3.12	6.16 ± 1.46	5.48 ± 0.87	1.5 ± 0.51	1.14 ± 0.61	4.06 ± 0.48	2.78 ± 0.48	4.0 ± 0.83	6.8 ± 0.6	8.48 ± 0.38	10.6 ± 0.97	5.18 ± 0.08
S202	4.58 ± 0.08	4.16 ± 0.63	4.04 ± 1.31	3.96 ± 0.9	4.26 ± 0.56	1.82 ± 0.79	3.38 ± 0.74	3.62 ± 0.77	1.78 ± 0.59	9.58 ± 0.35	5.16 ± 0.4	11.52 ± 0.77	1.64 ± 0.15

Appendix NN: CPS/CVS Scores: Self-Selected Slow Cycle: Both 170mm Crank Arms: Unadjusted Side

subject	GPS_Overall	trunk_tilt	trunk_obl	trunk_rot	pel_tilt	pel_obl	pel_rot	hip_flex	hip_abd	hip_rot	knee_flex	ank_dors	foot_prg
S101	6.2 ± 0.19	6.68 ± 1.86	2.58 ± 0.69	2.8 ± 0.45	12.9 ± 0.32	2.14 ± 0.15	2.24 ± 0.18	6.16 ± 0.44	2.38 ± 0.28	8.28 ± 0.63	15.0 ± 0.16	9.26 ± 0.42	3.86 ± 0.13
S102	3.08 ± 0.08	9.74 ± 0.5	0.72 ± 0.29	0.66 ± 0.18	5.12 ± 0.29	0.88 ± 0.24	2.16 ± 0.4	6.08 ± 0.61	1.42 ± 0.32	1.1 ± 0.29	2.48 ± 0.36	3.1 ± 1.27	3.38 ± 0.33
S103	5.2 ± 3.01	5.0 ± 2.83	5.3 ± 4.49	14.38 ± 17.5	3.58 ± 3.99	3.0 ± 1.3	5.82 ± 4.08	3.42 ± 2.9	4.92 ± 1.84	5.4 ± 1.21	2.58 ± 1.79	6.5 ± 2.36	2.72 ± 0.31
S104	4.76 ± 0.31	4.54 ± 3.41	1.42 ± 0.49	5.6 ± 0.78	11.86 ± 0.65	1.0 ± 0.32	1.32 ± 0.64	12.62 ± 0.69	1.54 ± 0.78	6.84 ± 0.52	3.06 ± 0.18	5.5 ± 0.91	1.62 ± 0.26
S105	4.1 ± 0.33	7.56 ± 1.14	1.66 ± 0.4	1.42 ± 0.37	9.16 ± 0.79	3.26 ± 0.26	1.16 ± 0.68	2.88 ± 0.62	2.54 ± 0.67	3.26 ± 0.11	6.26 ± 0.24	5.0 ± 2.29	4.94 ± 0.22
S106	2.94 ± 0.23	6.38 ± 2.44	1.08 ± 0.37	0.7 ± 0.31	1.84 ± 0.69	0.9 ± 0.42	1.64 ± 0.25	2.5 ± 0.38	2.04 ± 0.38	7.68 ± 0.62	3.34 ± 0.18	4.6 ± 1.09	2.52 ± 0.29
S107	5.9 ± 0.29	8.02 ± 1.24	1.76 ± 0.42	0.84 ± 0.13	15.5 ± 0.31	2.08 ± 0.8	1.2 ± 0.5	14.78 ± 0.51	1.88 ± 0.55	9.92 ± 0.75	3.3 ± 0.56	11.02 ± 3.5	0.62 ± 0.23
S108	6.26 ± 0.45	5.12 ± 2.55	2.58 ± 0.85	3.68 ± 0.82	9.4 ± 2.54	6.2 ± 0.39	2.84 ± 0.74	15.84 ± 1.95	3.76 ± 0.78	2.54 ± 0.75	5.14 ± 0.53	11.4 ± 1.53	6.52 ± 0.18
S109	3.04 ± 0.31	5.42 ± 1.64	2.24 ± 0.86	1.38 ± 0.69	2.4 ± 1.19	1.62 ± 0.4	2.54 ± 1.09	3.0 ± 1.07	5.72 ± 1.1	1.74 ± 0.26	3.64 ± 1.11	3.5 ± 0.94	3.38 ± 0.41
S110	6.2 ± 0.4	1.38 ± 0.83	2.34 ± 0.9	4.66 ± 0.68	19.86 ± 0.82	2.22 ± 0.46	2.94 ± 0.38	11.14 ± 0.92	2.48 ± 0.57	2.7 ± 0.28	12.9 ± 0.19	5.64 ± 1.35	5.98 ± 0.36
S111	5.92 ± 0.36	16.38 ± 1.16	1.86 ± 0.69	1.82 ± 0.82	10.96 ± 0.59	1.28 ± 0.53	1.72 ± 0.24	9.36 ± 1.0	1.26 ± 0.19	2.5 ± 0.25	7.88 ± 0.4	14.06 ± 2.38	1.9 ± 0.27
S112	5.55 ± 0.13	3.3 ± 0.56	1.23 ± 0.52	3.1 ± 0.26	7.98 ± 0.3	0.98 ± 0.35	3.2 ± 0.24	13.9 ± 0.37	2.7 ± 0.34	4.85 ± 0.26	8.68 ± 0.4	15.02 ± 0.74	1.68 ± 0.22
S113	4.1 ± 0.48	3.42 ± 1.43	1.82 ± 0.61	0.78 ± 0.2	3.78 ± 0.45	2.44 ± 0.51	3.18 ± 0.36	9.54 ± 1.19	2.42 ± 0.39	9.52 ± 0.41	1.90 ± 0.4	9.44 ± 2.67	1.14 ± 0.21
S201	4.78 ± 0.31	8.52 ± 2.82	5.85 ± 1.03	5.25 ± 1.05	1.68 ± 0.34	0.88 ± 0.3	3.75 ± 0.49	3.65 ± 0.34	1.75 ± 0.44	7.18 ± 0.4	5.12 ± 0.35	4.35 ± 1.41	9.32 ± 0.49
S202	4.08 ± 0.42	3.86 ± 0.93	4.42 ± 1.45	4.06 ± 0.76	4.52 ± 0.86	1.96 ± 0.89	3.2 ± 0.47	3.96 ± 0.36	4.46 ± 0.19	2.22 ± 0.6	4.86 ± 0.23	5.88 ± 2.66	5.44 ± 0.48

Appendix OO: CPS/CVS Scores: Self-Selected Fast Cycle: Both 170mm Crank Arms: Shortened Side

subject	GPS_Overall	trunk_tilt	trunk_obl	trunk_rot	pel_tilt	pel_obl	pel_rot	hip_flex	hip_abd	hip_rot	knee_flex	ank_dors	foot_prg
S101	6.08 ± 0.04	6.38 ± 1.22	2.82 ± 0.28	1.64 ± 0.66	15.74 ± 0.89	2.04 ± 0.34	2.74 ± 0.51	12.24 ± 0.68	2.56 ± 0.21	2.58 ± 0.23	11.02 ± 0.38	12.14 ± 0.96	1.1 ± 0.33
S102	3.5 ± 0.21	4.7 ± 0.62	2.68 ± 0.43	5.56 ± 1.25	4.36 ± 0.98	1.34 ± 0.3	1.32 ± 0.25	4.18 ± 0.63	4.8 ± 0.8	4.24 ± 0.56	3.46 ± 0.21	4.64 ± 1.25	0.84 ± 0.05
S103	6.76 ± 0.5	12.4 ± 1.69	4.64 ± 0.3	3.04 ± 1.64	16.5 ± 1.28	3.62 ± 0.48	3.48 ± 1.08	13.6 ± 1.4	4.8 ± 0.64	3.32 ± 0.34	3.06 ± 0.86	6.88 ± 3.63	5.7 ± 0.58
S104	4.22 ± 0.22	6.0 ± 0.65	0.96 ± 0.21	3.08 ± 0.36	4.82 ± 0.53	0.9 ± 0.1	0.8 ± 0.12	9.2 ± 0.53	1.62 ± 0.19	8.24 ± 0.36	6.84 ± 0.31	5.78 ± 0.66	2.62 ± 0.11
S105	4.0 ± 0.12	13.66 ± 0.56	1.86 ± 0.24	1.48 ± 0.45	1.9 ± 0.29	4.56 ± 0.21	1.9 ± 0.23	2.1 ± 0.35	4.62 ± 0.19	7.14 ± 0.21	1.12 ± 0.11	5.54 ± 0.86	2.14 ± 0.39
S106	3.6 ± 0.23	2.36 ± 0.88	2.52 ± 0.99	0.86 ± 0.5	7.88 ± 0.86	1.38 ± 0.29	2.66 ± 0.34	7.0 ± 0.64	1.5 ± 0.37	10.08 ± 0.33	2.94 ± 0.23	3.08 ± 0.63	1.0 ± 0.45
S107	4.78 ± 0.19	1.26 ± 0.72	4.8 ± 0.58	1.58 ± 0.43	13.52 ± 0.79	2.18 ± 0.44	1.12 ± 0.41	14.28 ± 0.75	1.72 ± 0.55	5.52 ± 0.58	2.2 ± 0.64	5.82 ± 2.52	3.3 ± 0.27
S108	6.2 ± 0.22	11.6 ± 2.59	4.02 ± 1.0	3.84 ± 1.3	12.96 ± 0.65	5.56 ± 0.38	2.64 ± 0.74	13.82 ± 0.79	4.28 ± 0.52	5.1 ± 0.51	4.88 ± 0.55	3.04 ± 0.84	2.44 ± 0.34
S109	3.68 ± 0.37	1.12 ± 0.33	4.76 ± 1.23	4.04 ± 0.4	2.04 ± 0.52	0.7 ± 0.16	2.56 ± 0.19	4.52 ± 0.33	2.82 ± 0.31	5.48 ± 0.38	4.22 ± 0.61	8.36 ± 1.44	3.44 ± 0.4
S110	7.86 ± 0.5	8.64 ± 3.85	2.26 ± 0.27	3.7 ± 1.29	18.26 ± 1.36	2.28 ± 0.28	6.5 ± 1.62	8.3 ± 1.44	5.14 ± 1.27	11.16 ± 0.93	16.52 ± 1.16	8.66 ± 1.78	3.02 ± 0.79
S111	6.5 ± 0.37	20.4 ± 0.61	2.8 ± 1.02	2.66 ± 0.53	12.44 ± 1.3	1.0 ± 0.29	2.66 ± 0.43	9.66 ± 1.31	2.5 ± 0.44	5.28 ± 0.5	7.16 ± 0.79	10.86 ± 0.66	0.76 ± 0.3
S112	3.32 ± 0.11	9.2 ± 1.16	1.46 ± 0.33	4.06 ± 0.55	2.54 ± 0.38	1.88 ± 0.61	1.94 ± 0.35	2.48 ± 0.83	1.7 ± 0.37	2.74 ± 0.67	4.1 ± 1.28	3.34 ± 0.45	4.58 ± 0.54
S113	4.16 ± 0.09	3.66 ± 0.65	3.5 ± 0.91	0.94 ± 0.26	2.6 ± 0.29	1.26 ± 0.18	2.72 ± 0.33	2.32 ± 0.19	3.9 ± 0.36	12.16 ± 0.11	4.78 ± 0.45	10.56 ± 0.65	1.74 ± 0.34
S201	5.68 ± 0.25	2.70 ± 1.4	2.44 ± 1.37	1.56 ± 0.88	4.76 ± 0.79	2.34 ± 0.3	2.94 ± 0.38	8.8 ± 1.05	4.88 ± 0.11	8.16 ± 0.3	8.76 ± 0.65	14.52 ± 0.44	6.26 ± 0.26
S202	6.18 ± 0.22	9.0 ± 0.45	4.02 ± 1.04	2.62 ± 0.68	10.5 ± 0.43	1.4 ± 0.19	4.16 ± 0.15	9.24 ± 0.48	2.1 ± 0.16	8.24 ± 0.43	4.46 ± 0.11	15.88 ± 0.11	2.48 ± 0.18

