Biomechanical Modeling of Children with Cerebral Palsy to Establish Recreational Rock Climbing Therapy

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ABSTRACT

In recent years, orthopedic clinicians and researchers have reconsidered their approaches to delivering therapy to children with movement disorders such as cerebral palsy (CP). Research shows increasing both intensity and frequency of activities have helped patients surmount physical obstacles or move past functional plateaus. Climbing is a proposed activity that could address issues which children with CP commonly have: muscle weakness, muscle tightness, spasticity, and coordination. The purpose of this thesis was to study the kinematics and dynamics of rock climbing in CP and typically developed (TD) child populations and identify specific strength and stretch benefits of climbing. A custom 18-ft climbing wall instrumented with force sensors was constructed, and the climbing gait of three climbers with CP and five TD climbers was recorded via motion capture as they completed a variety of vertical and lateral climbing steps. Subjects with CP continued climbing weekly for a month, then repeated motion capture. To analyze this data, subject-specific biomechanical models were created using LifeMOD/MSC.Adams and OpenSim software.

Initial climbing sessions revealed the TD population was more adept at body weight support and muscle force generation on the climbing wall; however, the CP population improved with climb training by producing greater lower limb force. The TD population also had larger lower limb joint range of motion (ROM), although similar or greater normalized muscle-fiber lengths were observed for the CP population, suggesting climbers with CP can get the same stretch from climbing as their TD peers. Compared to walking results, ankle dorsiflexion, knee flexion, and hip abduction ROM and corresponding normalized muscle-fiber lengths were significantly more extensive. Functional benefits were compared before and after climbing with minor improvements in crouch gait, even with relatively low climb frequency.

As a therapy, climbing addresses the whole body and multiple CP issues at once, and it has the advantage of appealing to children and parents as a positive, fun experience. These results should justify further investigation into the benefits of climbing and encourage clinicians to incorporate climbing into patient treatment plans.

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I would also like to thank Gregory Sawicki, my undergraduate research mentor, who took me into his budding lab as a lowly freshman and kept me on as it grew into a formidable force of scientific endeavors. So many people have been interested in his work because of his eager mind and willingness to teach to anyone.

My family has always been a strong anchor in my life, and I couldn't have done it all without my two sisters, Jessica and Elena, and my parents, Tom and Diane Miller. Jessica gave me valuable statistics advice and a refuge to indulge in my favorite things: NC State basketball, Raleigh, and tennis. Elena sent me ridiculously funny pictures and jokes, watched movies like Roadhouse with me ("You're too *stupid* to have fun!"), and shared her tastes in music so that I kept up with the latest tunes. My dad has always been an example to me of someone that pursues his work with the utmost drive and focus. He has supported my education and upbringing by going the extra mile to provide for me and the family, working thousands of hours of overtime so that I could have hearing equipment and attend a private school for three years. My mom has taught me so much about perseverance, determination, and how the world works. She has prepared me for adulthood far better than anyone else ever could, and I continue to put her teachings into action every day.

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Chapter 1: Introduction and Background

1.1 Introduction

Rock climbing requires an atypical series of movements that necessitates planning and multi-limb coordination, both upper and lower body strength, cardiovascular fitness, and a minimum range of motion for reaching climbing grips. It is unique from both physiological and biomechanical outlooks. Novice climbing is relatively instinctual and usually inefficient, although training and practice can improve efficiency and climbing prowess. Climbing mechanics are poorly understood relative to activities such as walking and running, even though the popularity of climbing recreationally and competitively is higher than ever before with nearly seven million participants in 2012 (Outdoor Foundation, 2013; Sheel, 2004).

This thesis focused on the biomechanical analysis of youth climbers, with an emphasis on a typically developed (TD) population and a cerebral palsy (CP) population. The need for improved, customizable recreational therapies for children with CP is apparent in the clinical setting. Early intervention to address developmental delays due to CP is crucial in order to establish beneficial functional motor pathways and avoid or eliminate negative pathways (Damiano, 2006). By offering fun recreational activities rather than traditional physical therapy routines, we hope to encourage more frequent child participation in biomechanically advantageous regimens.

In some isolated instances, physical therapy centers have already begun incorporating climbing into their facilities. However, it is important to quantitatively evaluate the kinematics and kinetics of climbing in both CP and TD populations to gain a complete understanding of its potential therapeutic benefits. We accomplished the following goals:

1. Discover similarities and differences between a cerebral palsy (CP) population and a typically developed (TD) population during climbing
2. Quantify climbing strength for the CP population and improvement over time, as well as their stretch/range of motion (ROM) compared to that achieved during walking
3. Investigate potential functional differences before and after participating in climb sessions

The data collected in this study were analyzed with the overarching goal of showing that climbing is a viable tool for clinicians to increase strength, flexibility, and normal function in the CP population.

1.2 Background and Literature Review

1.2.1 Climbing

Previous studies on human climbing have demonstrated the distinctive physiological demands of climbing. Both the upper body and lower body contribute to whole body locomotion, differentiating its motion mechanics considerably from that of standard walking or other common exercises (Russell, Zirker, & Blemker, 2012). Heart rate can peak between 130-180 beats per minute, yet VO_2 remains fairly low relative to treadmill running VO_2, which has been attributed to significant isometric contractions during static support periods, anaerobic bursts of activity with static support periods in between, and position of arms above the head (Sheel, 2004). Good or elite climbers typically boast high strength to body mass ratios and high endurance (Watts, 2004). The literature on rock climbing and flexibility is not extensive, but it is agreed that elite climbers have demonstrably greater hip flexibility and possess a great deal of posterior leg flexibility compared to non-climbers (Grant, Hynes, Whittaker, & Aitchison, 1996; Mermier, 2000; Watts, 2004).

The role of exercise plays a significant part in children's psychological and mental health. Physical activity correlates with higher child self-motivation and improved self-perception and esteem (S. Biddle & Armstrong, 1992; Taylor, Sallis, & Needle, 1985). It has also been shown that participating in exercise and improving fitness is highly correlated with academic achievement and executive brain function (Davis et al., 2011). On the other hand, sedentary lifestyles have been associated with higher incidences of anxiety and depression, as well as behavioral issues (S. J. H. Biddle & Asare, 2011; Brodersen, Steptoe, Williamson, & Wardle, 2005). Climbing serves as an excellent venue for social interaction and confidence-building thanks to its intrinsic camaraderie with belayers and fellow climbers and its well defined individual accomplishments, such as reaching the top of the climbing wall. These benefits are prominently on display in many team building exercises and leadership retreats that incorporate climbing.

1.2.2 Cerebral Palsy

Cerebral palsy (CP) is one of the most prevalent life-long development disabilities in the world (Sankar & Mundkur, 2005) with an incidence of 2 to 2.5 per 1000 live births (Rosen & Dickinson, 1992). CP is not the result of a progressive disease, but rather a general term referring to symptoms stemming from a central nervous system injury near or during birth. Some of the associated potential causes and risk factors include perinatal stroke, low birth weight, intrauterine exposure to infection, multiple pregnancy, and birth asphyxia (Nelson, 2003; Sankar & Mundkur, 2005). The result of the brain injury is abnormal/delayed motor development in children (Palmer et al., 2010), which leads to chronic dysfunction and impairments such as muscle weakness, spasticity, and poor coordination (Dodd, Taylor, & Damiano, 2002; Styer-Acevedo, 1999).

In patients with CP, structural abnormalities of muscle fiber type and motor unit function contribute to muscle weakness and coordination issues. Type I muscle fibers, otherwise known as slow twitch fibers, are used in low intensity, high endurance (aerobic) activities, whereas Type II fibers are fast twitch fibers that enable high intensity activities with a low level of endurance (Denny-Brown, 1929). Motor units are basic functional units consisting of a motor neuron and the muscle fibers it innervates (Lieber, 2002). In patients with CP, type I fiber predominance has been observed and attributed to strong tonic spasticity and the selective recruitment of lower frequency motor units (Ito et al., 1996; Rose et al., 1994). Additionally, patients with CP are unable to fully activate all available motor units compared to age-controlled peers, which in turn impacts their force-generation capabilities leading to muscle weakness (Rose & McGill, 2005; Stackhouse, Binder-Macleod, & Lee, 2005).

Patients with CP have high antagonist co-activation, which works against intended action and can lower net joint forces and torques (Elder et al., 2003; Stackhouse et al., 2005). Cocontraction is correlated with excessive energy expenditures and O_2 costs during walking (Unnithan, Dowling, Frost, & Bar-Or, 1996), establishing it as a likely factor in fatigue. Children with spastic diplegia typically have hip and knee flexors engaged even during extension of those joints, requiring extra muscle effort from extensor muscles, reducing natural walking speed, and doubling energy expenditure (Bernardi et al., 1999; Waters & Mulroy, 1999).

Muscle atrophy is another significant secondary condition that patients with CP encounter. The primary cause of atrophy is disuse, which can come about because of surgical bedrest, biased muscle recruitment, spasticity or frustration stemming thereof, pain associated with movement, and other factors (Pape, 1997). On average, MR imaging have revealed a 20% decrease in lower limb muscle volume for children with CP compared to TD peers (Handsfield, Meyer, Abel, & Blemker, 2015). However, children with CP can mitigate or reverse atrophy and increase their strength with training at a rate comparable to children without CP; these gains have been shown to lead to functional improvements (Damiano & Abel, 1998).

In developed countries, child obesity and its associated health problems have been steadily on the rise since the 1970s. In the United States, 25% of children are considered overweight and 11% are obese (Dehghan, Akhtar-Danesh, & Merchant, 2005). These statistics have been termed an “epidemic” and ascribed to poor diet and sedentary lifestyle. For children with cerebral palsy, the concern is even greater; the American Physical Therapy Association determined in 2003 that “there was a critical need to identify and promote effective physical fitness interventions” to prevent further health problems such as osteoporosis, chronic pain, type II diabetes, and rapid fatigue (Fowler et al., 2007). A child with cerebral palsy starts at a disadvantage when it comes to attaining physical fitness, because their physical impairments (e.g., muscle weakness, spasticity, poor balance) make it more difficult for them to engage in activities that promote muscular strength, low body mass index, and cardiorespiratory health. Consequently, it is exceedingly crucial to develop recreational activities that address the unique needs of children with cerebral palsy while improving their physical health.

While children with CP have the option to participate in effective strength, stretch, and neuromuscular training, one frequently overlooked aspect of fitness is its psychological impact. As discussed earlier, exercise programs and maintaining good fitness is a source of self-esteem and good body image for children and adolescents; it is important to encourage the same for children with CP. If the child enjoys the training activity and feels a sense of accomplishment, they are far more likely to continue engaging in the activity and ultimately assume responsibility for their own fitness (Darrah, Wessel, Nearingburg, & O’Connor, 1999). Since climbing has a tangible end goal (reaching the top of the rock wall) and a social component (building rapport with belayers and peers), it may be more personally satisfying to the individuals with CP to improve their strength, range of motion (ROM), and coordination through climbing rather than standard physical therapy routines.

1.2.3 Modeling and Analysis of Gait

While the body of research modeling and analyzing horizontal walking gait is large and well-documented, only a few studies have applied the same methods to climbing. The biological structure and dynamics behind skeletal muscle force generation (e.g., sliding filament theory, muscle activation, contraction velocity, fiber length) have previously been organized into mathematical algorithms which allow computer models such as OpenSim to produce muscle-tendon parameters derived from experimental data (Delp et al., 2007; Hoy, Zajac, & Gordon, 1990). These advances have made calculation of muscle-fiber operating lengths easy to obtain; this information would be valuable to determine how climbing can place muscles in positions that lengthen or allow optimal muscle contractions. Other software apply a purely mechanical method to the biological system, reducing the human body to a series of segments connected by joints and using motion capture marker data to drive the model's motion. Inverse kinematics are calculated and then used in conjunction with force data to calculate dynamic data such as joint torques. The LifeMOD plug-in (Biomechanics Research Group; San Clemente, CA) to Adams/View (MSC.Software Corporation; Santa Ana, CA) is one such tool for creating multi-body models and obtaining kinematics/dynamics of a motion such as climbing.

1.2.4 Conclusions of Background

For the uninitiated, the motivation to introduce children with cerebral palsy to rock climbing may not be intuitive. However, the current literature and reasoning makes a strong case for the benefits of climbing as a recreational therapy. Children with cerebral palsy need consistent recreational exercise for both physical and mental health, but they also require more controlled environments to accommodate their physical disabilities. These disabilities - a combination of muscle weakness, inflexibility, and poor coordination - may be safely addressed with an intelligently constructed climbing regimen and belaying system. This potential is explored through the use of experimental gait and force data as well as modeling software for kinematic, kinetic, and muscle calculations.

Chapter 2: Climbing Kinematics of Children with and without Pathologic Gait

2.1 Introduction and Background

By definition, children with pathologic gait have difficulty emulating the gait patterns and methods of their typically developed (TD) peers. Most children are unfamiliar with optimal climbing gait, but those with normal bipedal gait patterns tend to adapt adequately and swiftly to the demands of climbing. Children with cerebral palsy (CP) have more difficulty for reasons such as poor flexibility, low strength capabilities, hypersensitive stretch reflex (spastic) responses, and reduced coordination/neuromuscular control. By studying the CP and TD populations, we can establish whether or not climbers with CP can utilize range of motion (ROM) and body weight support in a manner similar to TD climbers. We can also identify the factors that most hinder climbers with CP and devise ways to alleviate the transition from bipedal to quadrupedal gait.

As noted in the introductory chapter, children with CP require significant physical interventions to attenuate their physical challenges and attain a higher standard of living. Yet another characteristic obstacle of living with a disability is its psychological impact; individuals with impairment may feel isolated or singled out in a standard class, even in situations where peers are friendly and understanding. Having to interrupt class to attend physical therapy or being unable to fully participate in class recreation transfers the locus of control to external factors; in turn, that individual tends to experience more distress, a lower likelihood of taking social actions, and face generally worse outcomes due to diminished internal motivation. Climbing gives children opportunities to build confidence, interact socially with peers, and grow their internal locus of control. Studies demonstrate that sports have served as a healthy mechanism for addressing the negative psychological impact of a disability (Valliant, Bezzubyk, Daley, & Asu, 1985). Recreational climbing can place children with CP on a more equal social footing with their peers and provide them with experiences over which to bond.

This study is motivated by the idea that introducing climbing as a physical activity where children with CP are given the opportunity to match their peers may lead to physical benefits coupled with emotional satisfaction. As a load-bearing exercise, research reveals climbing is associated with increased bone mineral content/mass, and as a neuromuscular-intensive exercise, studies identify specific improvements in motor ability, i.e., bipedal speed, muscle power generation, and aerobic endurance (Morrison & Schoffl, 2007) for TD children and adults. Two important metrics for examining the biomechanical effects of climbing is force generation and muscle stretch/ROM. Skeletal muscle produces force to propel climbing motions. With adequate training, the climber should improve muscle strength, a primary goal of patients with CP who wish to see better function. Optimal force production depends on the joint angle during force generation, while operating muscle length determines the maximum force possible due to the force-length relationship (Lieber, 2002). It is important that climbers can generate a ROM that allows them to utilize their optimal fiber lengths or at least get closer to that length. Because of existing modeling software such as OpenSim (Delp et al., 2007), muscle lengths can be determined based on joint angles from experimental data. These lengths reveal ROM throughout a specified climbing step, which is valuable information when designing recreational climbing step routines to encourage targeted stretch.