Appendix PP: CPS/CVS Scores: Self-Selected Fast Cycle: Both 170mm Crank Arms: Unadjusted Side

subject	GPS_Overall	trunk_tilt	trunk_obl	trunk_rot	pel_tilt	pel_obl	pel_rot	hip_flex	hip_abd	hip_rot	knee_flex	ank_dors	foot_prg
S101	6.28 ± 0.13	5.12 ± 1.19	2.8 ± 0.23	1.48 ± 0.65	16.26 ± 0.79	1.96 ± 0.44	2.92 ± 0.37	9.32 ± 0.68	2.16 ± 0.4	6.9 ± 0.2	14.24 ± 0.69	10.38 ± 0.55	2.18 ± 0.22
S102	3.32 ± 0.08	3.76 ± 0.89	2.82 ± 0.48	5.54 ± 1.32	4.82 ± 0.91	1.24 ± 0.23	1.36 ± 0.18	5.4 ± 0.57	1.96 ± 0.72	2.56 ± 0.43	2.16 ± 0.15	4.48 ± 0.64	3.70 ± 0.1
S103	6.34 ± 1.05	10.76 ± 2.03	4.36 ± 1.12	2.82 ± 1.26	15.42 ± 2.43	3.58 ± 0.52	3.74 ± 0.99	9.86 ± 2.19	4.3 ± 0.63	3.5 ± 0.64	4.24 ± 2.02	12.34 ± 5.54	1.16 ± 0.55
S104	3.66 ± 0.15	5.1 ± 0.84	1.12 ± 0.26	3.32 ± 0.38	4.36 ± 0.6	0.88 ± 0.04	0.88 ± 0.22	6.92 ± 0.66	1.12 ± 0.37	8.18 ± 0.23	4.4 ± 0.39	5.1 ± 0.42	2.5 ± 0.19
S105	4.2 ± 0.0	14.66 ± 0.88	1.82 ± 0.41	1.48 ± 0.23	1.64 ± 0.39	4.58 ± 0.19	2.22 ± 0.26	5.98 ± 0.22	2.4 ± 0.23	3.68 ± 0.29	3.74 ± 0.17	3.98 ± 1.35	4.22 ± 0.2
S106	3.8 ± 0.2	1.98 ± 0.16	2.74 ± 0.91	1.12 ± 0.44	8.32 ± 0.59	1.38 ± 0.45	2.6 ± 0.25	6.48 ± 0.47	1.98 ± 0.39	8.82 ± 0.33	4.6 ± 0.49	4.46 ± 0.38	1.16 ± 0.19
S107	5.42 ± 0.26	1.06 ± 0.42	4.86 ± 0.69	1.58 ± 0.42	14.06 ± 0.58	2.36 ± 0.39	1.24 ± 0.44	13.32 ± 0.45	1.64 ± 0.19	10.16 ± 0.58	2.52 ± 0.41	11.28 ± 1.72	1.0 ± 0.27
S108	6.42 ± 0.31	11.5 ± 2.3	4.12 ± 0.65	3.86 ± 0.78	12.36 ± 1.04	5.62 ± 0.53	2.68 ± 1.3	15.54 ± 1.25	3.08 ± 0.93	3.68 ± 0.44	4.20 ± 0.6	3.86 ± 0.61	6.4 ± 0.43
S109	2.92 ± 0.23	1.7 ± 0.47	4.5 ± 1.04	3.86 ± 0.49	1.64 ± 0.59	0.74 ± 0.25	2.58 ± 0.37	2.22 ± 0.16	4.52 ± 0.34	1.72 ± 0.24	3.58 ± 0.93	4.30 ± 0.8	3.78 ± 0.13
S110	7.82 ± 0.51	8.1 ± 3.73	2.32 ± 0.56	3.54 ± 1.51	17.74 ± 1.68	2.26 ± 0.48	6.12 ± 1.64	10.04 ± 0.93	4.1 ± 2.04	6.84 ± 0.91	14.82 ± 0.79	13.38 ± 1.4	4.78 ± 0.68
S111	6.7 ± 0.24	20.94 ± 0.8	2.8 ± 0.85	2.52 ± 0.45	12.74 ± 1.43	1.02 ± 0.38	2.66 ± 0.48	10.64 ± 1.39	2.04 ± 0.21	2.42 ± 0.55	8.7 ± 0.48	12.24 ± 1.32	1.56 ± 0.27
S112	4.06 ± 0.13	10.08 ± 1.28	1.6 ± 0.58	4.34 ± 0.22	2.84 ± 0.43	1.86 ± 0.42	2.08 ± 0.34	6.56 ± 0.36	3.04 ± 0.29	1.9 ± 0.27	8.22 ± 0.52	4.92 ± 0.77	1.12 ± 0.13
S113	3.8 ± 0.07	4.34 ± 0.73	3.58 ± 0.86	0.78 ± 0.3	2.3 ± 0.35	1.32 ± 0.19	2.92 ± 0.38	7.46 ± 0.6	1.46 ± 0.19	11.72 ± 0.13	1.44 ± 0.27	7.82 ± 0.04	0.54 ± 0.13
S201	4.6 ± 0.2	2.12 ± 1.2	2.54 ± 1.1	1.64 ± 0.84	5.2 ± 0.77	2.26 ± 0.32	2.72 ± 0.31	5.68 ± 1.23	3.14 ± 0.26	11.12 ± 0.5	5.92 ± 0.58	3.74 ± 0.63	9.16 ± 0.22
S202	5.32 ± 0.22	9.7 ± 0.29	3.76 ± 0.81	2.6 ± 0.42	10.72 ± 0.41	1.4 ± 0.21	3.82 ± 0.36	9.66 ± 0.36	4.06 ± 0.19	2.26 ± 0.17	4.08 ± 0.19	5.08 ± 0.56	6.94 ± 0.26

Appendix QQ: CPS/CVS Scores: Self-Selected Slow Cycle: 170mm and 150mm Crank Arms: 150 Side

subject	GPS_Overall	trunk_tilt	trunk_obl	trunk_rot	pel_tilt	pel_obl	pel_rot	hip_flex	hip_abd	hip_rot	knee_flex	ank_dors	foot_prg
S101	4.12 ± 0.33	3.52 ± 1.94	2.88 ± 2.28	3.74 ± 2.13	8.5 ± 0.57	1.96 ± 0.54	1.04 ± 0.18	5.86 ± 0.36	2.5 ± 0.35	2.54 ± 0.36	11.08 ± 0.33	4.9 ± 0.54	0.72 ± 0.04
S102	3.06 ± 0.18	6.5 ± 0.42	2.12 ± 0.59	1.54 ± 0.29	3.34 ± 0.66	1.54 ± 0.47	1.76 ± 0.4	4.58 ± 0.58	4.5 ± 0.35	1.6 ± 0.16	3.36 ± 0.15	5.26 ± 0.98	0.74 ± 0.11
S103	5.1 ± 0.88	12.06 ± 1.06	3.34 ± 1.43	3.42 ± 1.29	2.06 ± 1.04	2.44 ± 0.85	3.8 ± 0.93	4.46 ± 2.05	6.7 ± 0.96	3.06 ± 0.74	3.72 ± 0.28	11.76 ± 7.27	4.74 ± 0.89
S104	4.32 ± 0.15	8.38 ± 1.33	1.26 ± 0.15	2.02 ± 0.46	4.48 ± 0.42	0.96 ± 0.15	1.04 ± 0.42	6.78 ± 0.56	1.34 ± 0.36	6.52 ± 0.22	5.96 ± 0.19	9.3 ± 0.84	3.98 ± 0.15
S105	3.68 ± 0.13	9.48 ± 0.93	2.26 ± 0.63	0.74 ± 0.23	3.82 ± 0.37	3.78 ± 0.65	1.84 ± 0.55	1.84 ± 0.47	2.62 ± 0.41	6.86 ± 0.3	1.42 ± 0.16	6.6 ± 0.73	2.98 ± 0.19
S106	2.42 ± 0.19	1.7 ± 0.67	1.58 ± 0.51	1.06 ± 0.05	1.2 ± 0.23	0.98 ± 0.34	2.76 ± 0.73	1.38 ± 0.48	2.1 ± 0.75	7.8 ± 0.39	3.24 ± 0.33	4.76 ± 1.32	0.64 ± 0.05
S107	7.88 ± 0.8	10.82 ± 0.36	1.74 ± 0.95	0.52 ± 0.13	17.54 ± 0.37	1.96 ± 0.42	2.26 ± 0.59	16.76 ± 1.47	1.86 ± 1.18	5.12 ± 1.03	6.32 ± 1.89	26.26 ± 10.05	3.46 ± 0.27
S108	5.64 ± 0.4	4.0 ± 1.78	2.44 ± 0.75	2.32 ± 1.16	12.04 ± 0.96	6.5 ± 0.41	2.94 ± 0.67	14.42 ± 1.17	4.4 ± 0.46	7.12 ± 0.79	4.18 ± 0.96	4.86 ± 2.09	2.58 ± 0.58
S109	3.66 ± 0.47	7.4 ± 0.41	4.02 ± 1.6	4.1 ± 1.67	2.76 ± 1.58	1.3 ± 0.23	1.98 ± 1.29	3.18 ± 0.62	2.42 ± 1.06	3.8 ± 0.89	4.24 ± 0.58	6.78 ± 1.89	1.84 ± 0.25
S110	6.12 ± 0.25	3.04 ± 1.81	1.84 ± 0.73	2.28 ± 0.65	17.58 ± 0.54	2.0 ± 0.2	3.18 ± 0.47	10.02 ± 0.74	2.58 ± 0.19	6.96 ± 0.6	13.16 ± 0.38	6.72 ± 0.24	4.28 ± 0.26
S111	5.38 ± 0.59	14.52 ± 1.83	2.4 ± 0.82	1.34 ± 0.49	12.46 ± 2.85	2.06 ± 0.59	1.9 ± 0.48	9.28 ± 2.78	1.06 ± 0.3	6.14 ± 0.29	6.34 ± 0.34	5.54 ± 1.45	1.6 ± 0.34
S112	3.46 ± 0.21	2.98 ± 0.54	1.7 ± 0.54	1.78 ± 0.22	1.46 ± 0.18	0.66 ± 0.11	1.42 ± 0.4	4.26 ± 0.56	1.1 ± 0.34	1.4 ± 0.23	7.28 ± 0.86	13.2 ± 1.16	4.24 ± 0.09
S113	4.6 ± 0.43	1.68 ± 0.97	3.16 ± 0.43	0.6 ± 0.16	4.02 ± 0.54	2.58 ± 0.7	2.92 ± 1.11	2.4 ± 0.56	3.36 ± 0.64	14.2 ± 0.91	4.4 ± 0.86	14.24 ± 3.47	1.88 ± 0.36
S201	5.36 ± 0.39	3.28 ± 1.4	2.3 ± 0.82	6.36 ± 0.61	5.9 ± 1.84	2.72 ± 0.41	3.22 ± 0.57	5.54 ± 2.12	2.76 ± 0.75	4.9 ± 0.33	9.4 ± 0.24	13.88 ± 1.1	3.78 ± 0.4
S202	4.46 ± 0.11	2.54 ± 1.04	3.82 ± 0.72	8.0 ± 1.23	4.26 ± 0.68	1.26 ± 0.52	3.88 ± 0.4	6.08 ± 0.81	1.58 ± 0.08	8.5 ± 0.21	2.88 ± 0.16	7.46 ± 0.36	3.08 ± 0.13