Climbing invites synergy on several levels: cooperation between the climber and the belayer; utilization of both stretch/ROM and strength; highly coordinated effort from all four upper and lower limbs; and a likely connection between physical action and psychological wellbeing. This study explores the comparison between CP and TD populations as a basis for continuing climbing-based therapy research, using body weight support, forces measured from each limb, and ROM/muscle length. Are the populations both able to support their body weight on the climbing wall, and are there differences in how they support themselves? What ROM differences distinguish the two populations, if any? This information may pinpoint future special considerations for climbers with CP, as well as areas of deficiency where additional therapy is needed.

2.2 Methods

2.2.1 Subject Recruitment

Three subjects with diplegic CP and the ability to independently ambulate were recruited for this study (denoted by subject ID CP#). Five control subjects were recruited for comparison (denoted by subject ID TD#). All pertinent demographic information is located in Table 2.1. All subjects with CP were inexperienced climbers but active in other sporting and recreational activities; three out of five control subjects were inexperienced climbers but active in other sporting and recreational activities. Subject consent was approved by the University of Virginia's Institutional Review Board and was obtained for all subjects with parental permission.

Table 2.1. Demographics of the CP and TD populations recruited for climbing.

Subject ID	***Gender (M/F)***	***GMFCS classification***	***Experienced climber (Y/N)***	***Age (years)***	***Height (m)***	***Weight (kg)***
CP1	M	Level II	N	16	1.68	64.2
CP2	F	Level III	N	10	1.18	22.0
CP3	F	Level III	N	6	1.07	16.6
TD1	M	N/A	Y	7	1.15	22.4
TD2	M	N/A	N	5	1.25	22.4
TD3	M	N/A	Y	7	1.36	29.4
TD4	F	N/A	N	7	1.35	32
TD5	M	N/A	N	17	1.87	98.2

2.2.2 Climbing Protocol

a) Climbing wall diagram b) Climbing wall configuration with climber

Figure 2.1. The climbing wall configuration. a) On the right wall, climb grips were positioned in a 3x3 grid on the right side for a variety of lateral, vertical, and combined vertical/lateral steps. b) A climber is shown climbing up to the starting position (the grip labeled 11 and its blue lateral counterpart).

All climbers followed the same protocol. All wore a size-appropriate climbing harness with locking carabiners for attaching the belay rope. Each subject wore a modified full body Plug-in Gait set of 43 markers and had anthropometric data measurements taken prior to marker attachment for entry into Vicon Nexus software (Vicon Motion Systems Ltd., Oxford, UK).

Subjects were allowed to warm up and make adjustments to the climbing harness and data collection tools before performing a series of steps on a uniform 3x3 grid of climbing grips spaced eight inches laterally and vertically (see Fig. 2.1). This configuration characterized the right side of the wall, while the left side only had a column of three climbing grips spaced eight inches vertically.

All steps began with both feet placed at the initial position at the two innermost and lowest climbing grips. Both hands were placed on climbing grips above the head and at a sufficient height not to overlap multiple limbs on a single force plate. There were eight possible destinations for the right foot: two on the lowest level, three on the middle level, and three on the top level. Climbers were instructed to match the height of their left foot to their right foot to conclude the step. One subject with CP was short to the point that the middle level (eight inch vertical relative to initial location) was the maximum anatomically achievable height; other subjects were able to reach all steps. All data were collected and synchronized using Vicon software.

2.2.3 Measuring Outside Assistance and Limb Contributions to Body Weight Support during Climbing

Outside assistance to the climber was quantified to evaluate his or her ability to climb independently. A uniaxial load cell (Interface Inc., Scottsdale, AZ) was placed in series with the belay rope to measure potential lift assistance from the belayer to the climber. Forces on the climbing wall were measured using six vertically mounted Bertec force plates (Bertec Corp., Columbus, OH) (see Fig. 2.2a). All data were processed using custom MATLAB software and used to construct computational models.

a) Bertec force plates mounted on wall *b) Interface Inc. load cell in series with rope*

Figure 2.2. Force plates and belay rope load cell. a) Uncovered force plates mounted vertically to collect information from multiple limbs. b) The load cell (circled in yellow) measured amount of force exerted on climber via belay rope (held by a belayer, unpictured).

2.2.4 Measuring Joint Excursion Angles

3-D positions for each marker on subjects' bodies were collected by Vicon and extracted by custom MATLAB software, which converted them to viable file formats for the LifeMOD plug-in (Biomechanics Research Group, San Clemente, CA) to Adams/View (MSC.Software Corporation, Santa Ana, CA). Full 3-D, 17-segment, 16-joint models were created for each subject based on anthropometric and marker data (Russell et al., 2012). All joints were tri-axis hinge joints aside from the elbow and wrist joints (bi-axis hinge) and the knee joints (single axis). Default physical properties of the segments were based on values from the Generator of

Body Data database. Model inverse kinematics were calculated based on motion driven by experimental Vicon marker data. All joint excursion angles were calculated and available for post-analysis.

Forces measured from the six climbing wall plates were applied to the hands and feet. For the belay rope force, the direction of force application was determined using a vector from the midpoint of the two ASIS markers and the 3D position of the chained carabiner through which the rope loops at the top of the wall. This vector represented the straight line of the rope running from the climber to the top of the wall. In the LifeMOD models, a virtual marker was created between the two ASIS markers to apply belay rope force to the model pelvis during dynamic simulations.

2.2.5 Computing OpenSim muscle lengths

Custom MATLAB software adjusted LifeMOD joint angles and assembled them into a motion file for OpenSim. Lower body joint angles were imposed onto the gait2392_simbody model over the course of the climb motion (Delp et al., 2007). The normalized lower body muscle lengths were exported to Excel for final statistical analysis.

2.3 Results

2.3.1 Belay rope support

Average belay rope assistance during various steps is shown in Figure 2.1. The data shown were taken from initial climbing sessions for subjects with CP; all data came from three steps (16 inch lateral, 16 inch vertical; 16 inch vertical, 0 inch lateral; 8 inch vertical and 16 inch lateral, respectively). Average body weight support required for climbers were significantly different between CP and TD groups: 43.9 and 8.37% ($p < 0.01$), 47.7 and 10.3% ($p < 0.01$), 45.5 and 10.1% ($p < 0.01$).

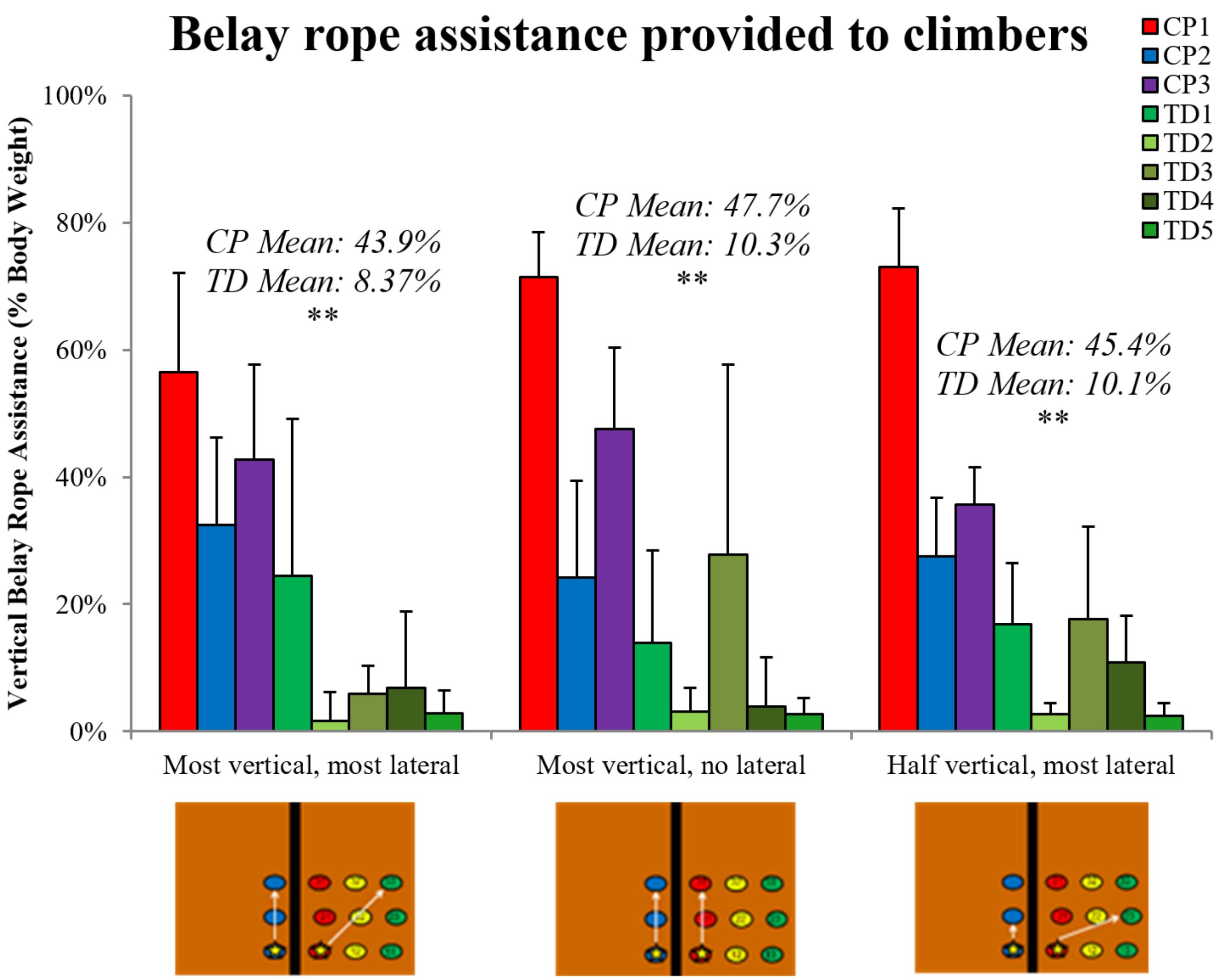

Figure 2.1. Average vertical belay rope assistance normalized by body weight for three different step conditions. Green bars correspond to assistance given to control climbers; all other colors are for climbers with CP. *p<0.05, **p<0.01, ***p<0.001.

2.3.2 Force Contributions from Ambulatory Limbs

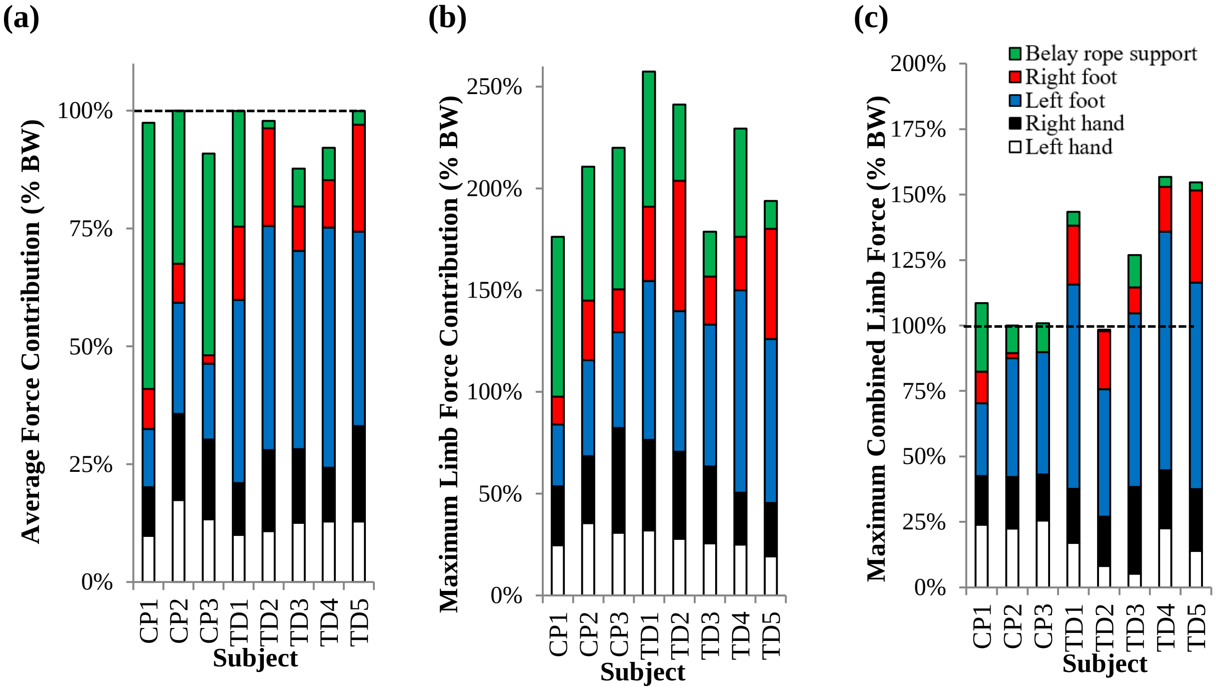

Figure 2.2. All graphs apply to most lateral, most vertical step. a) Average force contribution over course of step. b) Maximum independent limb force contribution with the maximum value for each limb, not necessarily concurrent. c) Concurrent limb contributions at the point of maximum vertical force magnitude exerted by climber.

Table 2.2. Mean ± SD information for the CP and TD population limb forces. Average forces correspond to force over the course of the step averaged. Maximum individual forces are the peak forces observed, whether simultaneous or asynchronous. Maximum combined forces are the forces observed from each limb at the point of maximum total force. A one-tailed unpaired t-test was performed for each variable. p-values are listed for comparison between the CP and TD populations. Significant differences were observed for the right and left feet. *p<0.05, **p<0.01, ***p<0.001.

	CP population Mean (±SD)	TD population Mean (±SD)	p-value
AVERAGE FORCES			
Right hand (% BW)	15.2 (4.3)	15.1 (3.9)	0.485
Left hand (% BW)	13.5 (3.8)	11.8 (1.3)	0.191
Right foot (% BW)	6.2 (3.8)	15.7 (6.0)	<0.05*
Left foot (% BW)	17.3 (5.72)	44.1 (4.9)	<0.001***
MAXIMUM INDIVIDUAL FORCES			
Right hand (% BW)	37.8 (12.0)	35.4 (9.0)	0.381
Left hand (% BW)	30.3 (5.4)	25.8 (4.6)	0.130
Right foot (% BW)	21.3 (7.7)	40.9 (17.6)	0.063
Left foot (% BW)	41.6 (9.7)	79.4 (12.3)	<0.01**
MAXIMUM COMBINED FORCES			
Right hand (% BW)	18.6 (0.98)	35.1 (26.1)	0.165
Left hand (% BW)	24.0 (1.5)	13.3 (6.9)	<0.05*
Right foot (% BW)	4.7 (6.5)	21.4 (9.2)	<0.05*
Left foot (% BW)	39.9 (10.6)	72.6 (16.0)	<0.05*

Table 2.3. Comparing right and left sides for CP and TD populations. A one-tailed unpaired t-test was performed for each variable. *p<0.05, **p<0.01, ***p<0.001.