Appendix RR: CPS/CVS Scores: Self-Selected Slow Cycle: 170mm and 150mm Crank Arms: 170 Side

subject	GPS_Overall	trunk_tilt	trunk_obl	trunk_rot	pel_tilt	pel_obl	pel_rot	hip_flex	hip_abd	hip_rot	knee_flex	ank_dors	foot_prg
S101	4.46 ± 0.33	3.5 ± 1.72	3.52 ± 2.11	3.50 ± 1.3	8.42 ± 0.86	1.92 ± 0.4	1.02 ± 0.19	2.82 ± 0.57	2.1 ± 0.43	6.66 ± 0.47	11.76 ± 0.42	7.76 ± 0.67	0.72 ± 0.04
S102	2.9 ± 0.1	6.28 ± 0.44	1.54 ± 0.73	1.6 ± 0.42	3.42 ± 0.66	1.62 ± 0.38	1.74 ± 0.4	3.86 ± 0.19	1.28 ± 0.34	1.18 ± 0.32	3.0 ± 0.16	6.42 ± 0.69	3.00 ± 0.1
S103	4.4 ± 0.27	11.26 ± 1.69	3.14 ± 1.01	3.38 ± 1.11	1.88 ± 1.38	2.24 ± 1.04	3.6 ± 0.96	2.4 ± 1.17	3.7 ± 1.42	5.68 ± 0.93	2.84 ± 1.28	7.86 ± 1.78	4.72 ± 1.42
S104	3.68 ± 0.15	8.64 ± 0.85	1.54 ± 0.43	2.16 ± 0.45	4.44 ± 0.62	1.0 ± 0.22	1.04 ± 0.31	5.7 ± 0.42	1.86 ± 0.62	7.54 ± 0.38	3.04 ± 0.15	5.0 ± 0.53	2.30 ± 0.1
S105	4.06 ± 0.19	9.76 ± 0.83	2.58 ± 0.62	0.78 ± 0.29	3.8 ± 0.3	4.02 ± 0.57	1.74 ± 0.55	4.78 ± 0.61	4.02 ± 0.72	2.88 ± 0.43	5.28 ± 0.28	4.22 ± 1.01	5.1 ± 0.35
S106	2.5 ± 0.27	2.04 ± 1.35	2.12 ± 0.38	1.24 ± 0.19	1.22 ± 0.41	0.94 ± 0.33	3.08 ± 0.4	1.36 ± 0.34	2.66 ± 0.97	7.6 ± 0.63	3.92 ± 0.29	3.22 ± 0.66	0.5 ± 0.16
S107	6.94 ± 0.54	10.18 ± 1.47	1.64 ± 1.32	0.6 ± 0.07	17.38 ± 0.78	1.98 ± 0.54	2.0 ± 0.44	16.48 ± 1.94	2.46 ± 0.93	8.6 ± 1.32	3.18 ± 0.51	15.28 ± 8.46	3.36 ± 0.09
S108	5.72 ± 0.18	3.5 ± 1.05	2.52 ± 0.61	2.94 ± 1.25	11.48 ± 1.45	6.68 ± 1.04	2.94 ± 0.82	16.32 ± 2.25	2.32 ± 0.43	2.26 ± 0.8	3.46 ± 0.88	7.24 ± 1.59	7.02 ± 0.43
S109	3.24 ± 0.46	7.88 ± 0.74	3.42 ± 1.34	3.62 ± 2.04	2.98 ± 1.64	1.5 ± 0.37	1.66 ± 0.57	3.38 ± 0.87	3.36 ± 1.32	2.28 ± 0.54	3.1 ± 0.62	4.18 ± 0.9	1.54 ± 0.21
S110	5.1 ± 0.29	2.48 ± 1.68	1.66 ± 0.47	2.14 ± 1.01	17.46 ± 0.48	2.06 ± 0.26	3.0 ± 0.89	11.68 ± 0.36	2.5 ± 0.37	2.24 ± 0.29	10.8 ± 0.6	4.62 ± 0.63	0.66 ± 0.15
S111	6.36 ± 0.34	14.64 ± 2.12	2.12 ± 1.15	1.4 ± 0.31	12.76 ± 2.92	2.28 ± 0.71	2.06 ± 0.26	12.0 ± 2.29	2.16 ± 0.38	5.2 ± 0.7	6.16 ± 0.23	12.76 ± 3.4	2.74 ± 0.46
S112	3.58 ± 0.27	3.48 ± 0.4	1.4 ± 0.52	1.96 ± 0.21	1.38 ± 0.08	0.74 ± 0.15	1.3 ± 0.29	4.92 ± 0.58	1.38 ± 0.43	1.66 ± 0.34	8.48 ± 0.54	13.3 ± 1.38	3.12 ± 0.08
S113	4.08 ± 0.28	1.86 ± 0.54	2.52 ± 0.52	0.74 ± 0.19	4.02 ± 0.38	2.46 ± 0.59	2.48 ± 1.27	9.84 ± 0.55	2.62 ± 0.72	10.18 ± 0.6	1.42 ± 0.3	10.22 ± 1.72	0.52 ± 0.13
S201	5.54 ± 0.32	2.9 ± 1.17	2.28 ± 0.54	6.5 ± 0.59	5.3 ± 2.0	2.72 ± 0.41	3.44 ± 0.89	7.94 ± 2.82	2.52 ± 0.73	8.06 ± 0.62	3.48 ± 1.02	12.28 ± 2.2	8.9 ± 0.72
S202	4.24 ± 0.09	2.88 ± 1.24	4.04 ± 0.62	7.98 ± 1.07	4.26 ± 0.65	1.1 ± 0.58	3.86 ± 0.42	5.32 ± 0.79	4.48 ± 0.61	1.62 ± 0.39	4.68 ± 0.24	5.3 ± 1.31	5.46 ± 0.17

Appendix SS: CPS/CVS Scores: Self-Selected Fast Cycle: 170mm and 150mm Crank Arms: 150 Side

subject	GPS_Overall	trunk_tilt	trunk_obl	trunk_rot	pel_tilt	pel_obl	pel_rot	hip_flex	hip_abd	hip_rot	knee_flex	ank_dors	foot_prg
S101	4.42 ± 0.13	9.2 ± 1.15	1.06 ± 0.36	0.98 ± 0.41	7.9 ± 0.62	1.86 ± 0.15	1.68 ± 0.31	6.28 ± 0.56	3.16 ± 0.34	2.08 ± 0.54	8.58 ± 0.86	8.42 ± 0.54	1.72 ± 0.18
S102	3.52 ± 0.13	5.04 ± 0.97	2.92 ± 0.58	4.96 ± 0.72	4.72 ± 0.48	2.02 ± 0.33	1.22 ± 0.44	4.68 ± 0.25	4.62 ± 0.19	2.9 ± 0.27	3.02 ± 0.13	5.36 ± 0.59	0.92 ± 0.04
S103	9.2 ± 0.46	24.1 ± 2.39	1.6 ± 0.27	5.56 ± 2.18	20.22 ± 1.41	4.38 ± 0.85	3.04 ± 0.43	20.02 ± 1.31	7.5 ± 0.8	4.24 ± 0.3	2.44 ± 0.59	9.84 ± 3.58	7.42 ± 1.45
S104	4.14 ± 0.21	7.06 ± 1.4	1.78 ± 0.89	3.86 ± 0.97	1.62 ± 0.36	1.36 ± 0.13	1.14 ± 0.18	5.46 ± 0.7	1.34 ± 0.21	6.8 ± 0.47	7.38 ± 0.13	7.90 ± 1.2	3.82 ± 0.18
S105	3.86 ± 0.27	7.44 ± 1.9	3.7 ± 0.78	2.34 ± 0.38	1.84 ± 0.61	4.72 ± 0.54	1.76 ± 0.46	4.74 ± 0.55	3.5 ± 0.52	7.64 ± 0.31	1.68 ± 0.3	4.78 ± 1.53	2.2 ± 0.39
S106	3.56 ± 0.13	1.32 ± 0.59	2.6 ± 1.17	0.9 ± 0.29	8.44 ± 0.81	1.04 ± 0.19	2.68 ± 0.22	7.64 ± 0.46	2.16 ± 0.43	8.0 ± 0.25	3.6 ± 0.57	3.66 ± 0.56	0.94 ± 0.58
S107	5.78 ± 0.59	2.20 ± 1.2	1.74 ± 0.87	0.8 ± 0.29	17.3 ± 2.55	2.74 ± 0.75	2.38 ± 1.7	16.68 ± 1.37	1.72 ± 1.14	3.34 ± 0.59	2.38 ± 0.44	11.02 ± 6.43	7.2 ± 0.73
S108	6.24 ± 0.66	4.6 ± 1.33	2.14 ± 0.5	2.92 ± 0.93	15.08 ± 2.08	6.98 ± 0.52	2.1 ± 1.44	14.24 ± 1.64	4.32 ± 0.65	5.68 ± 0.81	5.32 ± 1.37	9.62 ± 1.31	2.06 ± 0.34
S109	3.54 ± 0.29	4.78 ± 1.11	5.38 ± 1.02	1.7 ± 1.48	2.06 ± 0.84	0.88 ± 0.34	1.5 ± 0.81	1.98 ± 0.61	2.5 ± 0.75	5.46 ± 0.79	4.14 ± 0.63	8.72 ± 0.95	3.1 ± 0.19
S110	6.08 ± 0.45	1.98 ± 0.82	1.7 ± 0.88	3.32 ± 0.66	16.12 ± 1.73	1.54 ± 0.25	3.38 ± 0.46	7.9 ± 1.29	1.82 ± 0.5	8.92 ± 1.22	14.34 ± 0.49	9.7 ± 0.62	2.32 ± 0.23
S111	6.22 ± 0.46	19.82 ± 0.82	1.88 ± 0.94	1.92 ± 1.45	13.16 ± 1.98	1.76 ± 0.6	2.48 ± 0.37	9.36 ± 1.56	2.1 ± 0.57	6.34 ± 0.46	6.94 ± 0.57	6.76 ± 0.81	1.96 ± 0.63
S112	3.24 ± 0.21	10.52 ± 0.66	1.7 ± 0.49	2.52 ± 0.22	1.34 ± 0.48	1.18 ± 0.36	1.24 ± 0.18	2.92 ± 0.74	1.78 ± 0.13	1.94 ± 0.19	5.98 ± 0.66	4.82 ± 0.79	3.1 ± 0.16
S113	3.98 ± 0.11	6.1 ± 1.18	3.02 ± 0.43	2.66 ± 0.3	1.46 ± 0.42	1.46 ± 0.23	2.18 ± 0.43	1.54 ± 0.15	2.84 ± 0.32	13.28 ± 0.27	3.2 ± 0.19	8.56 ± 0.86	1.5 ± 0.34
S201	9.44 ± 1.11	4.32 ± 1.74	3.2 ± 0.69	3.86 ± 0.44	26.2 ± 5.92	2.9 ± 0.55	3.82 ± 0.28	29.2 ± 6.36	6.5 ± 0.42	5.58 ± 0.18	8.36 ± 0.7	14.76 ± 0.28	4.64 ± 0.09
S202	7.32 ± 0.22	10.3 ± 0.75	5.26 ± 0.62	4.7 ± 0.31	12.14 ± 1.03	1.64 ± 0.36	4.48 ± 0.4	10.78 ± 0.98	2.4 ± 0.22	8.54 ± 0.11	4.82 ± 0.08	17.76 ± 0.63	5.08 ± 0.25