Right and left side comparisons	
CP population	**p-value**
Average right hand (% BW) *Average left hand (% BW)*	0.315
Average right foot (% BW) *Average left foot (% BW)*	<0.05*
Maximum right hand (% BW) *Maximum left hand (% BW)*	0.191
Maximum right foot (% BW) *Maximum left foot (% BW)*	<0.05*
Max. combined right hand (% BW) *Max. combined left hand (% BW)*	<0.01**
Max. combined right foot (% BW) *Max. combined left foot (% BW)*	<0.01**
TD population	**p-value**
Average right hand (% BW) *Average left hand (% BW)*	0.057
Average right foot (% BW) *Average left foot (% BW)*	<0.001***
Maximum right hand (% BW) *Maximum left hand (% BW)*	<0.05*
Maximum right foot (% BW) *Maximum left foot (% BW)*	<0.01**
Max. combined right hand (% BW) *Max. combined left hand (% BW)*	0.055
Max. combined right foot (% BW) *Max. combined left foot (% BW)*	<0.001***

Force contributions from all four individual limbs during the most difficult step achieved by climbers (most lateral, most vertical, also represented in Fig. 2.1a) were calculated three different ways, as shown in Fig. 2.2(a-c) and Table 2.2. In Fig. 2.2a, the average contribution over the course of the step was calculated to determine the value of each color bar in each subject's column. Lower limb contribution significantly differed between populations (right foot: $p < 0.05$; left foot: $p < 0.001$), reflecting the tendency for the TD population to support the majority of their body weight with their lower body in contrast to the CP population. No significant differences were observed for the upper limbs. Results totaling less than 100% may be due to noise filtering, variation in belay rope vector calculation, and experimental error such as briefly catching a toe under a climbing grip during positioning, which would register a negative vertical force and slightly reduce the overall average for that appendage.

In Figure 2.2b, the maximum force contribution from each limb determined the value of each color bar in subject columns, regardless of whether or not they occurred concurrently. Significant differences were found for the left foot ($p < 0.01$) and were close to significant for the right foot ($p = 0.063$) due to higher TD population lower limb forces.

In Figure 2.2c, the limb contributions from the singular timepoint at which maximum sum limb force occurred were graphed; this measurement demonstrates the strategy used when limb force was presumably paramount to climbing success. Significant differences were found for the left foot (39.9% vs. 72.6% CP and TD means, $p < 0.05$), right foot (4.7% vs. 21.4% CP and TD means, $p < 0.05$) and left hand (24.0% vs. 13.3% CP and TD means, $p < 0.05$).

2.3.3 Joint Excursion Ranges

Climbers with CP had decreased joint ROM compared to TD climbers (see Fig. 2.3). Significant or near-significant results were observed for the right side joint ranges in particular. Near-significant results were observed for left ankle dorsiflexion, knee flexion, and hip flexion. In all cases, the mean range was greater for the TD population than for the CP population (see Table 2.4 for full results). The p-values for all joint angle mean conditions except left ankle dorsiflexion and hip flexion approach near-significance, suggesting a trend towards differences between group means. However, for the CP population, high variability in joint angle means made statistically significant differences between group means unlikely, with particularly high standard deviations for right knee flexion, right and left hip flexion, and right hip adduction means. In contrast, standard deviations for the TD population means were relatively low.

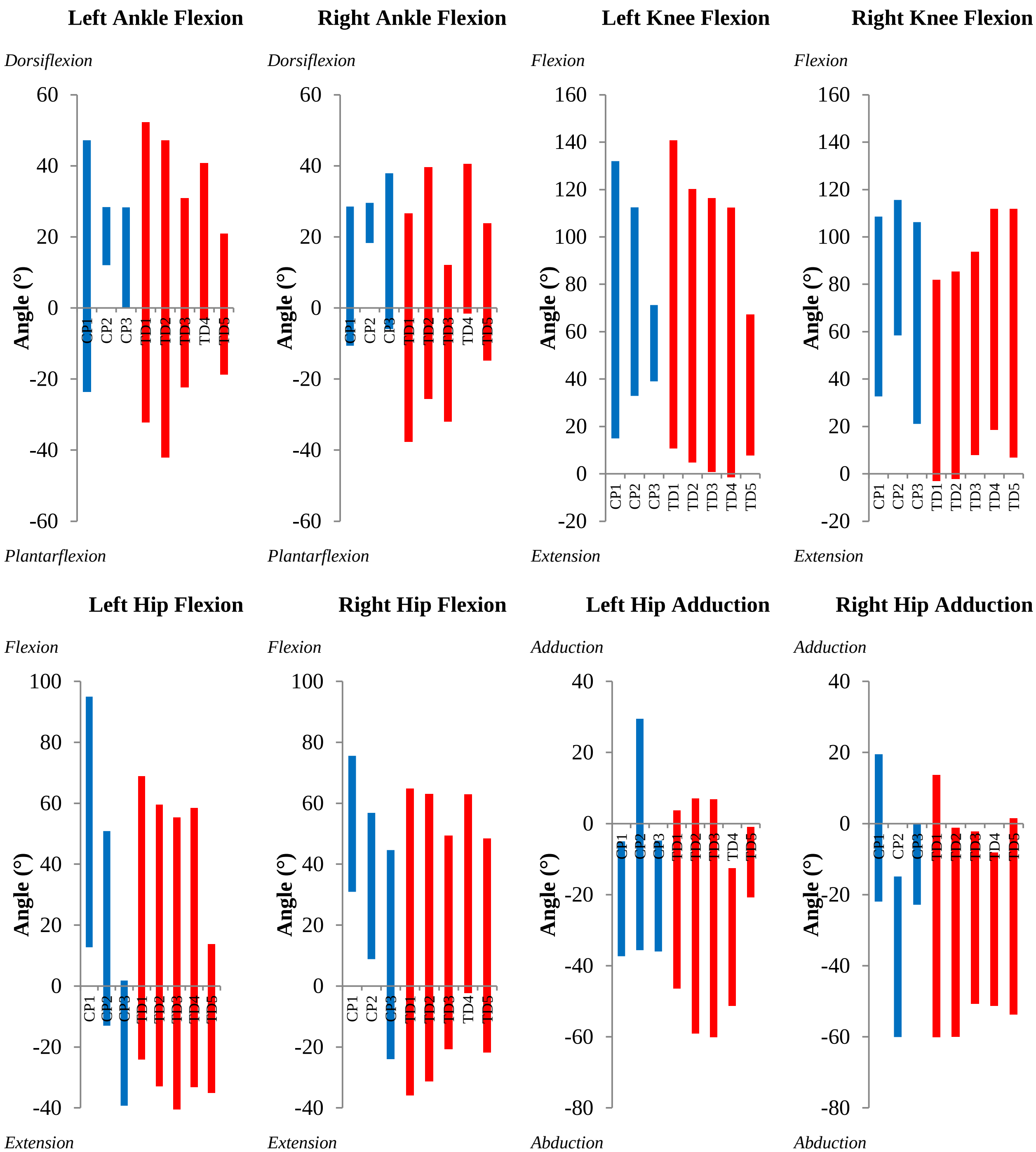

Figure 2.3. Joint excursion ranges (minimum to maximum) for the most vertical, most lateral step the climber was capable of. Climbers with CP are shown in blue; climbers from the TD population are shown in red. All data for CP population is taken from initial data collections.

Table 2.4. Mean ± SD information for the CP and TD population joint excursion angles. A one-tailed unpaired t-test was performed for each variable. Significant or near-significant results were found for all right side joint excursions. *p<0.05, **p<0.01, ***p<0.001.

	CP Mean (±SD)	TD Mean (±SD)	p-value	CP Range (±SD)	TD Range (±SD)	p-value
Right ankle dorsiflexion	15.4 (9.26)	5.28 (2.43)	0.111	31.4 (17.6)	50.8 (12.8)	0.059
Left ankle dorsiflexion	17.9 (3.30)	15.0 (2.75)	0.243	38.5 (28.7)	62.1 (23.2)	0.123
Right knee flexion	69.6 (13.8)	49.3 (3.81)	0.0958	72.8 (14.25)	89.0 (4.06)	<0.05*
Left knee flexion	54.2 (5.63)	44.1 (6.92)	0.158	76.3 (42.5)	106.8 (27.2)	0.127
Right hip flexion	31.1 (22.7)	14.2 (5.18)	0.119	53.7 (13.0)	80.1 (16.1)	<0.05*
Left hip flexion	11.3 (35.3)	2.94 (6.96)	0.316	62.4 (20.6)	84.6 (20.2)	0.093
Right hip adduction	-17.6 (22.4)	-29.9 (4.39)	0.139	36.5 (12.0)	55.9 (11.6)	<0.05*
Left hip adduction	-17.5 (8.59)	-24.3 (4.37)	0.113	42.9 (19.3)	48.4 (19.8)	0.358

2.3.4 OpenSim Muscle Length

Normalized muscle lengths for the ankle plantarflexor, knee extensor, hip extensor, and hip adductor muscle groups are shown in Figs. 2.4-2.7. In Table 2.5, normalized muscle length means were compared between the CP and TD populations using a one-tailed t-test assuming unequal variances.

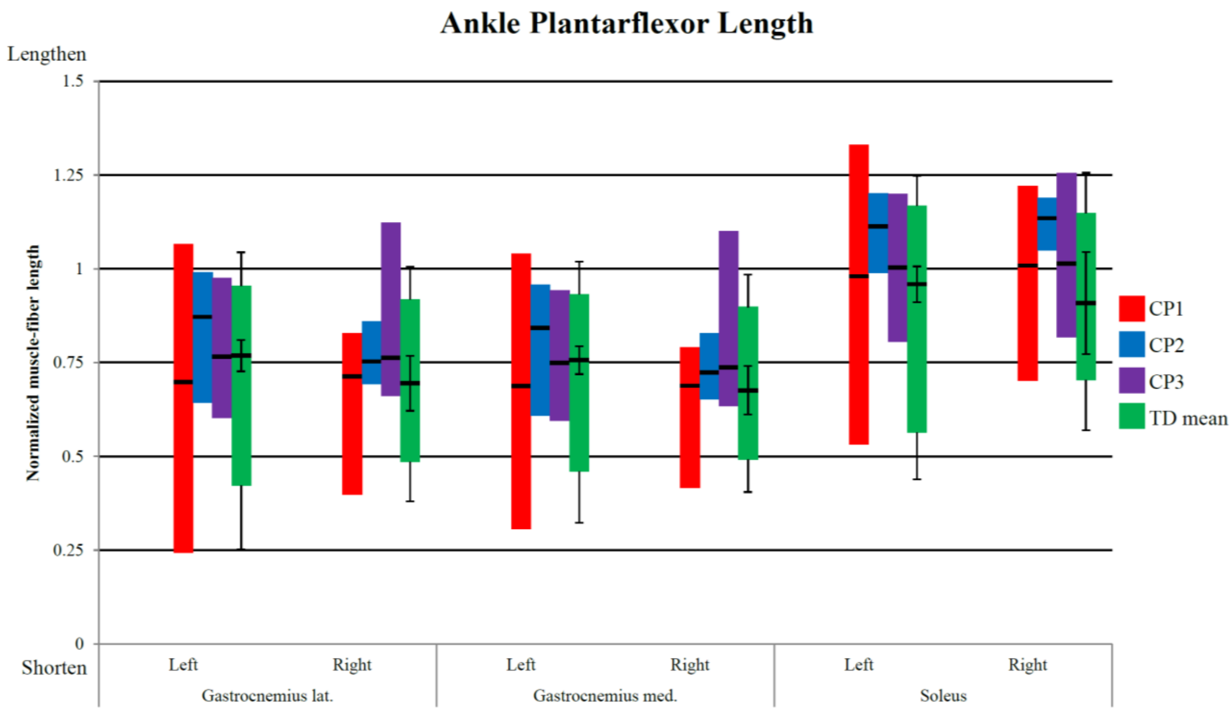

Figure 2.4. Ankle plantarflexor muscle groups (left and right leg: gastrocnemius lateralis and medialis; soleus) shown with columns representing minimum to maximum normalized muscle-fiber length, with mean depicted by black line. Both gastrocnemius muscles remain relatively short, while the soleus undergoes moderate stretch past the optimal fiber length.

In the ankle plantarflexor muscle group, there was one statistically significant difference between the CP and TD populations (right soleus: CP mean 1.05, TD mean 0.91, $p < 0.05$). Other muscles demonstrating near significance were the right gastrocnemius lateralis (CP mean 0.74, TD mean 0.69, $p = 0.1182$), right gastrocnemius medialis (CP mean 0.72, TD mean 0.68, $p = 0.1299$), and left soleus (CP mean 1.03, TD mean 0.96, $p = 0.1050$). For all four muscles, the CP population mean was observed to be greater. The soleus muscles were shown in Fig. 2.4 to have the greatest muscle stretch past optimal fiber length out of the ankle plantarflexors.

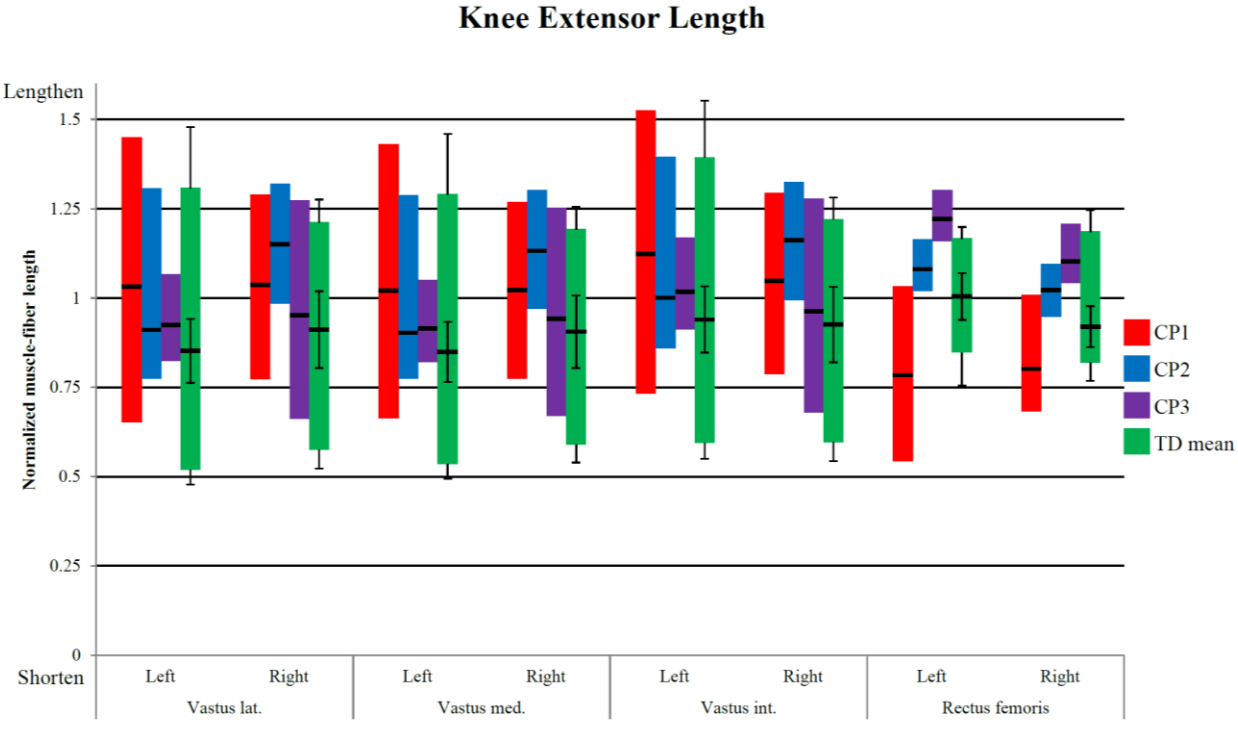

Figure 2.5. Knee extensor muscle groups (left and right leg: vastus lateralis, medialis and intermedius; rectus femoris) shown with columns representing minimum to maximum normalized muscle-fiber length, with mean depicted by black line. All muscles depicted show significant stretch past the optimal fiber length (1 for normalized muscle-fiber length) for the majority of climbers. In some instances, climbers with CP have a smaller range of fiber length than that of the TD population.

In the knee extensor muscle group, there were no statistically significant results, but all six vastus muscles had near significant results with p-values ranging from 0.0504 to 0.0649 (see Table 2.5 for complete results). For all six muscles, the reported mean length was greater for the CP population. The vastus muscles were shown in Fig. 2.5 to stretch far past the optimal fiber length in some cases.

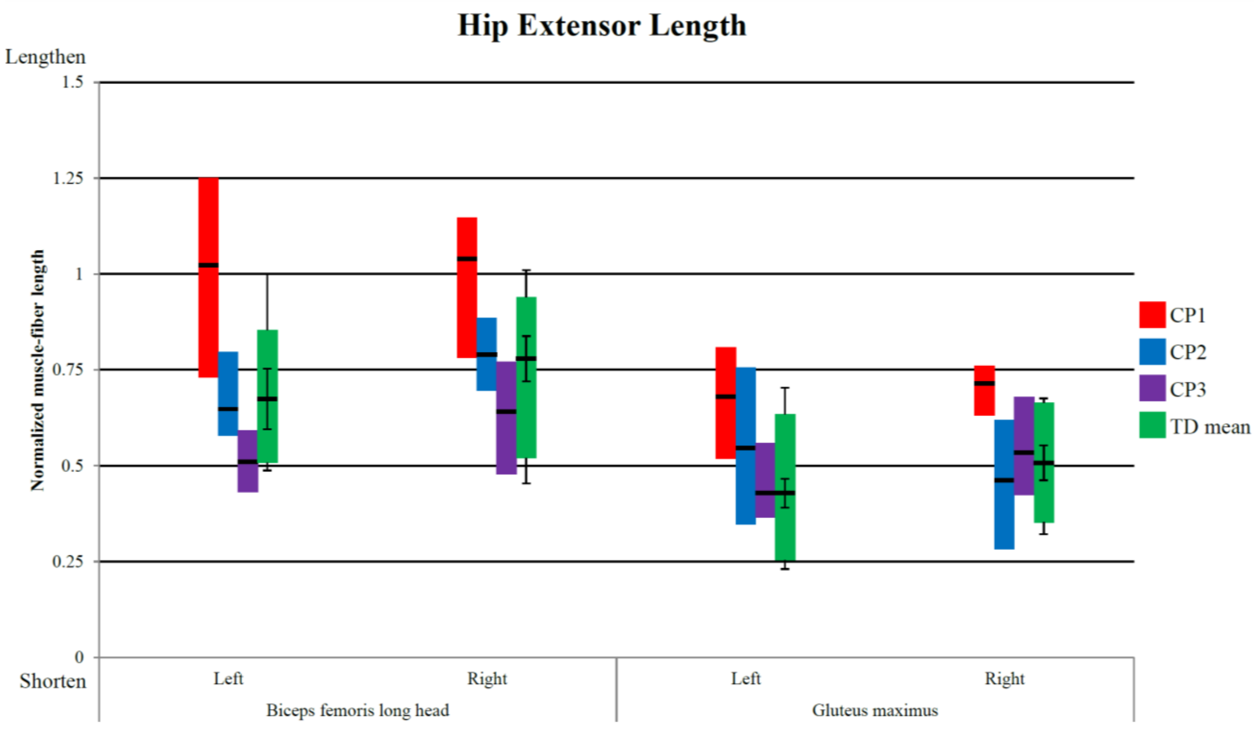

Figure 2.6. Hip extensor muscle groups (left and right leg: biceps femoris long head; gluteus maximus) shown with columns representing minimum to maximum normalized muscle-fiber length, with mean depicted by black line. For both populations, these muscles do not demonstrate stretch. The CP population has high variability compared to the TD population.

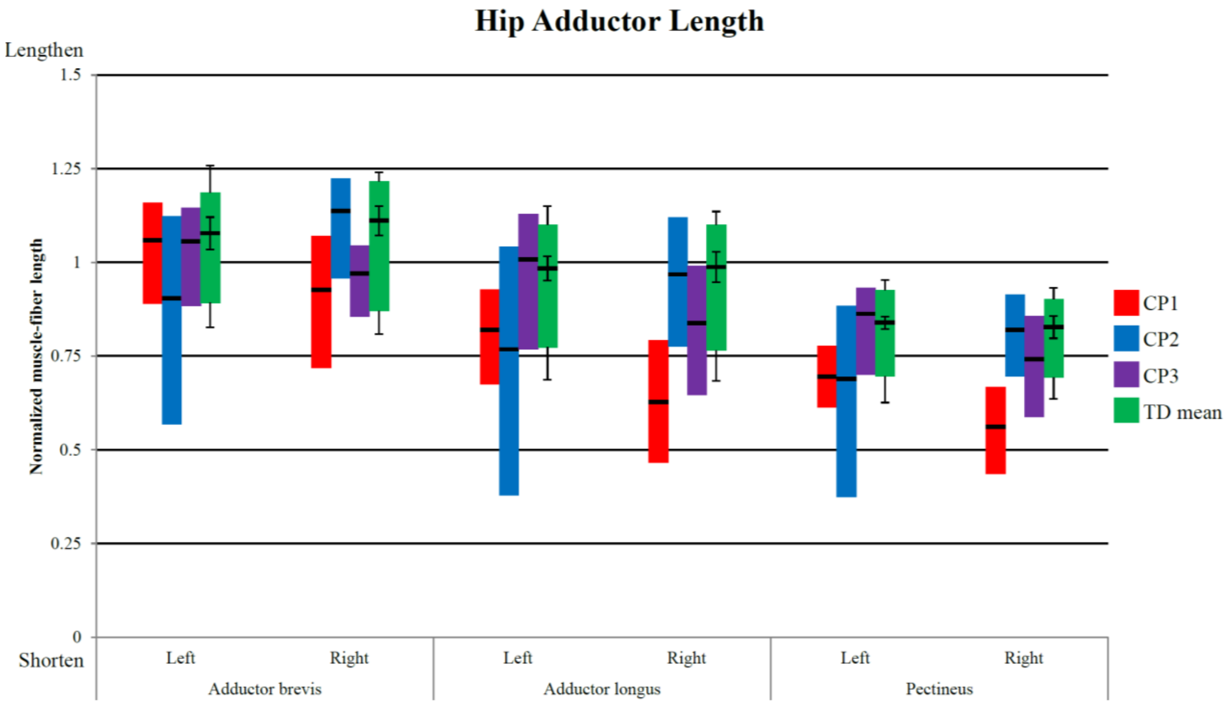

Figure 2.7. Hip adductor muscle groups (left and right leg: adductor brevis; adductor longus; pectineus) shown with columns representing minimum to maximum normalized muscle-fiber length, with mean depicted by black line. The pectineus muscle shows little stretch. Adductor brevis shows stretch beyond the optimal fiber length (1 for normalized muscle-fiber length) for both populations; adductor longus has minor stretch. CP and TD populations have similar results.

The hip extensor and adductor muscle groups demonstrated no statistically significant results. However, the left gluteus maximus was most likely to be different (CP mean 0.55, TD mean 0.43, $p = 0.1235$). Additionally, all hip adductor muscles in Table 2.5 had close-to-significant results; p-values ranged from 0.1166 to 0.1513 with greater mean lengths for the TD population (see Table 2.5 for complete results). Fig. 2.6-2.7 and Table 2.5 show high variability in CP population results for the hip extensors and some hip adductors relative to the other muscle length results.

Table 2.5. P-values for comparison of the CP and TD population means for muscle stretches of four lower limb muscle groups. *p<0.05, **p<0.01, ***p<0.001.

Muscle	CP Mean (±SD)	TD Mean (±SD)	p-value
Ankle Plantarflexors			
Left gastrocnemius lateralis	0.78 (0.087)	0.77 (0.042)	0.431
Right gastrocnemius lateralis	0.74 (0.026)	0.69 (0.073)	0.118
Left gastrocnemius medialis	0.76 (0.078)	0.76 (0.037)	0.477
Right gastrocnemius medialis	0.72 (0.025)	0.68 (0.065)	0.130
Left soleus	1.03 (0.071)	0.96 (0.048)	0.105
Right soleus	1.05 (0.071)	0.91 (0.14)	<0.05*
Knee Extensors			
Left vastus lateralis	0.96 (0.065)	0.85 (0.089)	0.052
Right vastus lateralis	1.04 (0.098)	0.91 (0.11)	0.063
Left vastus medialis	0.95 (0.064)	0.85 (0.084)	0.061
Right vastus medialis	1.03 (0.093)	0.91 (0.10)	0.065
Left vastus intermedius	1.05 (0.065)	0.94 (0.093)	0.050
Right vastus intermedius	1.06 (0.098)	0.93 (0.11)	0.065
Left rectus femoris	1.03 (0.23)	1.00 (0.066)	0.432
Right rectus femoris	0.98 (0.16)	0.92 (0.057)	0.304
Hip Extensors			
Left biceps femoris long head	0.73 (0.27)	0.67 (0.079)	0.386
Right biceps femoris long head	0.82 (0.20)	0.78 (0.059)	0.375
Left gluteus maximus	0.55 (0.13)	0.43 (0.037)	0.124
Right gluteus maximus	0.57 (0.13)	0.51 (0.046)	0.254
Hip Adductors			
Left adductor brevis	1.01 (0.087)	1.08 (0.043)	0.151
Right adductor brevis	1.01 (0.11)	1.11 (0.039)	0.147
Left adductor longus	0.86 (0.13)	0.98 (0.032)	0.132
Right adductor longus	0.81 (0.17)	0.99 (0.041)	0.117
Left pectineus	0.75 (0.099)	0.84 (0.016)	0.138
Right pectineus	0.71 (0.13)	0.82 (0.030)	0.141

2.4 Discussion and Conclusion

Significant differences were found between the CP and TD populations for both outside belay rope support and limb force contributions to self-support. All climbers with CP required significantly greater belay rope support, whereas TD climbers relied on little outside support other than tension kept in the rope for safety reasons. Additionally, this extra outside support was required because of significant deficits in lower limb usage; there were no significant differences in upper body force application to the climbing wall. Because all three climbers with CP have diplegic symptoms, these results make sense. Diplegia affects the lower half of the body to a greater extent than the upper half; it may explain the reduced ability to exert lower body force and execute lower limb joint excursions (discussed later in this section).

The climbing wall is well suited to managing CP weakness with built-in tools for outside support, i.e., the belay rope, without altering the experience from that of TD climbers. The clinical goal would likely be to encourage greater input from the climbers' legs and wean them off belay support (explored in greater detail in Chapter 3); another tool could be to change climbing grip shape in order to train fine motor skills more directly (not explored in this thesis). For other variations of CP such as hemiplegia, monoplegia, or even quadriplegia, climbers could similarly target their weaker limbs, work on strengthening them, and decrease reliance on belay support. Further investigation should work with these specific CP populations in order to see how their limb weaknesses influences body weight support and limb force contribution results. Extent of belay rope support would be expected to depend on the respective limb deficits of the climber and severity of limb weakness, as it did not appear that climbers with diplegia made up for lower limb deficits with greater than normal upper limb force contributions.

Joint excursion ranges were higher for the TD population, with joint angle means unlikely to be similar to those of the CP population in most cases. More subjects would likely strengthen statistical inferences due to high variability in joint excursion results for the small CP population in this study. CP population normalized ankle plantarflexor, knee extensor, and hip extensor muscle lengths were greater or equivalent to TD population values, suggesting that similar or greater stretch can be elicited for these muscles. Significant or near-significant differences were observed in the soleus muscles and vastus muscles where CP muscle lengths exceeded TD muscle lengths; otherwise group length means were similar. The hip adductor muscle group was the only one in which CP population means were lower than that of the TD population with near-significant results. There are several possible reasons for this result. Genu valgum, a common problem for patients with cerebral palsy, is a condition attributed to excessive knee flexion and abnormal muscle forces in which the knees angle in and touch when the feet are not touching; this may have reduced climbers' abilities to generate lower limb forces and bring legs apart to make lateral movements (Rethlefsen, Nguyen, Wren, Milewski, & Kay, 2015). Poor balance may also have played a factor in hip adductor muscle lengths. Keeping both feet on the climbing wall was difficult for climbers with CP, which may have led to the body midline moving closer to the lateral grip and decreasing hip abduction (see Table 2.4: CP population mean > TD population for mean hip adduction values, resulting in less hip abduction). Further research should explore the effect of climb training on hip adductor muscle lengths; it may be that over time, climbers with CP achieve better hip abduction on the climbing wall when stepping to lateral steps. Other than the hip adductor muscle group, there is little statistical evidence to suggest that climbers with CP cannot achieve the same muscle stretch as TD climbers. Chapter 4 will explore this topic more in depth by comparing muscle lengths during climbing relative to corresponding walking values.

Limitations in this study depend on the validity of the model assumptions made to obtain joint kinematics and muscle lengths. The joint kinematics in MSC.Adams were calculated using a minimization of error between the experimental marker positions and the model marker positions, which may have introduced some latent error into the joint angle results. Additionally, assumptions were made about the behavior of the joints: the knee joint was a hinge joint in the sagittal plane since varus/valgus and internal torsion were assumed to be negligible. For the

OpenSim muscle model, potential individual differences in muscle-to-tendon ratios, biomechanical stretch coefficients, and precise attachment points were not taken into account. It is possible these variables were influenced by CP in unanticipated ways, although it would be very difficult to confirm with a reasonable degree of accuracy in an experimental setting.