Appendix TT: CPS/CVS Scores: Self-Selected Fast Cycle: 170mm and 150mm Crank Arms: 170 Side

subject	GPS_Overall	trunk_tilt	trunk_obl	trunk_rot	pel_tilt	pel_obl	pel_rot	hip_flex	hip_abd	hip_rot	knee_flex	ank_dors	foot_prg
S101	4.64 ± 0.09	9.52 ± 1.37	0.86 ± 0.3	1.14 ± 0.44	7.68 ± 0.59	1.96 ± 0.09	1.76 ± 0.31	3.16 ± 0.34	3.14 ± 0.54	5.78 ± 0.44	11.28 ± 0.45	8.82 ± 0.59	0.84 ± 0.09
S102	3.44 ± 0.15	5.34 ± 1.14	2.86 ± 0.46	4.5 ± 0.74	4.28 ± 0.41	2.14 ± 0.32	1.14 ± 0.3	3.98 ± 0.51	1.46 ± 0.32	3.54 ± 0.36	2.7 ± 0.37	6.06 ± 0.62	3.14 ± 0.29
S103	8.44 ± 0.69	23.92 ± 2.69	1.6 ± 0.53	6.2 ± 1.65	20.28 ± 1.65	4.36 ± 1.06	2.76 ± 0.7	16.22 ± 1.72	4.94 ± 1.3	5.46 ± 1.56	2.88 ± 0.29	7.8 ± 1.06	4.86 ± 0.4
S104	3.48 ± 0.19	7.22 ± 1.36	1.88 ± 0.36	3.62 ± 1.08	1.74 ± 0.46	1.46 ± 0.17	1.0 ± 0.25	4.5 ± 0.66	1.76 ± 0.23	8.68 ± 0.18	4.0 ± 0.25	4.18 ± 0.44	2.16 ± 0.09
S105	4.48 ± 0.15	6.9 ± 1.84	3.64 ± 0.77	2.14 ± 0.38	1.58 ± 0.39	4.84 ± 0.44	1.64 ± 0.42	9.08 ± 0.15	4.22 ± 0.28	3.66 ± 0.44	5.74 ± 0.63	5.68 ± 1.24	4.64 ± 0.3
S106	3.42 ± 0.16	1.22 ± 0.57	2.52 ± 1.13	0.72 ± 0.27	7.86 ± 0.76	1.16 ± 0.34	2.34 ± 0.61	6.7 ± 0.68	2.64 ± 0.48	6.7 ± 0.53	4.92 ± 0.43	3.42 ± 0.52	0.76 ± 0.11
S107	5.68 ± 0.36	1.72 ± 0.48	1.84 ± 1.03	0.8 ± 0.57	17.46 ± 1.83	2.8 ± 0.53	2.28 ± 1.94	17.62 ± 1.29	2.1 ± 0.78	9.66 ± 0.96	2.64 ± 0.64	8.04 ± 3.22	1.32 ± 0.29
S108	6.48 ± 0.38	4.38 ± 2.23	2.06 ± 0.46	3.02 ± 0.93	15.84 ± 2.22	6.78 ± 0.51	2.4 ± 0.9	18.06 ± 1.08	3.72 ± 1.06	3.6 ± 0.42	6.0 ± 0.97	4.96 ± 1.79	7.08 ± 0.96
S109	2.74 ± 0.27	4.46 ± 0.89	5.54 ± 0.59	1.8 ± 1.63	1.96 ± 0.9	0.98 ± 0.4	1.58 ± 0.39	2.58 ± 0.83	2.46 ± 0.53	1.7 ± 0.48	3.64 ± 0.84	5.54 ± 0.74	0.7 ± 0.23
S110	5.56 ± 0.23	1.86 ± 0.49	1.98 ± 1.04	3.46 ± 0.42	16.08 ± 2.12	1.36 ± 0.27	3.1 ± 0.41	10.64 ± 1.74	2.44 ± 0.42	3.68 ± 0.5	11.86 ± 0.52	8.74 ± 1.38	1.64 ± 0.49
S111	6.9 ± 0.47	19.44 ± 1.24	2.06 ± 0.9	2.46 ± 1.47	13.2 ± 1.65	1.64 ± 0.36	2.42 ± 0.28	11.14 ± 1.27	3.08 ± 0.48	5.38 ± 0.72	8.26 ± 0.26	13.0 ± 0.74	0.68 ± 0.26
S112	3.68 ± 0.16	10.36 ± 0.49	1.98 ± 0.95	2.4 ± 0.35	1.14 ± 0.42	1.14 ± 0.29	1.36 ± 0.26	4.96 ± 0.42	2.18 ± 0.19	1.56 ± 0.5	9.36 ± 0.83	5.16 ± 0.62	2.5 ± 0.14
S113	3.88 ± 0.11	6.1 ± 0.97	3.14 ± 0.42	2.36 ± 0.58	1.52 ± 0.51	1.4 ± 0.25	2.34 ± 0.61	5.86 ± 0.36	1.64 ± 0.46	10.6 ± 0.31	1.52 ± 0.4	8.62 ± 0.83	1.62 ± 0.08
S201	8.38 ± 0.58	4.04 ± 1.69	3.34 ± 0.54	3.74 ± 0.34	27.04 ± 3.91	3.1 ± 0.16	3.78 ± 0.11	26.76 ± 4.37	2.24 ± 0.59	7.98 ± 0.52	5.08 ± 0.54	4.52 ± 1.8	8.8 ± 0.14
S202	6.18 ± 0.15	10.1 ± 0.67	5.3 ± 0.56	4.74 ± 0.53	11.7 ± 0.85	1.66 ± 0.37	4.4 ± 0.29	10.98 ± 0.58	5.24 ± 0.4	1.34 ± 0.21	5.12 ± 0.27	8.52 ± 0.91	4.72 ± 0.25

Appendix UU: CPS/CVS Scores: Self-Selected Slow Cycle: 170mm and 130mm Crank Arms: 130 Side

subject	GPS_Overall	trunk_tilt	trunk_obl	trunk_rot	pel_tilt	pel_obl	pel_rot	hip_flex	hip_abd	hip_rot	knee_flex	ank_dors	foot_prg
S101	3.78 ± 0.35	5.62 ± 2.7	2.36 ± 0.73	2.66 ± 1.35	4.0 ± 1.28	2.0 ± 0.35	2.08 ± 0.78	2.84 ± 0.84	1.96 ± 0.45	1.74 ± 0.49	10.26 ± 1.29	4.58 ± 0.85	5.34 ± 0.3
S102	5.26 ± 0.36	6.62 ± 1.0	2.58 ± 1.08	1.76 ± 0.32	9.2 ± 0.49	1.52 ± 0.43	1.98 ± 0.65	10.98 ± 0.75	4.82 ± 0.65	5.64 ± 0.67	4.68 ± 0.79	12.26 ± 2.88	1.14 ± 0.09
S103	6.12 ± 0.87	9.3 ± 4.38	7.06 ± 3.5	6.42 ± 4.84	4.26 ± 1.78	3.88 ± 1.52	3.58 ± 2.32	5.5 ± 2.74	2.9 ± 1.65	2.48 ± 0.33	4.64 ± 0.72	17.86 ± 9.36	5.66 ± 0.64
S104	4.72 ± 0.3	6.88 ± 2.72	1.8 ± 0.27	2.7 ± 0.28	4.28 ± 0.55	1.76 ± 0.42	1.3 ± 0.31	5.96 ± 0.35	0.96 ± 0.29	5.26 ± 0.55	6.62 ± 0.22	14.52 ± 0.79	4.74 ± 0.48
S105	4.22 ± 0.11	10.74 ± 0.94	2.62 ± 0.44	1.88 ± 0.08	1.16 ± 0.25	3.44 ± 0.32	2.08 ± 0.36	2.12 ± 0.44	3.3 ± 0.4	5.8 ± 0.24	2.28 ± 0.27	10.76 ± 1.63	4.16 ± 0.36
S106	3.14 ± 0.38	5.82 ± 1.14	1.14 ± 0.62	0.84 ± 0.27	2.56 ± 1.4	1.04 ± 0.55	1.64 ± 0.36	2.62 ± 1.78	2.2 ± 0.28	8.72 ± 0.55	3.38 ± 0.33	6.72 ± 0.51	0.84 ± 0.29
S107	5.68 ± 0.55	5.2 ± 1.76	2.9 ± 1.97	0.92 ± 0.19	14.12 ± 2.15	2.5 ± 0.75	1.96 ± 0.49	13.3 ± 2.24	2.04 ± 1.0	3.44 ± 0.89	3.36 ± 0.73	14.74 ± 2.91	3.36 ± 0.5
S108	5.9 ± 0.84	4.7 ± 2.64	1.96 ± 0.66	3.28 ± 0.81	12.92 ± 1.59	6.28 ± 0.48	2.6 ± 1.39	13.4 ± 0.47	4.1 ± 0.9	6.36 ± 0.41	3.98 ± 1.65	8.54 ± 3.89	2.60 ± 0.8
S109	3.04 ± 0.46	4.36 ± 2.59	2.58 ± 1.06	1.66 ± 0.67	1.04 ± 0.43	2.18 ± 0.65	1.78 ± 0.46	3.38 ± 0.71	2.6 ± 0.9	2.88 ± 0.58	4.3 ± 0.77	7.26 ± 2.99	2.42 ± 0.52
S110	5.56 ± 0.42	2.38 ± 1.13	1.72 ± 0.75	2.76 ± 0.59	15.24 ± 2.51	2.74 ± 0.68	2.44 ± 0.45	9.04 ± 2.16	3.84 ± 1.02	6.56 ± 0.6	10.98 ± 0.47	5.10 ± 1.9	3.8 ± 0.64
S111	4.9 ± 0.22	16.2 ± 0.45	3.92 ± 1.05	1.8 ± 0.51	7.6 ± 0.97	0.86 ± 0.42	2.52 ± 0.72	4.44 ± 1.0	1.42 ± 0.4	4.18 ± 0.54	7.06 ± 0.37	6.96 ± 1.24	2.0 ± 0.29
S112	4.94 ± 0.64	4.88 ± 0.53	2.46 ± 0.36	4.3 ± 0.39	1.04 ± 0.55	2.0 ± 0.23	2.42 ± 0.54	5.94 ± 1.75	2.1 ± 0.39	2.56 ± 0.73	8.76 ± 2.56	20.2 ± 3.35	2.82 ± 0.15
S113	3.84 ± 0.25	1.88 ± 1.26	1.24 ± 0.05	0.9 ± 0.23	1.66 ± 0.3	1.3 ± 0.81	3.56 ± 0.43	3.18 ± 0.34	3.04 ± 0.67	13.8 ± 0.71	4.44 ± 0.62	10.08 ± 2.06	0.90 ± 0.7
S201	4.44 ± 0.21	2.96 ± 0.88	3.12 ± 0.93	5.62 ± 0.86	2.56 ± 0.69	1.48 ± 0.15	2.6 ± 0.43	1.18 ± 0.38	3.38 ± 0.18	5.84 ± 0.05	6.14 ± 0.37	14.54 ± 1.16	4.0 ± 0.23
S202	4.74 ± 0.22	4.44 ± 0.3	4.86 ± 0.77	9.34 ± 0.8	2.96 ± 0.39	1.3 ± 0.24	3.04 ± 0.49	1.38 ± 0.22	2.68 ± 0.23	10.32 ± 0.25	2.16 ± 0.36	10.46 ± 1.0	3.8 ± 0.07