The findings from this study present intriguing future directions. Training climbers to support their own body weight or use non-favored limbs to climb could incorporate force feedback, a realtime learning tool. For example, a warning tone could sound every time the climber exceeds a weight limit set in proportion to the climber's abilities, helping them to realize when they need to put forth more effort to support their own body weight on the climbing wall. This technique has already been tested in previous studies with TD climbers in our laboratory and proven highly effective in promoting rapid learning. Additionally, it would be simple to revise this method so that climbers have to generate enough force on a climbing wall to make a celebratory sound and to direct this effort towards a weaker limb in need of extra training.

Other studies should delve deeper into the source of force generation, fatigue, and coordination by comparing electromyography (EMG) measurements between climbers from the TD and CP populations. Muscle weakness is known to be caused by muscle atrophy and improper or inadequate neuromuscular signals, but is one factor more responsible than the other? Is low-level spasticity present that influences force generation, joint excursion, and coordination? Are there changes observed with climb training? Does fatigue set in more quickly for climbers with CP, and if so, can endurance be improved with climb training? Additionally, EMG can be used to tease out precise impact of muscle weakness and/or limited ROM on climbing success. For example, if subjects are in a position where joint angles negatively impact their ability to exert optimum muscle force, EMG may show that a large number of muscle fibers were recruited even when subjects struggle to complete a step, identifying tight muscles' influence on joint angles as the culprit rather than muscle weakness. This information would be valuable to clinicians deciding how best to move forward with patient therapy. For this study, EMG collection was impractical because of the extensive marker set and climbing gear already on each climber, but it could be valuable in future studies.

While it is apparent that climbing comes more naturally to children that do not have CP, these results suggest that climbing is a viable activity for children with CP. Deficits in function due to CP were easily handled without adapting the wall specially for climbers with CP: the belay rope allows for outside body weight support, and clinicians can assist with ROM by guiding limbs manually in cases where the climber cannot achieve the movement alone. The force and muscle length results suggest that a patient with CP can climb and exert forces similar to TD children, and that deficits can be identified and targeted precisely. Climbing is a promising therapy that can deliver innate therapeutic strength and stretch benefits to children with CP while eliciting active participation and providing a positive experience.

Chapter 3: Impact of Climb Training on Body Weight Support and Limb Forces for Children with Cerebral Palsy

3.1 Introduction and Background

One of the key challenges for children with cerebral palsy is pathologic muscle weakness. As one of the most common symptoms of CP, muscle weakness is ascribed to a central nervous system injury that inhibits neurological ability to maximally activate muscles and causes non-productive coactivation with antagonist muscle groups (Elder et al., 2003; Fowler et al., 2007) . In recent years, the notion that strength training might have unintended negative consequences, i.e., increased spasticity and decreased range of motion (ROM), has been rebutted with multiple studies (Damiano & Abel, 1998; Dodd et al., 2002).

From a clinical perspective, strength training is seen as imperative to address muscle weakness and restore function, or at least slow loss of function. Muscle weakness becomes a more severe symptom as children with CP age and grow, because their strength-to-mass ratio declines to their detriment (Damiano & Abel, 1998). Based on a systematic review of various strength-building programs for patients with CP, improving muscle strength has led to statistical improvements in activity levels and Gross Motor Function Measure (GMFM) scores; in turn, no adverse effects were observed on spasticity and ROM, and in some cases were improved (Dodd et al., 2002).

In the past clinicians may have recommended body weight exercises, resistance bands, and basic weight training regimens to improve strength; presently they have sought to customize therapy to the individual. The fields of physical therapy and rehabilitation have shifted to incorporate more inventive and engaging therapies. Not only is personalized strength training more interesting for patients, but also it has been argued that pursuing activities where strength is a byproduct rather than the primary or only outcome of the exercise places a better emphasis on function in daily life and positive psychological impacts (Law & Darrah, 2014). It is recognized that clinicians need to encourage long-term physical conditioning to achieve sustained success; practically speaking, recreational activities such as climbing could garner that commitment (Damiano, 2006).

Climbing has been shown to mimic some of the physiological effects of weight lifting due to its combination of long isometric position holds and short explosive muscle output. Regular and elite climbers tend to exhibit higher muscular strength, longer endurance, and increased power generation; these physiological adaptations are seen particularly in the upper body but can extend to the lower body as well (Grant et al., 1996; Mermier, 2000). Practiced climbers have excellent strength-to-mass ratios, which is precisely the ratio that children with CP need to improve or maintain as they age to retain or better their functional abilities (Watts, 2004).

Data in the previous chapter showed that children with CP are able to match or come close to typically developed (TD) children in the majority of ROM measurements. Similar upper body force generation was also seen for the population evaluated in this thesis. Therefore it is reasonable to surmise that children with CP can reap comparable benefits to those expected from the TD population, given the appropriate intensity and quantity of climb training. The goal of this study is to examine body weight support and limb force generation for the CP population before and after four sessions of weekly climb training sessions. Are there detectable differences in quality of force generation during climbing after relatively short training periods? Are there shifts in force application strategy? What potential implications are there to support or undermine climbing as a recreational therapy?

3.2 Methods

3.2.1 Subject Recruitment

Climbers were recruited from the Motion and Motor Performance clinical laboratory at the University of Virginia. Three subjects with diplegic CP completed the full climbing protocol. All subjects with CP were novice climbers but active in other sporting and recreational activities. Subject consent was approved by the University of Virginia's Institutional Review Board and was obtained for all subjects with parental permission.

Table 3.2. Demographics of the CP population recruited for climbing.

Subject ID	*Gender (M/F)*	*GMFCS classification*	*Experienced climber (Y/N)*	*Age (years)*	*Height (m)*	*Weight (kg)*
CP1	M	Level II	N	16	1.68	64.2
CP2	F	Level III	N	10	1.18	22.0
CP3	F	Level III	N	6	1.07	16.6

3.2.2 Climb Protocol

a) Climbing wall diagram b) Climbing wall configuration with climber

Figure 3.1. The climbing wall configuration. a) On the right wall, climb grips were positioned in a 3x3 grid on the right side for a variety of lateral, vertical, and combined vertical/lateral steps. b) A climber is shown climbing up to the starting position (the grip labeled 11 and its blue lateral counterpart).

All climbers followed the same protocol. All wore a size-appropriate climbing harness with locking carabiners for attaching the belay rope. Each subject wore a modified full body Plug-in Gait set of 43 markers and had anthropometric data measurements taken prior to marker attachment for entry into Vicon Nexus software (Vicon Motion Systems Ltd., Oxford, UK). Subjects were allowed to warm up and make adjustments to the climbing harness and data collection tools before performing a series of steps on a uniform 3x3 grid of climbing grips spaced eight inches laterally and vertically (see Fig. 3.1). This configuration characterized the right side of the wall, while the left side only had a column of three climbing grips spaced eight inches vertically.

All steps began with both feet placed at the initial position at the two innermost and lowest climbing grips. Both hands were placed on climbing grips above the head and at a sufficient height not to overlap multiple limbs on a single force plate. There were eight possible destinations for the right foot: two on the lowest level, three on the middle level, and three on the top level. Climbers were instructed to match the height of their left foot to their right foot to conclude the step. One subject with CP was short to the point that the middle level (eight inch vertical relative to initial location) was the maximum anatomically achievable height; other subjects were able to reach all steps. All data were collected and synchronized using Vicon software.

Participants returned to free climb on a weekly basis the following four weeks to establish consistent training. All climbers attempted at least four full wall climbs (18 ft) per session with a limit of six full wall climbs (cumulative 108 ft). Climbers were given special tasks to challenge ROM and strength exertion, such as skipping different color grips and relying on belay rope assistance as little as feasible.

For the follow-up climbing data collection, the initial collection protocol was repeated for direct comparison. This chapter focuses on results from the maximum vertical step achieved with no lateral movement, the maximum vertical step achieved with maximum lateral movement, and the vertical level beneath maximum with maximum lateral movement. These particular grip positions encompassed different body positions while prompting climbers to tackle moderate to significant challenges in order to achieve the step.

3.2.3 Measuring Outside Assistance and Limb Contributions to Body Weight Support during Climbing

Outside assistance to the climber was quantified to evaluate his or her ability to climb independently. A uniaxial load cell (Interface Inc., Scottsdale, AZ) was placed in series with the belay rope to measure potential lift assistance from the belayer to the climber. Forces on the climbing wall were measured using six vertically mounted Bertec force plates (Bertec Corp., Columbus, OH) (see Fig. 3.2a). All data were processed using custom MATLAB software and used to construct computational models.

a) Bertec force plates mounted on wall *b) Interface Inc. load cell in series with rope*

Figure 3.2. Force plates and belay rope load cell. a) Uncovered force plates mounted vertically to collect information from multiple limbs. b) The load cell (circled in yellow) measured amount of force exerted on climber via belay rope (held by a belayer, unpictured).

3.2.4 Measuring Outside Assistance, Limb Contributions, and Joint Torque for Body Weight Support during Climbing

Forces measured from the six climbing wall plates were applied to the hands and feet. For the belay rope force, the direction of force application was determined using a vector from the midpoint of the two ASIS markers and the 3D position of the chained carabiner through which the rope loops at the top of the wall. This vector represented the straight line of the rope running from the climber to the top of the wall. In the LifeMOD models, a virtual marker was created between the two ASIS markers to apply belay rope force to the model pelvis during dynamic simulations. Forward dynamic joint torques were calculated using the LifeMOD plug-in for MSC Adams, with experimental forces and torques applied at the hands and feet of the skeletal models and previously recorded joint angles from inverse kinematics used as target figures in PD-servo controller joint elements. Subsequently, all joint torques were exported to MATLAB where they underwent a low pass filter of 7Hz to remove noise. This data is located in Appendix A.2.

3.3 Results

3.3.1 Climbing Gait: Belay rope support

The data shown in Fig. 3.3 were taken from initial and final climbing sessions for subjects with CP; all data came from three steps (16 inch lateral, 16 inch vertical; 16 inch vertical, 0 inch lateral; 8 inch vertical and 16 inch lateral, respectively). Average body weight support required for climbers with CP were only significantly different from initial to final data for one step: 43.9 ± 12.0% and 45.0% ± 34.0% ($p = 0.477$); 47.7% ± 23.6% and 30.1% ± 28.8% ($p < 0.05$), 45.5% ± 24.3% and 40.6% ± 26.4% ($p = 0.294$). The statistically significant drop in body weight support from initial to final groups was the step that did not require lateral movement.

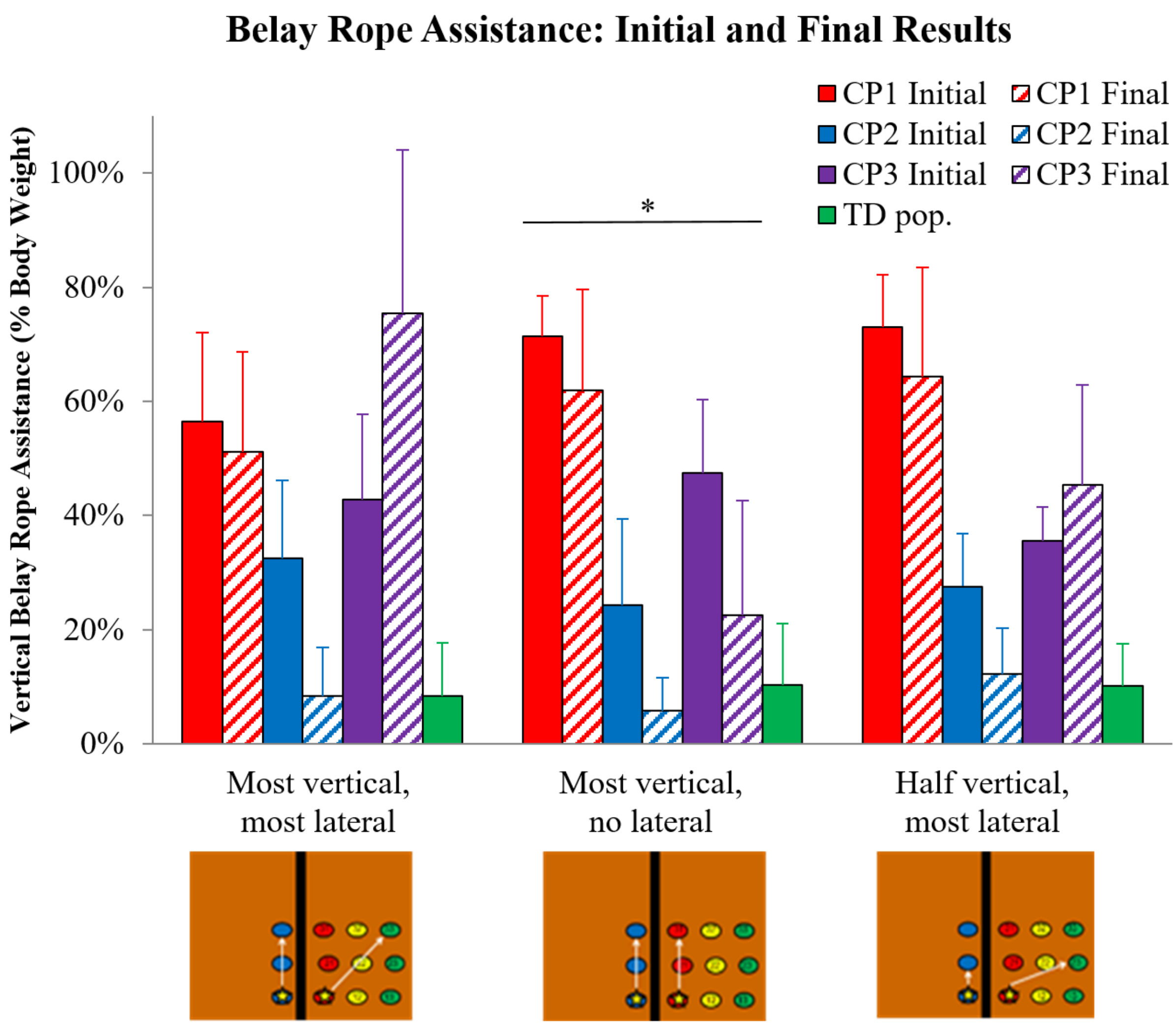

Figure 3.3. Vertical belay rope assistance normalized by body weight for three different step conditions. Each color corresponds to one climber, with solid bars indicating initial results and striated bars showing final results.

Table 3.2 contains results comparing climbers' initial results with their final results for all three steps shown in Fig. 3.3. Subject CP1, represented in red, showed small decreases in mean belay rope support after climb training ($p < 0.05$). Subject CP2, shown in blue, demonstrated highly significantly decreases in mean belay rope support ($p < 0.01$), on par with the TD population means in all three steps. Subject CP3 did not show significant differences ($p = 0.381$), but Fig. 3.4, Fig. 3.5, and corresponding text explain this result further.

Table 3.2. Mean ± SD information for three different steps completed by each climber with CP. Initial and final results were compared for each climber to ascertain climb training impact on each individual. Significant differences were observed for two out of three climbers. *p<0.05, **p<0.01, ***p<0.001.

Subject	Initial CP Mean (±SD)	Final CP Mean (±SD)	p-value
CP1	67.0 (9.1)	59.1 (7.0)	<0.05*
CP2	28.1 (4.1)	8.76 (3.2)	<0.01**
CP3	42.0 (6.0)	47.8 (26.6)	0.381

Subject CP3 saw improvement in non-lateral steps (initial 47.5%, final 22.5%) but an increase in body weight support for steps requiring lateral movements (initial 42.8 and 35.6%, final 75.5 and 45.3%). A closer look at belay rope support over trial time (Fig. 3.4) reveals the reason for these results: “concentrated strength” effort. A climbing step consists of four stages: Stage 1 is moving the right foot towards its destination; Stage 2 is planting the right foot down; Stage 3 is moving the left foot towards its destination; Stage 4 is planting the left foot down. During the initial climbing session, the subject required belay rope assistance throughout the entirety of the step she completed, regardless of stages. However, after climb training, subject CP3 learned to move her limbs to the appropriate climbing grips (see Stage 1 and 3 in Fig. 3.4), then exert muscle force to advance up the wall independently (Stage 2 and 4 in Fig. 3.4). This phenomenon is explored further in the next section.

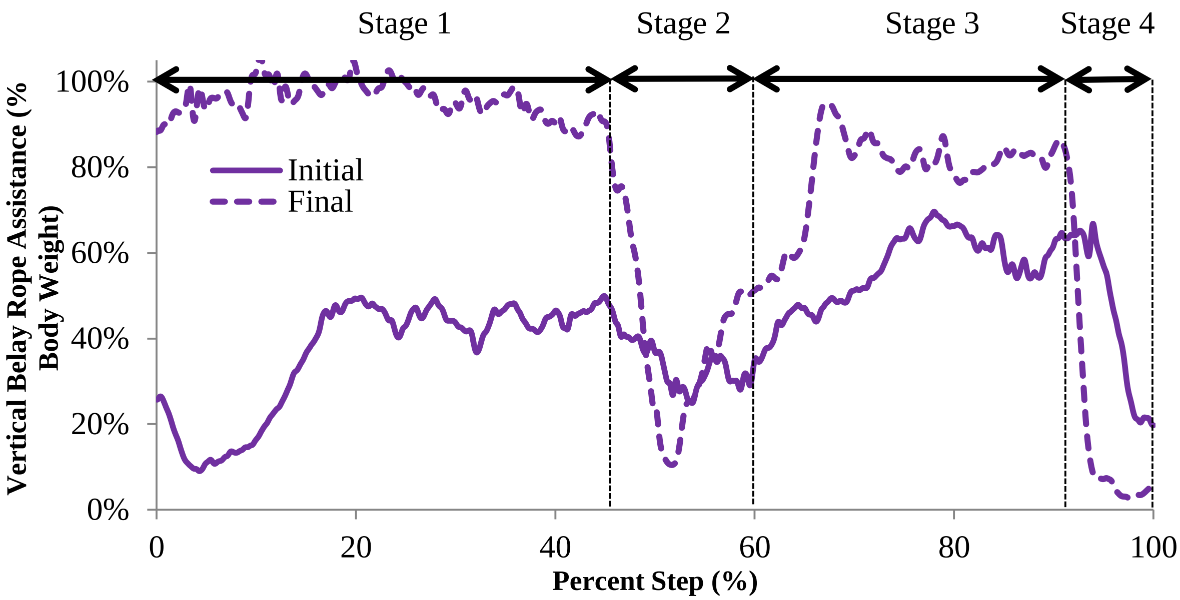

Figure 3.4. A representative step requiring lateral movement for subject CP3. Her initial attempt exhibits a consistent body weight support requirement. After training, her final attempt demonstrates that she relied on outside support while configuring lower limbs for the step (Stages 1 and 3, right and left foot placement respectively), then independently lifted herself up to the climbing grip (Stages 2 and 4, right and left foot respectively).

3.3.2 Climbing Gait Results: Limb forces

In Fig. 3.5, three different methods of analyzing limb forces during climbing are presented.

Fig. 3.5a shows the average force contribution from each limb over a single climbing step; initial and final results are shown in adjacent columns. Subject CP1 increased overall force contributions thanks to left leg utilization (12.3% to 23.1% BW). Subject CP2 showed the most improvement (67.5% to 99.3% BW cumulatively) as a result of better lower limb utilization. Subject CP3 did not improve by this measure (48.0% to 17.8% BW). Results totaling less than 100% may be due to noise filtering, variation in belay rope vector calculation, and experimental error such as briefly catching a toe under a climbing grip during positioning, which would register a negative vertical force and slightly reduce the overall average for that appendage.

For Fig. 3.5b, each column corresponds to the climber's maximum force from each of the four limbs, not necessarily occurring at simultaneous timepoints. Subject CP1 nearly doubled maximum left leg force generation; CP2 exerted a higher maximum right lower limb force; and CP3 did not improve by this measure with a decrease in all but left leg force generation.

Fig. 3.5c portrays the state of limb force generation at the point of maximum total body weight support, usually during the physical act of stepping up. For subject CP1, body weight support shifts from other limbs to the left leg. CP2's improvement is supported by an increase in right leg force generation. For CP3, the result after training was an increase in lower limb force generation. Inconsistency with the apparent results of Figs. 3.5a-b are due to this subject's preferred method of "concentrated strength"; she produced the muscle force desired as a result of climbing, but heavily relied on belay rope support while adjusting limbs to reach climbing grips.

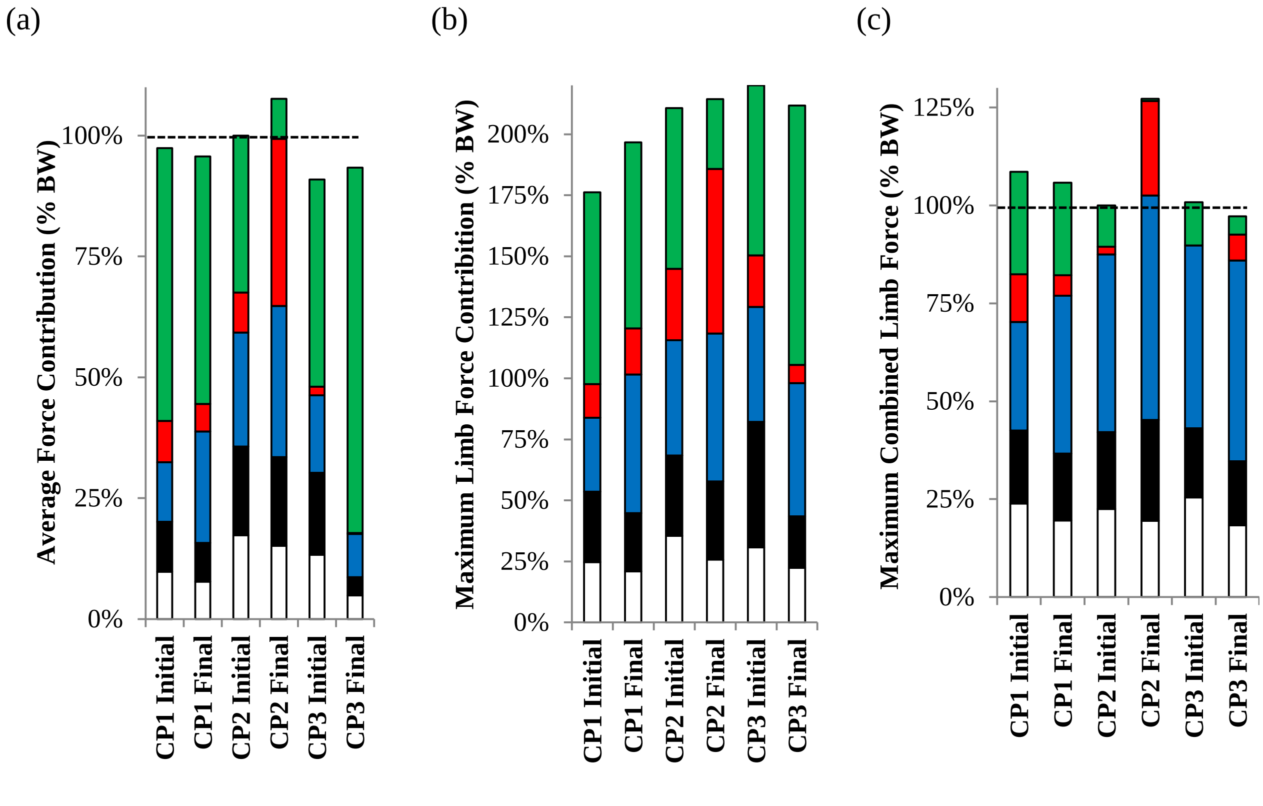

Figure 3.5. All graphs apply to most lateral, most vertical step. Results for the three climbers with CP are shown with initial and final results constituting two separate columns per climber. a) Average force contribution over course of step. b) Maximum independent limb force contribution with the maximum value for each limb, not necessarily concurrent. c) Concurrent limb contributions at the point of maximum vertical force magnitude exerted by climber.

Table 3.3 compares all initial results of the CP population to their final results, and Table 3.4 shows p-values comparing the right and left sides for the initial data as well as the final data. One key difference in climbing strategy before and after climb training is a shift of BW support from the upper limbs to the lower limbs. During maximum combined force, the upper limbs contributed more equally (initial right/left hand $p < 0.01$; final right/left hand $p = 0.419$). In turn, the lower limbs both assumed larger contributions.

Other differences with statistical significance or near-significance between initial and final climbing include decreased upper limb forces for average (right hand $p = 0.178$, left hand $p = 0.163$), maximum individual (right hand $p = 0.095$, left hand $p = 0.051$), and maximum combined forces (left hand $p < 0.01$). Additionally, there were increased lower limb forces for maximum individual (left foot $p < 0.05$) and maximum combined forces (right foot $p = 0.184$, left foot $p = 0.144$). These results also support the shift in BW distribution from the initial climbing session to the final one.

Table 3.3. Mean ± SD information for the CP initial and final climb sessions. Average forces correspond to force over the course of the step averaged. Maximum individual forces are the peak forces observed, whether simultaneous or asynchronous. Maximum combined forces are the forces observed from each limb at the point of maximum total force. A one-tailed unpaired t-test was performed for each variable. p-values are listed for comparison between the initial and final data groups. *p<0.05, **p<0.01, ***p<0.001.

	CP Initial Mean (±SD)	**CP Final Mean (±SD)**	**p-value**
AVERAGE FORCES			
Right hand (% BW)	15.2 (4.3)	10.0 (7.5)	0.178
Left hand (% BW)	13.5 (3.8)	9.26 (5.3)	0.163
Right foot (% BW)	6.2 (3.8)	13.5 (18.5)	0.270
Left foot (% BW)	17.3 (5.7)	21.1 (11.3)	0.316
MAXIMUM INDIVIDUAL FORCES			
Right hand (% BW)	37.8 (12.0)	25.7 (5.7)	0.095
Left hand (% BW)	30.3 (5.4)	23.0 (2.5)	0.051
Right foot (% BW)	21.3 (7.7)	31.3 (31.8)	0.314
Left foot (% BW)	41.6 (9.7)	57.3 (3.1)	<0.05*
MAXIMUM COMBINED FORCES			
Right hand (% BW)	18.6 (0.98)	19.7 (5.2)	0.366
Left hand (% BW)	24.0 (1.5)	19.1 (0.66)	<0.01**
Right foot (% BW)	4.7 (6.5)	12.0 (10.5)	0.184
Left foot (% BW)	39.9 (10.6)	49.6 (8.6)	0.144

Table 3.4. Comparing right and left sides for CP initial and final data. A one-tailed unpaired t-test was performed for each variable. This analysis shows a statistically significant shift in climbing strategy from initial to final climbing session, with hands assuming more equal body weight distributions and the left foot sustaining more body weight support during the point of maximum combined body weight support after training. *p<0.05, **p<0.01, ***p<0.001.

Right and left side comparisons		
CP comparison groups	**CP Initial p-value**	**CP Final p-value**
Average right hand (% BW) *Average left hand (% BW)*	0.315	0.446
Average right foot (% BW) *Average left foot (% BW)*	<0.05*	0.288
Maximum right hand (% BW) *Maximum left hand (% BW)*	0.191	0.251
Maximum right foot (% BW) *Maximum left foot (% BW)*	<0.05*	0.115
Max. combined right hand (% BW) *Max. combined left hand (% BW)*	<0.01**	0.419
Max. combined right foot (% BW) *Max. combined left foot (% BW)*	<0.01**	<0.01**

3.4 Discussion and Conclusions

The climbers in this study demonstrated clear and significant improvements in reducing their reliance on outside belay rope assistance and utilizing lower limbs more effectively when taking steps. Their climbing strategies changed over time to reflect more focused, efficient effort. All three subjects' successes demonstrated the value of the climbing wall as a malleable tool for children with diverse levels and variations of CP symptoms. Even with a statistically small population (n = 3), the data still revealed statistically significant differences after training, making a strong case that the differences should hold with a larger population.

Subject CP1 was the oldest climber (17 years old at final collection) and had the highest mass (64.2 kg). Academic studies have confirmed the clinical observations that youth with CP are at risk of losing motor function as they mature into adolescents and adults in spite of the non-progressive nature of CP; the standing hypotheses for the roots of this issue are increased energy costs due to mass/size, fewer opportunities for physical activity during the day, and realignments in (or damage to) bone/body structure as a consequence of the patient's pathological symptoms over time (Bottos & Gericke, 2007; Hanna et al., 2009). As a result, his statistically significant but small improvement on belay rope support (Fig. 3.3) may be attributed to his age/size. A more rigorous/frequent climbing regimen would likely be necessary to attain higher leaps in functions for individuals of his age and size. His coordination issues led to low left foot force generation in his initial limb force results (Fig. 3.5a-c). However, by the completion of climb training, his final results suggest that he was better able to coordinate all four limbs on the wall.

While coordination is not explicitly analyzed in this study, it is an important symptom of CP that theoretically could be addressed by climbing and may have occurred in this study. Future work should consider climbing influence on coordination using motion capture data analysis to evaluate how quickly and directly climbers with CP ambulate to climbing grips after climb training, as well as whether or not improvements observed on the wall translate to functional differences in coordination for activities of daily living. Electromyography (EMG) work could also shed light on factors affecting coordination such as muscle fiber recruitment, spasticity, antagonist muscle activity, and fatigue.

For subject CP2, impressive improvements were seen as the younger, lighter climber was able to achieve belay rope support independence on the scale of control subjects (Fig. 3.3), sustaining upper body force generation while increasing lower body contributions (Fig. 3.5a-c). This subject was an excellent example of how to use the same climbing wall as others to pose more challenging tasks with minimal effort on the behalf of clinicians; additional challenges were posed to her during climb training, i.e., certain colored climbing grips being "lava" requiring her to reach further and generate higher torques to step up. Continuing training would likely focus on goals such as requiring larger steps with her non-preferred lower limb and dictating that she equally favors left and right limbs throughout free climbs, both with verbal instructions and with rearrangement of climbing grips.