Appendix VV: CPS/CVS Scores: Self-Selected Slow Cycle: 170mm and 130mm Crank Arms: 170 Side

subject	GPS_Overall	trunk_tilt	trunk_obl	trunk_rot	pel_tilt	pel_obl	pel_rot	hip_flex	hip_abd	hip_rot	knee_flex	ank_dors	foot_prg
S101	4.16 ± 0.27	6.2 ± 2.12	2.36 ± 0.57	2.2 ± 1.07	4.0 ± 1.21	1.58 ± 0.33	2.42 ± 1.28	3.7 ± 1.02	2.52 ± 1.37	5.82 ± 1.08	10.58 ± 0.56	7.48 ± 0.93	1.1 ± 0.16
S102	4.98 ± 0.5	6.78 ± 1.37	3.16 ± 0.63	1.68 ± 0.67	9.28 ± 0.27	1.18 ± 0.3	2.02 ± 0.54	8.34 ± 0.78	3.62 ± 1.55	2.64 ± 1.05	3.98 ± 0.55	13.04 ± 3.86	4.10 ± 0.2
S103	5.26 ± 0.67	9.04 ± 4.49	6.9 ± 3.44	6.22 ± 5.16	3.9 ± 1.85	3.94 ± 1.45	3.8 ± 2.02	3.18 ± 1.33	3.64 ± 0.99	6.16 ± 0.98	2.88 ± 1.15	9.22 ± 2.57	3.9 ± 0.45
S104	3.8 ± 0.44	6.4 ± 2.16	1.82 ± 0.51	2.42 ± 0.33	4.06 ± 0.58	1.36 ± 0.33	1.12 ± 0.2	5.48 ± 0.69	1.68 ± 0.26	9.22 ± 0.31	4.18 ± 0.38	5.58 ± 1.8	2.24 ± 0.09
S105	4.12 ± 0.18	10.72 ± 1.57	2.52 ± 1.04	1.72 ± 0.26	1.14 ± 0.41	3.1 ± 0.14	1.96 ± 0.28	6.94 ± 1.05	4.4 ± 0.32	2.68 ± 0.33	4.52 ± 0.22	6.12 ± 1.4	3.44 ± 0.6
S106	2.86 ± 0.21	5.5 ± 1.26	1.1 ± 0.21	0.94 ± 0.18	2.22 ± 1.12	0.88 ± 0.41	1.62 ± 0.52	2.48 ± 0.93	2.46 ± 0.61	5.56 ± 0.54	5.44 ± 0.27	5.0 ± 0.51	1.24 ± 0.47
S107	5.44 ± 0.85	5.5 ± 1.96	2.80 ± 2.0	0.88 ± 0.08	14.04 ± 2.67	2.72 ± 0.77	1.76 ± 0.59	13.76 ± 2.52	2.54 ± 0.83	8.26 ± 0.93	2.64 ± 0.9	8.86 ± 5.21	2.0 ± 0.72
S108	6.0 ± 0.34	4.72 ± 2.72	1.96 ± 0.84	3.44 ± 0.79	13.28 ± 1.24	6.86 ± 0.33	2.4 ± 1.43	16.78 ± 1.15	4.52 ± 0.77	1.64 ± 0.34	3.68 ± 1.11	5.84 ± 1.51	6.78 ± 0.29
S109	2.36 ± 0.36	4.14 ± 2.57	2.26 ± 0.64	1.64 ± 0.46	1.14 ± 0.52	1.76 ± 0.5	1.98 ± 0.7	2.34 ± 0.77	3.9 ± 1.0	2.18 ± 0.68	2.34 ± 0.73	3.56 ± 1.7	1.06 ± 0.45
S110	4.78 ± 0.24	2.76 ± 1.46	1.62 ± 0.55	2.88 ± 0.51	14.64 ± 1.66	2.86 ± 0.74	2.62 ± 0.44	10.32 ± 1.17	2.66 ± 0.57	1.52 ± 0.45	8.52 ± 0.81	5.64 ± 0.81	1.28 ± 0.7
S111	5.98 ± 0.33	16.16 ± 0.81	3.98 ± 1.44	1.9 ± 0.74	7.68 ± 0.85	0.84 ± 0.34	2.42 ± 0.23	6.74 ± 0.58	2.5 ± 0.6	4.42 ± 0.7	8.5 ± 0.72	13.32 ± 2.94	3.14 ± 0.49
S112	5.16 ± 0.21	4.6 ± 0.54	2.44 ± 0.69	4.28 ± 0.4	1.12 ± 0.73	2.48 ± 0.15	2.26 ± 0.75	7.6 ± 0.88	3.7 ± 0.99	2.4 ± 0.19	11.74 ± 0.94	16.3 ± 0.9	2.92 ± 0.28
S113	4.02 ± 0.23	1.96 ± 1.22	1.02 ± 0.19	0.78 ± 0.18	1.62 ± 0.31	1.06 ± 0.52	3.56 ± 0.77	6.72 ± 0.69	3.92 ± 0.86	12.86 ± 0.9	1.74 ± 0.44	12.28 ± 1.7	0.68 ± 0.19
S201	4.16 ± 0.22	3.06 ± 0.69	3.38 ± 1.01	5.72 ± 0.88	2.6 ± 0.55	1.18 ± 0.28	2.86 ± 0.19	4.24 ± 0.4	1.92 ± 0.35	7.48 ± 0.45	2.1 ± 0.56	4.4 ± 0.63	11.18 ± 0.13
S202	4.26 ± 0.15	4.36 ± 0.52	4.98 ± 0.65	9.16 ± 0.95	3.1 ± 0.44	0.9 ± 0.32	2.78 ± 0.68	3.8 ± 0.48	3.3 ± 0.17	2.1 ± 0.14	4.78 ± 0.16	4.46 ± 1.06	7.26 ± 0.29

Appendix WW: CPS/CVS Scores: Self-Selected Fast Cycle: 170mm and 130mm Crank Arms: 130 Side

subject	GPS_Overall	trunk_tilt	trunk_obl	trunk_rot	pel_tilt	pel_obl	pel_rot	hip_flex	hip_abd	hip_rot	knee_flex	ank_dors	foot_prg
S101	4.64 ± 0.56	7.08 ± 5.88	1.7 ± 0.78	1.26 ± 0.68	9.3 ± 1.1	2.1 ± 0.45	1.82 ± 0.76	7.38 ± 0.68	2.68 ± 0.75	1.32 ± 0.5	7.24 ± 0.84	7.3 ± 2.09	6.32 ± 0.43
S102	4.54 ± 0.18	5.9 ± 0.72	4.58 ± 0.85	6.98 ± 0.63	4.64 ± 0.47	1.6 ± 0.16	2.32 ± 0.46	7.84 ± 0.65	3.94 ± 0.34	6.92 ± 0.39	3.66 ± 0.18	3.96 ± 1.3	2.16 ± 0.15
S103	8.42 ± 0.67	18.88 ± 4.07	6.36 ± 2.3	7.86 ± 1.39	16.0 ± 2.43	4.22 ± 0.77	3.66 ± 2.22	15.84 ± 2.68	6.42 ± 2.14	3.66 ± 0.77	1.94 ± 0.99	9.98 ± 2.72	6.18 ± 1.15
S104	4.56 ± 0.4	8.42 ± 2.04	1.18 ± 0.43	1.68 ± 1.06	3.22 ± 0.88	2.28 ± 0.54	0.9 ± 0.44	6.58 ± 1.18	1.66 ± 0.88	5.7 ± 0.69	7.46 ± 0.43	11.14 ± 1.21	4.4 ± 0.26
S105	4.92 ± 0.22	18.22 ± 1.15	1.22 ± 0.59	1.72 ± 0.54	4.42 ± 0.91	3.58 ± 0.3	2.38 ± 0.2	4.48 ± 0.71	4.16 ± 0.24	6.56 ± 0.29	3.16 ± 0.23	5.28 ± 1.9	3.74 ± 0.38
S106	4.28 ± 0.4	5.38 ± 1.66	3.08 ± 0.69	3.28 ± 0.91	5.88 ± 1.08	1.46 ± 0.36	2.96 ± 0.61	5.02 ± 1.1	2.56 ± 0.73	8.08 ± 0.47	4.76 ± 0.29	6.62 ± 0.51	2.3 ± 1.02
S107	6.48 ± 1.26	6.38 ± 4.17	4.48 ± 3.09	2.08 ± 0.62	17.9 ± 1.65	2.42 ± 0.92	3.1 ± 1.31	17.72 ± 0.78	1.66 ± 0.73	4.22 ± 0.85	3.8 ± 0.91	10.68 ± 4.0	3.6 ± 0.85
S108	6.26 ± 0.28	11.18 ± 1.98	3.82 ± 0.74	5.98 ± 1.03	10.96 ± 1.06	6.0 ± 0.51	2.72 ± 0.35	12.04 ± 1.18	3.8 ± 0.51	4.8 ± 0.94	4.02 ± 0.72	7.42 ± 2.52	2.44 ± 0.27
S109	3.5 ± 0.16	6.72 ± 1.1	5.0 ± 2.25	2.22 ± 0.73	1.36 ± 0.43	1.18 ± 0.08	1.56 ± 0.5	3.76 ± 0.84	2.38 ± 0.8	4.12 ± 0.29	3.48 ± 0.34	8.56 ± 1.22	1.5 ± 0.43
S110	6.12 ± 0.51	2.8 ± 1.85	1.98 ± 0.68	2.6 ± 0.49	18.22 ± 1.47	3.18 ± 0.44	3.9 ± 0.79	10.86 ± 0.96	4.54 ± 0.74	7.76 ± 0.4	10.94 ± 0.68	4.42 ± 1.32	2.24 ± 0.23
S111	6.12 ± 0.45	21.8 ± 1.15	1.44 ± 0.94	1.2 ± 0.24	13.28 ± 0.48	1.16 ± 0.4	2.64 ± 0.72	10.26 ± 0.51	2.02 ± 0.58	4.3 ± 0.95	6.52 ± 0.56	7.44 ± 2.03	1.3 ± 0.21
S112	3.5 ± 0.2	9.32 ± 1.02	2.16 ± 0.74	3.16 ± 1.39	2.68 ± 0.44	1.66 ± 0.54	1.64 ± 0.11	2.86 ± 0.37	1.76 ± 0.32	3.34 ± 0.15	4.88 ± 0.36	5.72 ± 2.07	2.96 ± 0.11
S113	3.52 ± 0.22	3.3 ± 0.86	3.54 ± 0.54	0.94 ± 0.34	1.04 ± 0.29	1.26 ± 0.38	4.02 ± 0.5	1.62 ± 0.19	2.96 ± 0.18	13.3 ± 0.4	3.68 ± 0.58	6.22 ± 0.68	0.66 ± 0.28
S201	4.96 ± 0.09	6.1 ± 1.61	2.42 ± 1.11	3.48 ± 0.79	2.0 ± 0.53	1.62 ± 0.49	2.22 ± 0.29	3.66 ± 0.54	5.90 ± 0.2	6.9 ± 0.31	5.92 ± 0.62	14.74 ± 0.39	4.74 ± 0.27
S202	6.76 ± 0.15	12.14 ± 0.17	5.26 ± 0.44	4.82 ± 0.16	9.54 ± 0.26	1.68 ± 0.19	3.76 ± 0.17	5.36 ± 0.18	2.08 ± 0.24	10.28 ± 0.15	4.9 ± 0.22	16.08 ± 1.38	5.38 ± 0.16