Subject CP3, the youngest and smallest of the study subjects, had interesting results that required extra analysis. While Fig. 3.3 may have led one to believe that she was unable to attain body weight support independence, her adaptive climbing strategy separated ROM and body weight support into two non-concurrent events. Fig. 3.4 (and video observation) shows that subject CP3 learned to completely sit back and allow the belayer to hold her in the air while she moved her right foot to the appropriate climbing grip (Stage 1). Then she stepped up almost independently, as evidenced by Stage 2 where belay rope body weight support dropped drastically. Subsequently she positioned her left foot to the corresponding climbing grip while relying on outside support (Stage 3) but then assumed full body support again (Stage 4). This "divide-and-conquer" approach of addressing ROM first, then independently advancing up the climbing wall, was different from the other subjects who focused on doing both simultaneously; however, it was not necessarily to her detriment, as she still accomplished both goals of stretching muscles and supporting most or all of her body weight as she climbed. Further work with her would probably focus on encouraging sustained body weight support and improving force generation during coordination tasks. One technique could be to integrate real time force feedback into her routine. By adding a beep or buzzer when she is leaning too much on outside support based on a simple force threshold, the act of self-sustaining body weight support could be made into a game for her.

Climbing lends itself to rapid and natural personalization to fit each climber's needs. For subject CP2, it was easy to declare certain climbing grips off limits, and it made the activity more fun for her while ideally increasing difficulty and level of therapy intensity. Another example is subject CP3's approach, which may be a good secondary strategy in clinical practice. Increasing ROM and the increasing strength are often addressed by two different targeted exercises in traditional physical therapies. By separating the two objectives in climbing, at least initially, clinicians may avoid patient frustration or discouragement and develop their motivation to achieve both at once after extended training. However, more work is necessary to determine whether or not sustaining full body weight in impulse periods yields equivalent or satisfactory benefits compared to partial body weight sustained over the full trial.

The limitations of modeling proved to be overwhelming in this study for joint torque calculations; they were noisy, and different experimental errors made it difficult to identify trends. A careful evaluation of joint torques in future studies would be valuable by identifying muscle groups that increase in force exertion throughout climb training, or else antagonist muscle groups that decrease in force exertion. Otherwise the measurements shown in this chapter were direct measurements where the only improvement would be data from more subjects in future studies.

In general, the two younger climbers demonstrated improvement at a higher level than the oldest climber, upholding research outlined in the introduction that recommends early-age intervention to prevent symptoms from growing in severity and to reinforce the habit of pursuing physical activity. Nevertheless, improvements were shown even in the oldest climber, suggesting that latecomers to climbing therapy can still reap benefit through regular participation. Regarding support of body weight, climbing has proven to be an effective recreational therapy option for children with CP. The body of work in this study proves that it can encourage these diverse individuals to exert coordinated forces with all four limbs while sustaining their interest and motivation to do so.

Chapter 4: Impact of Climbing on Range of Motion and Muscle Stretch for Children with Cerebral Palsy

4.1 Introduction and Background

Issues with limited range of motion (ROM) and excess muscle tightness (MT) are compellingly linked to reduction of functional ability in the cerebral palsy (CP) population (Damiano, 2006; Levin & Feldman, 1994). Negative physiological adaptations as a result of these symptoms are a major concern to clinicians, predicating the widespread intervention to lengthen muscle either through passive stretch (in therapy sessions and using splints or orthotic devices) or by surgically lengthening the shortened muscle (Granata, Abel, & Damiano, 2000; Mansouri, Clark, Seth, & Reinbolt, 2016; Pin, Dyke, & Chan, 2006). Neither option is appealing to patients, who often have to tolerate uncomfortable and repetitive physical therapy routines or lengthy recovery periods from invasive surgery. If a mentally stimulating alternative could be offered, participants could be independently driven to succeed and improve ROM and MT.

Over time, physiological changes occur as a result of consistently shortened muscle, a state brought about by hypertonia, sedentary habits or immobilization, atrophy, lack of muscle growth in proportion to bone growth, spasticity, or other factors. Muscles working at shortened lengths reduce number of sarcomeres, add connective tissue between fibers that increase resistance to muscle compliance, and decrease the cross-sectional area of the muscle fibers (Farmer & James, 2001; Handsfield et al., 2015; Rose & McGill, 2005; Williams, Catanese, Lucey, & Goldspink, 1988; Williams & Goldspink, 1984). Lack of motion related to symptoms or surgical intervention can thin cartilage between articulated joints and induce ligament disorganization, which can lead to joint pain that discourages further motion that could otherwise reverse this trend (Akeson, Amiel, Abel, Garfin, & Woo, 1987). While current research is still identifying the precise biomechanical impetus that drives optimal tissue organization so as to effect nominal muscle, cartilage, tendon, and ligament properties, there is a strong body of research from the past four decades to suggest shortened operating muscle lengths are detrimental to long term function.

Because these physiological changes evoke a cycle of deterioration without intervention, clinicians take treatment seriously for individuals with CP. Therapists provide passive stretching to patients, but research evidence supporting its benefits have been weak with conflicting results (Pin et al., 2006). Additionally, studies have proposed at least 30-50 minutes of dedicated daily stretching in order to ward off adverse effects of muscle shortening, an amount of time that may be challenging to sustain for young children and adolescents (Farmer & James, 2001; Tardieu, Lespargot, Tabary, & Bret, 1988; Williams, 1990). Casting and splinting are another technique to encourage muscle lengthening, where the joint can be held at the limit of ROM for the patient. However, this method may exchange one problem for another as the pseudo-immobilization could lead to muscle atrophy or unintended effects on the antagonist muscle to the one being lengthened (Farmer & James, 2001). Muscle-tendon surgical interventions can rectify shortened muscles barring complications, but its invasive nature and lengthy recoveries make surgery impractical for consistent, lifelong therapy.

Many of the traditional regimens have limited efficacy or significant drawbacks, which necessitates the development of new therapies to try and improve clinical care for the CP population. Recreational climb therapy may be one possibility that sidesteps some of the issues listed previously. The act of reaching for a climbing grip cultivates active stretching, and the classic structure of an indoor rock climbing wall - with interchangeable climbing grips and extra placements - makes it possible to carefully tailor the lateral and vertical movements of each individual to challenge the limits of his or her ROM. The sporting component to climbing may promote better participation from younger patients. With the strength component (covered in Chapter 3), muscle atrophy should be less of a concern. It goes without saying that non-invasive therapy, if effective, is preferable to surgery and its potential complications. In Chapter 2, it was found that for the majority of muscles, climbers with CP elicited comparable or greater muscle lengths to that of climbers in the typically developed (TD) population. This study seeks to compare muscle stretch and ROM due to climbing versus overground walking. Does climbing encourage more lengthened muscle and wider ROM compared to walking? Is there a significant difference between muscle lengths means, maximum lengths, and range of length in any muscle groups for these two conditions? Should climb therapy be viewed as a potential alternative to more traditional muscle lengthening measures?

4.2 Methods

4.2.1 Collection of Climbing Motion Data

The same three subjects with CP from Chapters 2 and 3 are examined in this study. (Refer to Tables 2.1 and 3.1 for demographic information.) This climbing research was conducted in parallel with the methods described in Chapter 3. 10 Vicon Nexus cameras were placed behind and above the climbing wall in order to track marker motion. During climbing, a belay rope was attached to the subject’s climbing harness, which is used to prevent climbers from falling and/or provide lift assistance when necessary. Each subject wore a modified full body Vicon Plug-in Gait marker set with additional marker clusters. Anthropometric data measurements were taken prior to marker attachment. All data was synchronized and recorded using Vicon Nexus software.

Subjects performed a standard set of eight climbing steps that required lateral and/or vertical movement. Gait collection sessions went as follows:

1. Free climb (warm-up)
2. Climber-determined break
3. Steps beginning at starting position (termed '11' for column and row position)
    a. Lateral steps
    b. Vertical steps
    c. Lateral and vertical steps
4. Climber-determined break upon completion of four steps (half completion)
5. Resume steps beginning at starting position
6. Climber-determined break upon completion of four steps
7. Free climb (cooldown)

Climbers were allowed to employ their own strategy for completing each step, as long as all four limbs were placed on separate force plates. However, they were verbally encouraged to pursue strategies that engaged all four limbs and minimized necessity for belay assistance. The Results section focuses on results from the maximum vertical and lateral step achieved by the climber.

4.2.2 Collection of Walking Data

Walking motion data was collected prior to all climbing trials via use of an overground motion capture methodology. Eight Vicon cameras captured fifteen lower limb markers placed on each subject. All subjects performed a minimum of six walking trials so that a sufficiently populated average gait cycle was obtained from Vicon software. Subjects CP2 and CP3 used forearm crutches in the walking trials, because they used them regularly in daily life. While two Bertec force plates imbedded in the walking path were collected, the use of forearm crutches made kinetic results impractical for analysis.

4.2.3 LifeMOD and OpenSim Analysis of Motion Data

Climbing motion data was analyzed according to the methods laid out in Chapter 2: custom MATLAB software processed Vicon data, and full 3-D, 17-segment, 16-joint models were created for each subject based on anthropometric and experimental data. Model inverse kinematics were calculated based on motion driven by experimental Vicon marker data. Operating muscle lengths as a percentage of normalized optimal fiber length were modeled in OpenSim (Delp et al., 2007). Because joint angles were calculated from experimental data in the previous Adams model, these joint angles were imposed directly onto the OpenSim model.

Walking motion data was analyzed using Vicon's built-in Plug-in Gait model to output joint angles. Vicon Polygon and a custom Excel plug-in produced average joint angles over six different walking trials. Joint angles were loaded directly into OpenSim and imposed on the OpenSim model; normalized muscle-fiber lengths were output and plotted with climbing data for comparison.

4.3 Results

4.3.1 Climbing Gait: Joint angle excursions

As anticipated, climbing leads to unique ROM patterns compared to those from walking, with more extensive ranges in general. Examples of joint configurations are pictured in Fig. 4.1. Results comparing climbing and walking data for the CP population is found in Table 4.1.

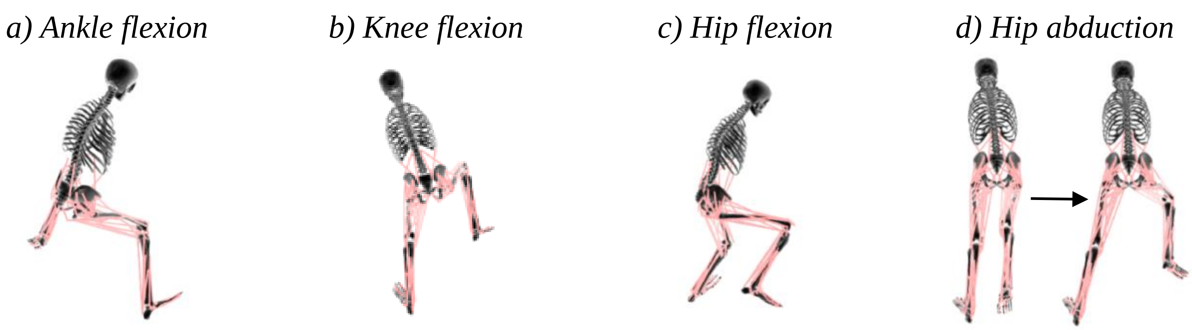

Figure 4.1a-d. Visual representations of joint angles at different points in the climbing trial. The ankle joint is dorsiflexed, the knee joints are flexed, and the hip joints are flexed and abducted. Black represents the skeleton, and pink shows muscle lines of action in the model for the lower limbs.

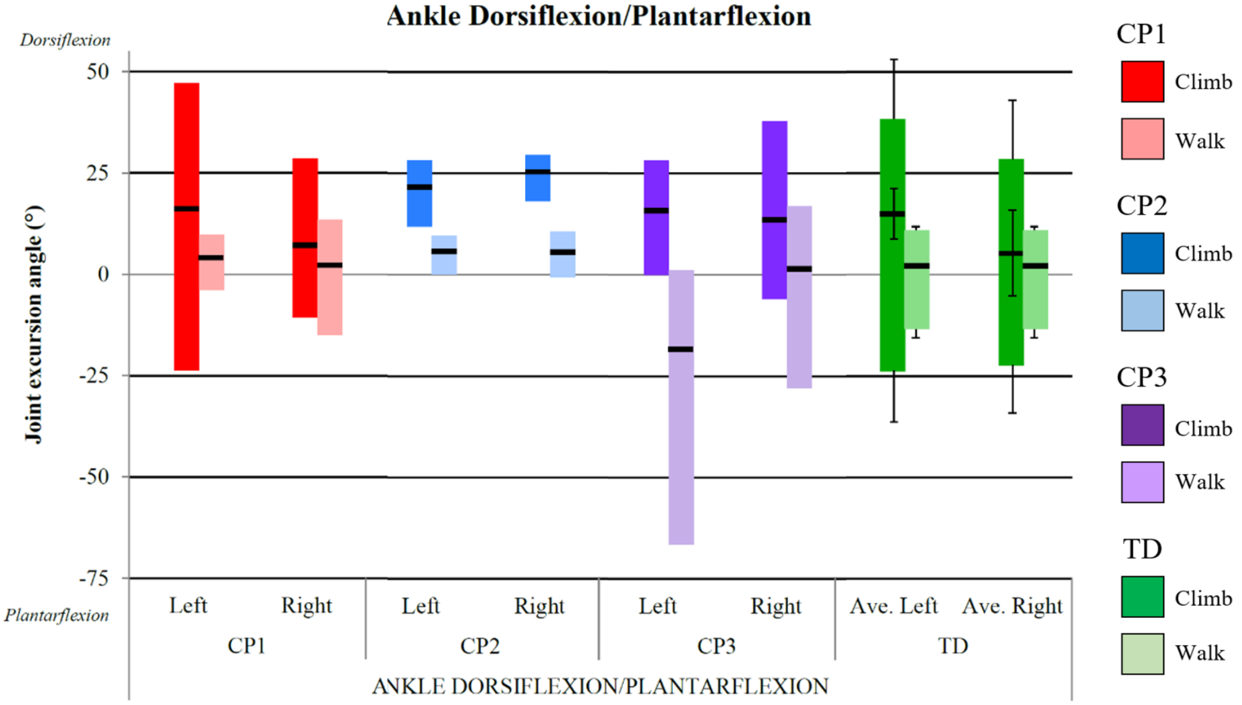

Figure 4.2. Ankle joint excursion angles for all three CP subjects and the TD population. Climbing (dark) results in wider ROM for CP1, CP2, and the TD population compared to walking ROM (light). All subjects experience higher mean and maximum dorsiflexion compared to those of walking.

Figure 4.2 shows how ankle dorsiflexion is different during climbing from overground walking. Maximum right and left ankle dorsiflexion were significantly higher during climbing ($p < 0.01$ and < 0.05). Mean dorsiflexion was significantly or near-significantly higher during climbing ($p = 0.054$ and < 0.05). Plantarflexion was higher during walking ($p = 0.057$).