Appendix XX: CPS/CVS Scores: Self-Selected Fast Cycle: 170mm and 130mm Crank Arms: 170 Side

subject	GPS_Overall	trunk_tilt	trunk_obl	trunk_rot	pel_tilt	pel_obl	pel_rot	hip_flex	hip_abd	hip_rot	knee_flex	ank_dors	foot_prg
S101	4.46 ± 0.46	6.78 ± 4.78	1.88 ± 0.41	1.18 ± 0.66	9.16 ± 1.11	2.04 ± 0.42	1.6 ± 0.92	3.74 ± 0.68	2.56 ± 0.98	5.66 ± 0.67	9.34 ± 0.75	8.62 ± 0.41	1.24 ± 0.27
S102	4.1 ± 0.1	5.86 ± 0.48	4.3 ± 0.92	6.54 ± 0.8	4.38 ± 0.48	1.64 ± 0.27	2.16 ± 0.27	3.6 ± 0.55	1.74 ± 0.44	3.62 ± 0.22	2.82 ± 0.2	8.68 ± 2.21	4.0 ± 0.41
S103	8.06 ± 0.65	19.24 ± 4.42	6.36 ± 2.61	7.46 ± 1.58	16.44 ± 2.36	4.18 ± 0.63	3.72 ± 1.53	12.7 ± 1.88	5.34 ± 1.7	6.16 ± 0.97	2.04 ± 0.32	9.32 ± 2.78	3.94 ± 1.0
S104	3.86 ± 0.28	8.82 ± 1.16	1.04 ± 0.22	1.5 ± 1.01	3.6 ± 0.74	2.14 ± 0.54	1.0 ± 0.52	6.36 ± 0.65	2.24 ± 0.47	9.82 ± 0.7	4.24 ± 0.22	3.98 ± 0.54	1.56 ± 0.18
S105	5.24 ± 0.21	17.84 ± 2.06	1.18 ± 0.33	1.36 ± 0.47	4.28 ± 0.54	3.56 ± 0.35	2.3 ± 0.19	10.78 ± 0.54	4.72 ± 0.11	2.66 ± 0.32	4.28 ± 0.15	6.82 ± 2.87	3.14 ± 0.29
S106	3.92 ± 0.37	5.78 ± 0.83	3.42 ± 0.44	3.34 ± 0.86	5.58 ± 1.25	1.4 ± 0.62	2.74 ± 0.48	4.74 ± 1.15	3.12 ± 0.69	6.66 ± 0.43	4.62 ± 0.4	4.84 ± 0.99	1.08 ± 0.16
S107	6.72 ± 1.22	6.06 ± 3.63	3.68 ± 3.26	2.16 ± 0.91	17.34 ± 2.17	2.54 ± 0.76	3.24 ± 1.47	16.46 ± 2.4	2.9 ± 1.34	9.46 ± 1.75	2.48 ± 0.88	12.48 ± 2.72	2.02 ± 0.41
S108	6.7 ± 0.32	10.74 ± 2.77	4.1 ± 0.93	6.46 ± 0.84	11.38 ± 0.99	6.1 ± 0.62	2.48 ± 0.41	14.76 ± 1.01	4.24 ± 0.58	3.72 ± 0.55	5.0 ± 1.32	3.78 ± 1.01	7.42 ± 0.29
S109	2.84 ± 0.3	6.72 ± 1.15	4.8 ± 2.12	2.4 ± 0.86	1.4 ± 0.47	1.04 ± 0.4	1.72 ± 0.24	2.22 ± 0.58	3.08 ± 0.33	1.78 ± 0.52	4.28 ± 1.24	3.56 ± 0.75	1.1 ± 0.58
S110	5.74 ± 0.18	2.02 ± 1.0	1.96 ± 0.56	2.88 ± 0.7	17.92 ± 0.76	3.36 ± 0.3	3.52 ± 0.36	12.28 ± 0.55	1.2 ± 0.61	4.12 ± 0.63	10.38 ± 1.28	7.8 ± 0.48	1.38 ± 0.48
S111	7.06 ± 0.11	21.86 ± 0.53	1.86 ± 0.89	1.44 ± 0.55	12.82 ± 1.07	1.0 ± 0.31	2.84 ± 0.6	11.78 ± 0.61	2.32 ± 0.95	4.02 ± 1.41	7.04 ± 1.02	15.4 ± 3.19	2.22 ± 0.78
S112	4.5 ± 0.34	9.28 ± 1.13	2.38 ± 0.22	3.24 ± 1.53	3.22 ± 0.7	1.68 ± 0.54	1.76 ± 0.26	3.46 ± 0.26	2.82 ± 0.65	2.32 ± 0.33	11.4 ± 0.98	10.14 ± 1.83	2.48 ± 0.15
S113	3.82 ± 0.11	3.68 ± 1.43	3.24 ± 0.51	0.6 ± 0.23	1.3 ± 0.25	1.26 ± 0.45	4.26 ± 0.48	5.26 ± 0.8	3.6 ± 0.4	12.28 ± 0.37	1.34 ± 0.43	8.24 ± 1.0	0.58 ± 0.15
S201	3.9 ± 0.14	5.94 ± 1.73	2.52 ± 1.17	3.38 ± 0.79	1.92 ± 0.33	1.68 ± 0.48	2.12 ± 0.3	1.46 ± 0.25	1.22 ± 0.3	9.38 ± 0.56	3.02 ± 0.54	2.8 ± 0.51	11.52 ± 0.53
S202	5.84 ± 0.21	12.2 ± 0.25	5.32 ± 0.29	4.92 ± 0.08	9.28 ± 0.28	1.62 ± 0.19	3.32 ± 0.31	8.44 ± 0.32	3.94 ± 0.26	1.84 ± 0.11	5.02 ± 0.46	7.18 ± 1.79	7.34 ± 0.33

Appendix YY: Variance Accounted For: Self-Selected Slow Walk

Total Variance Accounted for During Slow Walk: Right

subject	1 Synergy	2 Synergy	3 Synergy	4 Synergy
S101	0.71 ± 0.02	0.89 ± 0.01	0.97 ± 0.01	0.99 ± 0.01
S102	0.71 ± 0.05	0.89 ± 0.03	0.96 ± 0.02	0.99 ± 0.0
S103	0.69 ± 0.05	0.84 ± 0.04	0.93 ± 0.03	0.98 ± 0.01
S104	0.61 ± 0.03	0.86 ± 0.01	0.94 ± 0.02	0.99 ± 0.0
S105	0.75 ± 0.02	0.87 ± 0.01	0.94 ± 0.01	0.99 ± 0.01
S106	0.51 ± 0.05	0.79 ± 0.02	0.9 ± 0.02	0.99 ± 0.01
S107	0.75 ± 0.05	0.9 ± 0.03	0.96 ± 0.01	0.99 ± 0.01
S108	0.62 ± 0.03	0.8 ± 0.02	0.92 ± 0.02	0.99 ± 0.01
S109	0.74 ± 0.02	0.91 ± 0.02	0.97 ± 0.01	1.0 ± 0.0
S110	0.62 ± 0.06	0.9 ± 0.04	0.97 ± 0.02	0.99 ± 0.01
S111	0.74 ± 0.04	0.88 ± 0.02	0.96 ± 0.01	0.99 ± 0.0
S112	0.71 ± 0.04	0.85 ± 0.03	0.97 ± 0.01	0.99 ± 0.0
S201	0.81 ± 0.02	0.95 ± 0.0	0.98 ± 0.0	1.0 ± 0.0
S202	0.59 ± 0.03	0.8 ± 0.04	0.9 ± 0.03	0.97 ± 0.01

Total Variance Accounted for During Slow Walk: Left

subject	1 Synergy	2 Synergy	3 Synergy	4 Synergy
S101	0.74 ± 0.02	0.87 ± 0.03	0.94 ± 0.01	0.98 ± 0.01
S102	0.63 ± 0.04	0.85 ± 0.02	0.97 ± 0.01	0.99 ± 0.0
S103	0.63 ± 0.05	0.84 ± 0.06	0.93 ± 0.04	0.99 ± 0.01
S104	0.59 ± 0.02	0.79 ± 0.01	0.93 ± 0.01	0.99 ± 0.0
S105	0.79 ± 0.03	0.9 ± 0.01	0.96 ± 0.01	0.99 ± 0.01
S106	0.62 ± 0.02	0.82 ± 0.04	0.91 ± 0.03	0.99 ± 0.02
S107	0.84 ± 0.03	0.93 ± 0.03	0.97 ± 0.02	0.99 ± 0.01
S108	0.58 ± 0.04	0.85 ± 0.02	0.96 ± 0.02	1.0 ± 0.0
S109	0.71 ± 0.02	0.92 ± 0.02	0.98 ± 0.0	0.99 ± 0.0
S110	0.62 ± 0.03	0.9 ± 0.03	0.97 ± 0.02	0.99 ± 0.01
S111	0.72 ± 0.04	0.89 ± 0.01	0.96 ± 0.01	0.99 ± 0.0
S112	0.72 ± 0.01	0.88 ± 0.01	0.96 ± 0.0	0.99 ± 0.0
S201	0.78 ± 0.02	0.87 ± 0.02	0.94 ± 0.01	0.99 ± 0.01
S202	0.78 ± 0.02	0.9 ± 0.01	0.96 ± 0.01	1.0 ± 0.0

Appendix ZZ: Variance Accounted For: Self-Selected Fast Walk

Total Variance Accounted for During Fast Walk: Right

subject	1 Synergy	2 Synergy	3 Synergy	4 Synergy
S101	0.71 ± 0.04	0.89 ± 0.02	0.95 ± 0.0	0.99 ± 0.0
S102	0.72 ± 0.04	0.85 ± 0.02	0.92 ± 0.02	0.98 ± 0.01
S103	0.72 ± 0.02	0.86 ± 0.02	0.94 ± 0.02	0.98 ± 0.01
S104	0.64 ± 0.04	0.81 ± 0.02	0.94 ± 0.01	0.98 ± 0.01
S105	0.76 ± 0.03	0.87 ± 0.02	0.94 ± 0.01	0.98 ± 0.0
S106	0.60 ± 0.01	0.77 ± 0.01	0.90 ± 0.03	0.96 ± 0.01
S107	0.76 ± 0.02	0.87 ± 0.02	0.94 ± 0.01	0.98 ± 0.0
S108	0.61 ± 0.03	0.78 ± 0.02	0.89 ± 0.02	0.96 ± 0.01
S109	0.68 ± 0.03	0.86 ± 0.02	0.95 ± 0.01	0.98 ± 0.01
S110	0.60 ± 0.06	0.80 ± 0.09	0.91 ± 0.05	0.98 ± 0.01
S111	0.71 ± 0.04	0.87 ± 0.03	0.95 ± 0.01	0.98 ± 0.0
S112	0.73 ± 0.03	0.86 ± 0.02	0.96 ± 0.01	0.99 ± 0.0
S201	0.82 ± 0.01	0.93 ± 0.01	0.97 ± 0.01	0.99 ± 0.0
S202	0.55 ± 0.02	0.76 ± 0.02	0.87 ± 0.03	0.95 ± 0.02

Total Variance Accounted for During Fast Walk: Left

subject	1 Synergy	2 Synergy	3 Synergy	4 Synergy
S101	0.67 ± 0.03	0.82 ± 0.02	0.94 ± 0.01	0.98 ± 0.01
S102	0.75 ± 0.02	0.87 ± 0.01	0.94 ± 0.01	0.99 ± 0.0
S103	0.70 ± 0.05	0.84 ± 0.03	0.93 ± 0.03	0.97 ± 0.01
S104	0.68 ± 0.03	0.83 ± 0.02	0.94 ± 0.01	0.99 ± 0.01
S105	0.78 ± 0.02	0.89 ± 0.02	0.95 ± 0.01	0.98 ± 0.01
S106	0.66 ± 0.03	0.80 ± 0.01	0.91 ± 0.01	0.97 ± 0.01
S107	0.78 ± 0.04	0.89 ± 0.02	0.95 ± 0.02	0.99 ± 0.01
S108	0.59 ± 0.04	0.78 ± 0.03	0.92 ± 0.02	0.98 ± 0.01
S109	0.69 ± 0.06	0.84 ± 0.03	0.92 ± 0.02	0.97 ± 0.01
S110	0.67 ± 0.05	0.84 ± 0.06	0.93 ± 0.04	0.98 ± 0.01
S111	0.71 ± 0.04	0.85 ± 0.05	0.94 ± 0.02	0.98 ± 0.0
S112	0.75 ± 0.02	0.89 ± 0.02	0.96 ± 0.01	0.99 ± 0.01
S201	0.73 ± 0.04	0.88 ± 0.02	0.94 ± 0.01	0.98 ± 0.01
S202	0.79 ± 0.03	0.9 ± 0.02	0.96 ± 0.01	1.0 ± 0.0

Appendix AAA: Variance Accounted For: Self-Selected Slow Cycle: Both 170mm Crank Arms

Total Variance Accounted for During Slow Cycling: Adjusted Side

subject	1 Synergy	2 Synergy	3 Synergy	4 Synergy
S101	0.75 ± 0.04	0.89 ± 0.01	0.98 ± 0.0	0.99 ± 0.0
S102	0.6 ± 0.01	0.89 ± 0.02	0.95 ± 0.01	0.99 ± 0.0
S103	0.68 ± 0.07	0.9 ± 0.03	0.97 ± 0.01	0.99 ± 0.0
S104	0.62 ± 0.01	0.81 ± 0.02	0.95 ± 0.01	0.98 ± 0.0
S105	0.7 ± 0.01	0.91 ± 0.02	0.98 ± 0.01	0.99 ± 0.0
S106	0.58 ± 0.06	0.87 ± 0.01	0.95 ± 0.01	0.99 ± 0.01
S107	0.68 ± 0.07	0.9 ± 0.02	0.97 ± 0.01	0.99 ± 0.01
S108	0.77 ± 0.01	0.96 ± 0.01	0.99 ± 0.01	1.0 ± 0.0
S109	0.65 ± 0.07	0.86 ± 0.05	0.95 ± 0.02	0.98 ± 0.01
S110	0.54 ± 0.03	0.85 ± 0.04	0.96 ± 0.01	0.98 ± 0.0
S111	0.7 ± 0.07	0.88 ± 0.02	0.97 ± 0.02	0.99 ± 0.01
S112	0.62 ± 0.04	0.88 ± 0.03	0.94 ± 0.01	0.99 ± 0.0
S201	0.76 ± 0.02	0.95 ± 0.01	0.98 ± 0.0	1.0 ± 0.0
S202	0.88 ± 0.01	0.97 ± 0.01	0.99 ± 0.0	0.99 ± 0.0

Total Variance Accounted for During Slow Cycling: Unadjusted Side

subject	1 Synergy	2 Synergy	3 Synergy	4 Synergy
S101	0.67 ± 0.03	0.84 ± 0.02	0.98 ± 0.0	1.0 ± 0.0
S102	0.65 ± 0.06	0.9 ± 0.02	0.98 ± 0.01	1.0 ± 0.0
S103	0.63 ± 0.05	0.86 ± 0.03	0.95 ± 0.01	0.98 ± 0.01
S104	0.66 ± 0.01	0.89 ± 0.01	0.95 ± 0.01	0.98 ± 0.0
S105	0.69 ± 0.05	0.91 ± 0.03	0.98 ± 0.01	1.0 ± 0.0
S106	0.58 ± 0.05	0.88 ± 0.02	0.97 ± 0.01	0.99 ± 0.0
S107	0.72 ± 0.09	0.91 ± 0.01	0.98 ± 0.01	0.99 ± 0.0
S108	0.64 ± 0.02	0.89 ± 0.03	0.97 ± 0.02	0.99 ± 0.0
S109	0.7 ± 0.04	0.93 ± 0.01	0.97 ± 0.01	0.99 ± 0.0
S110	0.6 ± 0.02	0.87 ± 0.01	0.96 ± 0.01	0.99 ± 0.0
S111	0.68 ± 0.07	0.87 ± 0.04	0.97 ± 0.01	0.99 ± 0.01
S112	0.72 ± 0.05	0.92 ± 0.0	0.98 ± 0.01	0.99 ± 0.0
S201	0.69 ± 0.02	0.92 ± 0.01	0.97 ± 0.01	0.99 ± 0.0
S202	0.71 ± 0.01	0.92 ± 0.01	0.97 ± 0.0	0.99 ± 0.0

Appendix BBB: Variance Accounted For: Self-Selected Fast Cycle: Both 170mm Crank Arms

Total Variance Accounted for During Fast Cycling: Adjusted Side

subject	1 Synergy	2 Synergy	3 Synergy	4 Synergy
S101	0.7 ± 0.03	0.93 ± 0.02	0.97 ± 0.02	0.99 ± 0.0
S102	0.6 ± 0.03	0.91 ± 0.02	0.98 ± 0.01	0.99 ± 0.0
S103	0.66 ± 0.04	0.89 ± 0.02	0.99 ± 0.01	1.0 ± 0.0
S104	0.58 ± 0.02	0.8 ± 0.01	0.96 ± 0.0	0.98 ± 0.0
S105	0.66 ± 0.03	0.83 ± 0.02	0.95 ± 0.02	0.99 ± 0.0
S106	0.58 ± 0.04	0.89 ± 0.01	0.97 ± 0.01	0.99 ± 0.0
S107	0.68 ± 0.06	0.93 ± 0.02	0.98 ± 0.0	1.0 ± 0.0
S108	0.65 ± 0.01	0.88 ± 0.02	0.97 ± 0.0	0.99 ± 0.0
S109	0.64 ± 0.03	0.87 ± 0.03	0.96 ± 0.01	0.99 ± 0.0
S110	0.6 ± 0.03	0.9 ± 0.03	0.96 ± 0.01	0.99 ± 0.01
S111	0.62 ± 0.04	0.89 ± 0.02	0.97 ± 0.02	0.99 ± 0.0
S112	0.66 ± 0.02	0.93 ± 0.01	0.98 ± 0.01	1.0 ± 0.0
S201	0.81 ± 0.01	0.91 ± 0.01	0.97 ± 0.0	1.0 ± 0.0
S202	0.87 ± 0.01	0.96 ± 0.01	0.99 ± 0.0	1.0 ± 0.0

Total Variance Accounted for During Fast Cycling: Unadjusted Side

subject	1 Synergy	2 Synergy	3 Synergy	4 Synergy
S101	0.61 ± 0.02	0.89 ± 0.02	0.97 ± 0.01	0.99 ± 0.01
S102	0.66 ± 0.06	0.9 ± 0.02	0.99 ± 0.0	1.0 ± 0.0
S103	0.63 ± 0.04	0.88 ± 0.02	0.98 ± 0.01	0.99 ± 0.0
S104	0.64 ± 0.02	0.87 ± 0.01	0.96 ± 0.01	0.99 ± 0.01
S105	0.65 ± 0.02	0.9 ± 0.02	0.96 ± 0.01	0.99 ± 0.0
S106	0.57 ± 0.01	0.89 ± 0.02	0.98 ± 0.01	0.99 ± 0.0
S107	0.68 ± 0.01	0.94 ± 0.01	0.97 ± 0.01	0.99 ± 0.0
S108	0.65 ± 0.02	0.88 ± 0.02	0.97 ± 0.01	0.99 ± 0.0
S109	0.69 ± 0.04	0.92 ± 0.01	0.97 ± 0.01	1.0 ± 0.0
S110	0.71 ± 0.05	0.9 ± 0.02	0.97 ± 0.01	0.99 ± 0.0
S111	0.63 ± 0.02	0.9 ± 0.01	0.98 ± 0.01	0.99 ± 0.0
S112	0.65 ± 0.01	0.88 ± 0.01	0.96 ± 0.01	0.99 ± 0.0
S201	0.65 ± 0.02	0.88 ± 0.02	0.97 ± 0.01	0.99 ± 0.0
S202	0.69 ± 0.01	0.9 ± 0.01	0.97 ± 0.01	0.99 ± 0.0

Appendix CCC: Variance Accounted For: Self-Selected Slow Cycle: 170mm and 150mm Crank Arms

Total Variance Accounted for During Slow Cycling: 150mm Side

subject	1 Synergy	2 Synergy	3 Synergy	4 Synergy
S101	0.85 ± 0.02	0.95 ± 0.01	0.98 ± 0.0	0.99 ± 0.0
S102	0.63 ± 0.04	0.9 ± 0.0	0.98 ± 0.01	0.99 ± 0.0
S103	0.65 ± 0.06	0.9 ± 0.05	0.98 ± 0.01	0.99 ± 0.01
S104	0.6 ± 0.02	0.81 ± 0.01	0.93 ± 0.01	0.97 ± 0.0
S105	0.78 ± 0.04	0.92 ± 0.02	0.98 ± 0.01	0.99 ± 0.0
S106	0.58 ± 0.01	0.83 ± 0.01	0.96 ± 0.01	0.99 ± 0.0
S107	0.78 ± 0.05	0.91 ± 0.02	0.98 ± 0.01	0.99 ± 0.01
S108	0.68 ± 0.05	0.95 ± 0.03	0.98 ± 0.01	0.99 ± 0.01
S109	0.7 ± 0.05	0.88 ± 0.03	0.96 ± 0.01	1.0 ± 0.0
S110	0.55 ± 0.04	0.87 ± 0.01	0.97 ± 0.01	0.99 ± 0.01
S111	0.8 ± 0.06	0.92 ± 0.03	0.98 ± 0.01	0.99 ± 0.01
S112	0.63 ± 0.03	0.94 ± 0.01	0.97 ± 0.01	0.99 ± 0.0
S201	0.73 ± 0.03	0.87 ± 0.01	0.98 ± 0.0	0.99 ± 0.0
S202	0.91 ± 0.01	0.97 ± 0.01	0.99 ± 0.0	1.0 ± 0.0

Total Variance Accounted for During Slow Cycling: 170mm Side

subject	1 Synergy	2 Synergy	3 Synergy	4 Synergy
S101	0.74 ± 0.02	0.91 ± 0.03	0.97 ± 0.01	1.0 ± 0.0
S102	0.66 ± 0.01	0.88 ± 0.03	0.97 ± 0.01	0.99 ± 0.0
S103	0.7 ± 0.06	0.91 ± 0.02	0.97 ± 0.01	0.99 ± 0.0
S104	0.66 ± 0.04	0.89 ± 0.02	0.95 ± 0.01	0.99 ± 0.0
S105	0.76 ± 0.04	0.93 ± 0.01	0.97 ± 0.01	1.0 ± 0.0
S106	0.58 ± 0.03	0.84 ± 0.02	0.96 ± 0.01	0.99 ± 0.0
S107	0.77 ± 0.07	0.9 ± 0.03	0.98 ± 0.01	0.99 ± 0.0
S108	0.75 ± 0.05	0.92 ± 0.02	0.97 ± 0.01	0.99 ± 0.0
S109	0.7 ± 0.03	0.93 ± 0.02	0.97 ± 0.01	0.99 ± 0.0
S110	0.6 ± 0.02	0.85 ± 0.03	0.96 ± 0.02	0.99 ± 0.0
S111	0.7 ± 0.03	0.92 ± 0.01	0.98 ± 0.01	1.0 ± 0.0
S112	0.67 ± 0.05	0.9 ± 0.01	0.98 ± 0.0	0.99 ± 0.0
S201	0.73 ± 0.05	0.94 ± 0.01	0.98 ± 0.01	0.99 ± 0.0
S202	0.73 ± 0.02	0.9 ± 0.01	0.98 ± 0.01	0.99 ± 0.0

Appendix DDD: Variance Accounted For: Self-Selected Fast Cycle: 170mm and 150mm Crank Arms

Total Variance Accounted for During Fast Cycling: 150mm Side

subject	1 Synergy	2 Synergy	3 Synergy	4 Synergy
S101	0.72 ± 0.02	0.92 ± 0.02	0.97 ± 0.01	0.99 ± 0.0
S102	0.6 ± 0.02	0.91 ± 0.02	0.98 ± 0.01	0.99 ± 0.0
S103	0.68 ± 0.03	0.92 ± 0.02	0.98 ± 0.01	0.99 ± 0.0
S104	0.58 ± 0.03	0.79 ± 0.01	0.94 ± 0.01	0.98 ± 0.0
S105	0.67 ± 0.02	0.85 ± 0.01	0.94 ± 0.02	0.99 ± 0.01
S106	0.57 ± 0.01	0.89 ± 0.01	0.98 ± 0.01	0.99 ± 0.0
S107	0.71 ± 0.08	0.91 ± 0.01	0.98 ± 0.0	0.99 ± 0.0
S108	0.63 ± 0.03	0.82 ± 0.01	0.96 ± 0.01	0.99 ± 0.01
S109	0.63 ± 0.02	0.87 ± 0.04	0.95 ± 0.02	0.99 ± 0.0
S110	0.58 ± 0.02	0.9 ± 0.02	0.97 ± 0.01	0.99 ± 0.01
S111	0.64 ± 0.03	0.9 ± 0.02	0.98 ± 0.01	0.99 ± 0.0
S112	0.67 ± 0.02	0.92 ± 0.01	0.98 ± 0.01	0.99 ± 0.0
S201	0.73 ± 0.02	0.89 ± 0.01	0.97 ± 0.01	0.99 ± 0.0
S202	0.88 ± 0.02	0.96 ± 0.01	0.99 ± 0.0	1.0 ± 0.0

Total Variance Accounted for During Fast Cycling: 170mm Side

subject	1 Synergy	2 Synergy	3 Synergy	4 Synergy
S101	0.64 ± 0.03	0.87 ± 0.03	0.97 ± 0.01	0.99 ± 0.0
S102	0.6 ± 0.01	0.9 ± 0.02	0.98 ± 0.0	0.99 ± 0.0
S103	0.64 ± 0.02	0.89 ± 0.01	0.98 ± 0.01	0.99 ± 0.0
S104	0.63 ± 0.02	0.87 ± 0.01	0.97 ± 0.01	0.99 ± 0.0
S105	0.69 ± 0.03	0.91 ± 0.01	0.97 ± 0.01	1.0 ± 0.0
S106	0.58 ± 0.02	0.87 ± 0.01	0.97 ± 0.01	0.99 ± 0.0
S107	0.72 ± 0.06	0.92 ± 0.01	0.97 ± 0.01	0.99 ± 0.0
S108	0.67 ± 0.03	0.86 ± 0.02	0.94 ± 0.02	0.99 ± 0.01
S109	0.64 ± 0.03	0.91 ± 0.02	0.97 ± 0.01	1.0 ± 0.0
S110	0.66 ± 0.02	0.91 ± 0.02	0.98 ± 0.01	0.99 ± 0.0
S111	0.66 ± 0.03	0.91 ± 0.03	0.98 ± 0.01	0.99 ± 0.0
S112	0.66 ± 0.03	0.9 ± 0.02	0.97 ± 0.0	0.99 ± 0.0
S201	0.73 ± 0.04	0.91 ± 0.02	0.98 ± 0.01	0.99 ± 0.0
S202	0.73 ± 0.02	0.92 ± 0.01	0.98 ± 0.0	0.99 ± 0.0

Appendix EEE: Variance Accounted For: Self-Selected Slow Cycle: 170mm and 130mm Crank Arms

Total Variance Accounted for During Slow Cycling: 130mm Side

subject	1 Synergy	2 Synergy	3 Synergy	4 Synergy
S101	0.82 ± 0.04	0.93 ± 0.01	0.99 ± 0.0	1.0 ± 0.0
S102	0.65 ± 0.04	0.88 ± 0.03	0.97 ± 0.01	0.99 ± 0.0
S103	0.65 ± 0.04	0.92 ± 0.04	0.98 ± 0.01	0.99 ± 0.0
S104	0.55 ± 0.02	0.77 ± 0.02	0.93 ± 0.01	0.98 ± 0.0
S105	0.78 ± 0.05	0.92 ± 0.04	0.98 ± 0.01	1.0 ± 0.0
S106	0.68 ± 0.02	0.86 ± 0.02	0.96 ± 0.01	0.99 ± 0.01
S107	0.86 ± 0.04	0.95 ± 0.01	0.98 ± 0.01	1.0 ± 0.0
S108	0.67 ± 0.06	0.93 ± 0.05	0.98 ± 0.02	1.0 ± 0.0
S109	0.79 ± 0.04	0.92 ± 0.04	0.97 ± 0.01	0.99 ± 0.0
S110	0.57 ± 0.06	0.81 ± 0.04	0.95 ± 0.03	0.99 ± 0.0
S111	0.69 ± 0.06	0.89 ± 0.01	0.97 ± 0.01	0.99 ± 0.0
S112	0.65 ± 0.06	0.89 ± 0.01	0.97 ± 0.01	0.99 ± 0.0
S201	0.75 ± 0.01	0.88 ± 0.01	0.98 ± 0.01	0.99 ± 0.0
S202	0.9 ± 0.02	0.97 ± 0.01	0.99 ± 0.0	1.0 ± 0.0

Total Variance Accounted for During Slow Cycling: 170mm Side

subject	1 Synergy	2 Synergy	3 Synergy	4 Synergy
S101	0.69 ± 0.04	0.86 ± 0.01	0.97 ± 0.01	0.99 ± 0.01
S102	0.76 ± 0.03	0.88 ± 0.02	0.98 ± 0.01	0.99 ± 0.0
S103	0.68 ± 0.02	0.87 ± 0.03	0.97 ± 0.01	0.99 ± 0.0
S104	0.65 ± 0.04	0.86 ± 0.04	0.95 ± 0.01	0.99 ± 0.01
S105	0.77 ± 0.04	0.96 ± 0.01	0.98 ± 0.01	1.0 ± 0.0
S106	0.59 ± 0.03	0.85 ± 0.02	0.97 ± 0.01	0.99 ± 0.0
S107	0.8 ± 0.08	0.92 ± 0.02	0.98 ± 0.0	0.99 ± 0.0
S108	0.71 ± 0.03	0.93 ± 0.01	0.98 ± 0.01	1.0 ± 0.0
S109	0.69 ± 0.03	0.91 ± 0.02	0.96 ± 0.01	0.99 ± 0.01
S110	0.67 ± 0.04	0.9 ± 0.02	0.98 ± 0.01	0.99 ± 0.0
S111	0.71 ± 0.06	0.89 ± 0.02	0.98 ± 0.01	1.0 ± 0.0
S112	0.62 ± 0.04	0.88 ± 0.02	0.96 ± 0.01	0.99 ± 0.0
S201	0.71 ± 0.04	0.91 ± 0.01	0.97 ± 0.01	0.99 ± 0.0
S202	0.75 ± 0.01	0.89 ± 0.02	0.98 ± 0.0	0.99 ± 0.0

Appendix FFF: Variance Accounted For: Self-Selected Fast Cycle: 170mm and 150mm Crank Arms

Total Variance Accounted for During Fast Cycling: 130mm Side

subject	1 Synergy	2 Synergy	3 Synergy	4 Synergy
S101	0.69 ± 0.05	0.9 ± 0.04	0.96 ± 0.02	0.99 ± 0.0
S102	0.62 ± 0.03	0.91 ± 0.01	0.98 ± 0.0	0.99 ± 0.0
S103	0.67 ± 0.05	0.91 ± 0.01	0.98 ± 0.01	0.99 ± 0.0
S104	0.61 ± 0.02	0.8 ± 0.02	0.94 ± 0.01	0.98 ± 0.0
S105	0.78 ± 0.03	0.93 ± 0.01	0.98 ± 0.0	1.0 ± 0.0
S106	0.63 ± 0.02	0.88 ± 0.01	0.97 ± 0.01	0.99 ± 0.0
S107	0.8 ± 0.05	0.92 ± 0.01	0.97 ± 0.01	0.99 ± 0.01
S108	0.67 ± 0.06	0.89 ± 0.02	0.97 ± 0.01	0.99 ± 0.0
S109	0.67 ± 0.03	0.89 ± 0.01	0.96 ± 0.01	0.99 ± 0.0
S110	0.58 ± 0.05	0.88 ± 0.02	0.96 ± 0.03	0.99 ± 0.0
S111	0.66 ± 0.04	0.9 ± 0.02	0.98 ± 0.01	1.0 ± 0.0
S112	0.66 ± 0.02	0.94 ± 0.02	0.98 ± 0.01	1.0 ± 0.0
S201	0.73 ± 0.02	0.89 ± 0.02	0.97 ± 0.01	0.99 ± 0.0
S202	0.88 ± 0.01	0.97 ± 0.0	0.99 ± 0.0	1.0 ± 0.0

Total Variance Accounted for During Fast Cycling: 170mm Side

subject	1 Synergy	2 Synergy	3 Synergy	4 Synergy
S101	0.66 ± 0.04	0.89 ± 0.03	0.97 ± 0.01	0.99 ± 0.0
S102	0.67 ± 0.02	0.9 ± 0.01	0.98 ± 0.01	0.99 ± 0.0
S103	0.6 ± 0.02	0.87 ± 0.04	0.99 ± 0.0	0.99 ± 0.0
S104	0.63 ± 0.01	0.86 ± 0.01	0.95 ± 0.01	0.98 ± 0.01
S105	0.72 ± 0.06	0.9 ± 0.05	0.97 ± 0.01	1.0 ± 0.0
S106	0.58 ± 0.02	0.85 ± 0.01	0.98 ± 0.01	0.99 ± 0.0
S107	0.76 ± 0.06	0.94 ± 0.01	0.98 ± 0.01	0.99 ± 0.0
S108	0.66 ± 0.04	0.89 ± 0.02	0.97 ± 0.01	0.99 ± 0.0
S109	0.65 ± 0.04	0.9 ± 0.03	0.95 ± 0.02	0.99 ± 0.01
S110	0.68 ± 0.06	0.92 ± 0.02	0.97 ± 0.01	0.99 ± 0.0
S111	0.67 ± 0.04	0.9 ± 0.01	0.98 ± 0.01	0.99 ± 0.0
S112	0.64 ± 0.01	0.88 ± 0.02	0.96 ± 0.01	0.99 ± 0.0
S201	0.68 ± 0.04	0.88 ± 0.01	0.97 ± 0.01	0.99 ± 0.0
S202	0.71 ± 0.01	0.9 ± 0.01	0.98 ± 0.0	0.99 ± 0.0

Vita

Sean Brown was born in Santa Rosa, CA, in 1988 to Eric and Catherine Brown. He is the younger brother of Brittany Brown and uncle of three nieces: Sierra, Sydney, and Savannah. Sean graduated from Maria Carrillo High School in Santa Rosa, CA, in 2006. After high school, Sean began studying mechanical engineering at Santa Rosa Junior College where he eventually changed majors to kinesiology. Upon completing his Associate's of Science degree, he transferred to California State University, Chico, where he earned a Bachelor of Science degree in Exercise Physiology. Sean decided to extend his time in Chico and stayed to earn a Master's degree in Kinesiology with a concentration in Biomechanics, where he studied barefoot versus shod running with the goal of pursuing a career in footwear biomechanics research.

Unable to find a position in the footwear research industry, Sean worked as a kinesiologist in a clinical pediatric gait lab at Shriners Hospital for Children in Sacramento, CA. In his four and a half years working with hundreds of children, Sean discovered a passion for understanding and helping this population. This experience inspired him to return to school, and he applied to the doctoral program at the University of Tennessee, Knoxville, where Sean earned a second Master's degree in Statistics and a Doctor of Philosophy in Kinesiology & Sport Studies with a concentration in Kinesiology and a specialization in Biomechanics in 2024. After completing his studies, Sean will return to California (see you soon, mother) for some relaxation (and quality Mexican food) while he searches for his next endeavor.