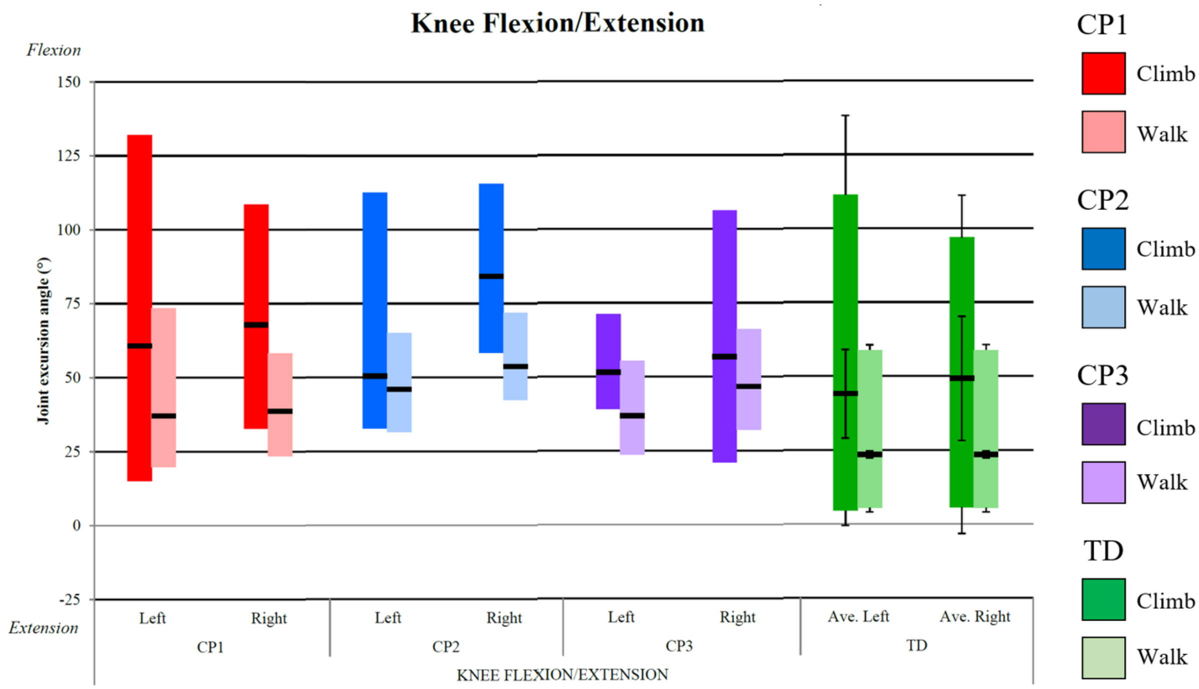

Figure 4.3. Knee joint excursion angles for all three CP subjects and the TD population. Climbing (dark) results in significantly more extensive ROM for all subjects with CP as well as the TD population compared to walking ROM (light).

The CP population underwent greater knee flexion during climbing (Fig. 4.3). Statistically, maximum flexion was significantly higher ($p < 0.01$ and < 0.05), mean flexion was higher ($p < 0.05$ and $= 0.061$), and complete ROM was greater ($p < 0.05$ and $= 0.095$) for climbing trials compared to walking. These results make sense, as climbing requires vertical motion rather than forward horizontal motion, clearly demonstrating how climbing inherently requires climbers with CP to enter different positions and challenging ROM.

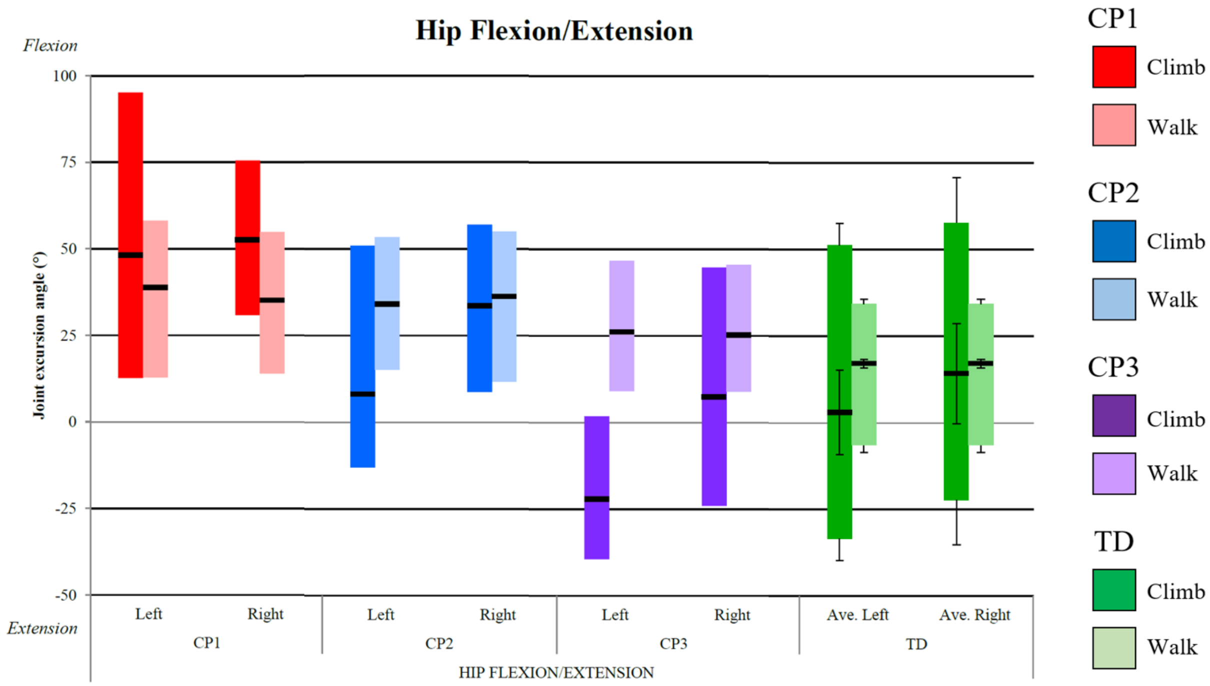

Figure 4.4. Hip flexion joint excursion angles for all three CP subjects and the TD population. Climbing (dark) results in significantly more extensive ROM for all subjects with CP as well as the TD population compared to walking ROM (light).

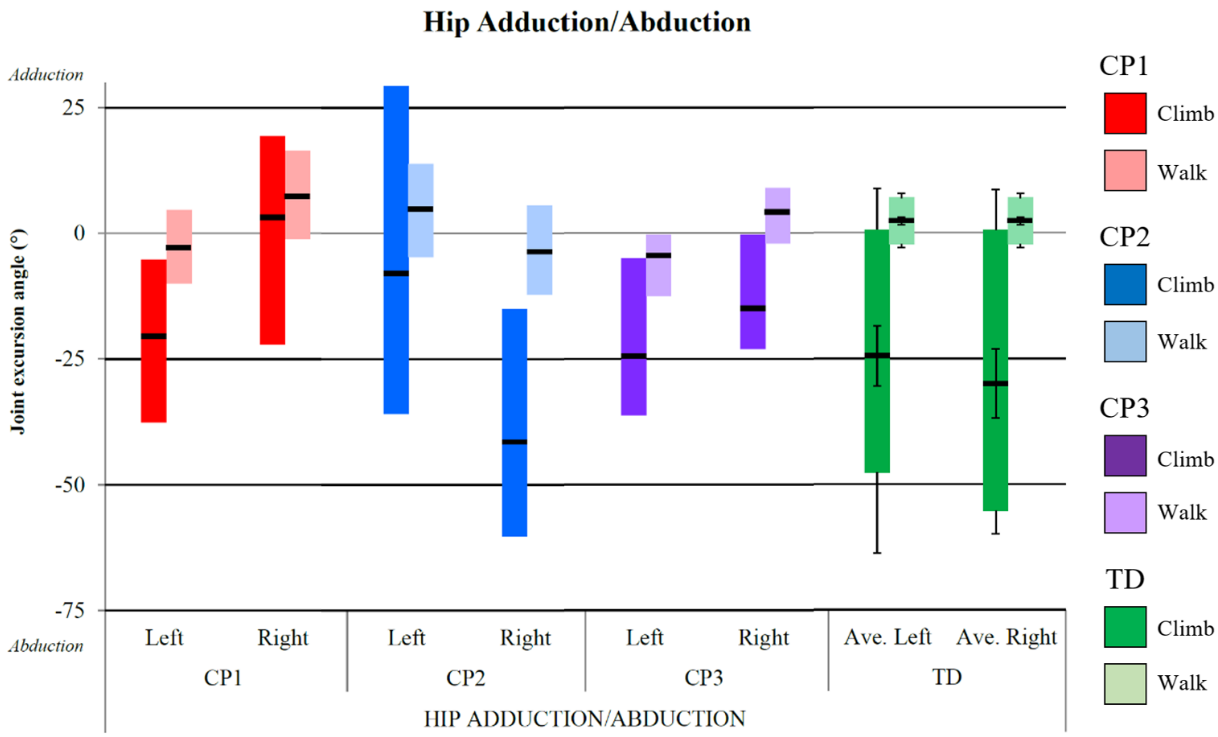

Figure 4.5. Hip adduction joint excursion angles for all three CP subjects and the TD population. Climbing (dark) results in significantly more extensive ROM for all subjects with CP as well as the TD population compared to walking ROM (light). Means are biased towards abduction for climbing, while means trend towards neutral or slight adduction for walking.

Large deviations made significant differences in hip flexion unlikely (Fig. 4.4). Because of climbers' ability to "sit down" in the climbing harness as well as stabilizing forces from the upper limbs, forward and backwards balance by lower limbs is not as important during climbing, which allows for greater flexion or extension during movement not feasible during walking. Climbing tended to elicit greater hip flexion ROM than walking ($p = 0.141$ and $= 0.078$).

In Figure 4.5, climbing resulted in significantly greater hip abduction than walking did. ROM was greater ($p < 0.05$ and < 0.05), abduction was higher ($p < 0.05$ and < 0.01), and means were biased towards abduction ($p = 0.085$ and < 0.01). These results distinguish climbing greatly from walking, as lateral movement is much more prevalent in climbing and cause different muscle stretch configurations.

Table 4.1. Mean ± SD information for CP population joint excursion angle data. A one-tailed paired t-test was performed comparing climbing data to walking data. *p<0.05, **p<0.01, ***p<0.001.

	CP Climb Mean Mean (±SD)	**CP Walk Mean** Mean (±SD)	**p-value**	**CP Climb Range** Mean (±SD)	**CP Walk Range** Mean (±SD)	**p-value**
Right ankle dorsiflexion	15.4 (9.27)	3.33 (2.17)	0.054	31.4 (17.6)	28.2 (16.8)	0.239
Left ankle dorsiflexion	17.9 (3.30)	-2.62 (13.5)	<0.05*	38.5 (28.7)	30.3 (32.5)	0.399
Right knee flexion	69.6 (13.8)	46.3 (7.56)	<0.05*	72.8 (14.3)	32.8 (2.86)	<0.05*
Left knee flexion	54.2 (5.63)	39.9 (5.24)	0.061	76.3 (42.5)	39.6 (12.2)	0.095
Right hip flexion	31.1 (22.7)	32.2 (6.04)	0.461	53.7 (13.0)	40.2 (3.48)	0.141
Left hip flexion	11.3 (35.3)	33.0 (6.39)	0.163	62.4 (20.6)	40.4 (4.18)	0.078
Right hip adduction	-17.6 (22.4)	2.76 (5.70)	0.085	36.5 (12.0)	15.4 (3.75)	<0.05*
Left hip adduction	-17.5 (8.59)	-0.70 (4.94)	<0.01**	42.9 (19.3)	15.1 (3.18)	<0.05*
	CP Climb Min Mean (±SD)	**CP Walk Min** Mean (±SD)	**p-value**	**CP Climb Max** Mean (±SD)	**CP Walk Max** Mean (±SD)	**p-value**
Right ankle dorsiflexion	0.590 (15.5)	-14.2 (13.7)	0.057	32.0 (5.14)	13.9 (3.12)	<0.01**
Left ankle dorsiflexion	-3.83 (18.2)	-23.2 (37.4)	0.262	34.6 (10.9)	7.11 (4.92)	<0.05*
Right knee flexion	37.4 (19.1)	32.9 (9.50)	0.314	110.2 (4.85)	65.6 (6.88)	<0.01**
Left knee flexion	29.0 (12.5)	25.2 (6.00)	0.298	105.3 (31.0)	64.9 (9.03)	<0.05*
Right hip flexion	5.27 (27.6)	11.6 (2.57)	0.353	59.0 (15.6)	51.8 (5.50)	0.198
Left hip flexion	-13.2 (26.0)	12.3 (3.08)	0.105	49.2 (46.6)	52.7 (5.70)	0.449
Right hip adduction	-35.0 (21.8)	-4.98 (6.05)	<0.05*	1.50 (17.3)	10.5 (5.60)	0.158
Left hip adduction	-36.3 (0.90)	-8.92 (3.96)	<0.01**	6.55 (19.9)	6.15 (7.13)	0.482

4.3.2 Climbing vs. Walking Gait: OpenSim modeled muscle lengths

Through OpenSim modeling analysis, it was found that specific muscles were stretched more during a climb stride than during a walk stride. These stretches were represented by the normalized muscle-fiber length (1.0 corresponding to the optimal fiber length) to make comparisons possible between different muscles and subjects of different sizes.

The ankle plantarflexor group (Fig. 4.6, Table 4.2) consists of the gastrocnemius muscles and soleus. The soleus was significantly longer during climbing, with higher mean and maximum lengths (mean: $p < 0.01$ and < 0.01; maximum: $p < 0.05$ and < 0.05). The gastrocnemius muscles tended to be shorter during climbing, most likely because of high knee flexion that reversed any potential stretch from ankle dorsiflexion; the gastrocnemius muscles cross both joints, while the soleus muscle only crosses the ankle joint. Because shortening/contraction of the gastrocnemius muscles were much more extensive during climbing (gastroc. lateralis minimum: $p = 0.090$ and < 0.05; gastroc. medialis minimum: $p = 0.058$ and < 0.05), ROM increased overall for those muscles nearly significantly (gastroc. lateralis range: $p = 0.099$ and 0.167; gastroc. medialis range: $p = 0.076$ and 0.157).

The knee extensor muscles (Fig. 4.7, Table 4.3) were significantly lengthened during climbing. The vastus lateralis and medialis muscles yielded highly significant increases in mean length, while all three vastus muscles demonstrated significant increases in maximum length achieved (see Table 4.3 for full results). The vastus intermedius appears to have the highest walking mean muscle-fiber lengths of the vastus muscles, which is likely caused by its central placement in the thigh. The rectus femoris achieved near significant increases in mean and maximum lengths, but there was high variability in this muscle data set due to subject CP1. The rectus femoris muscle also produced a reduced range of length; this may be a sign that less contraction occurred during high hip flexion for this muscle.

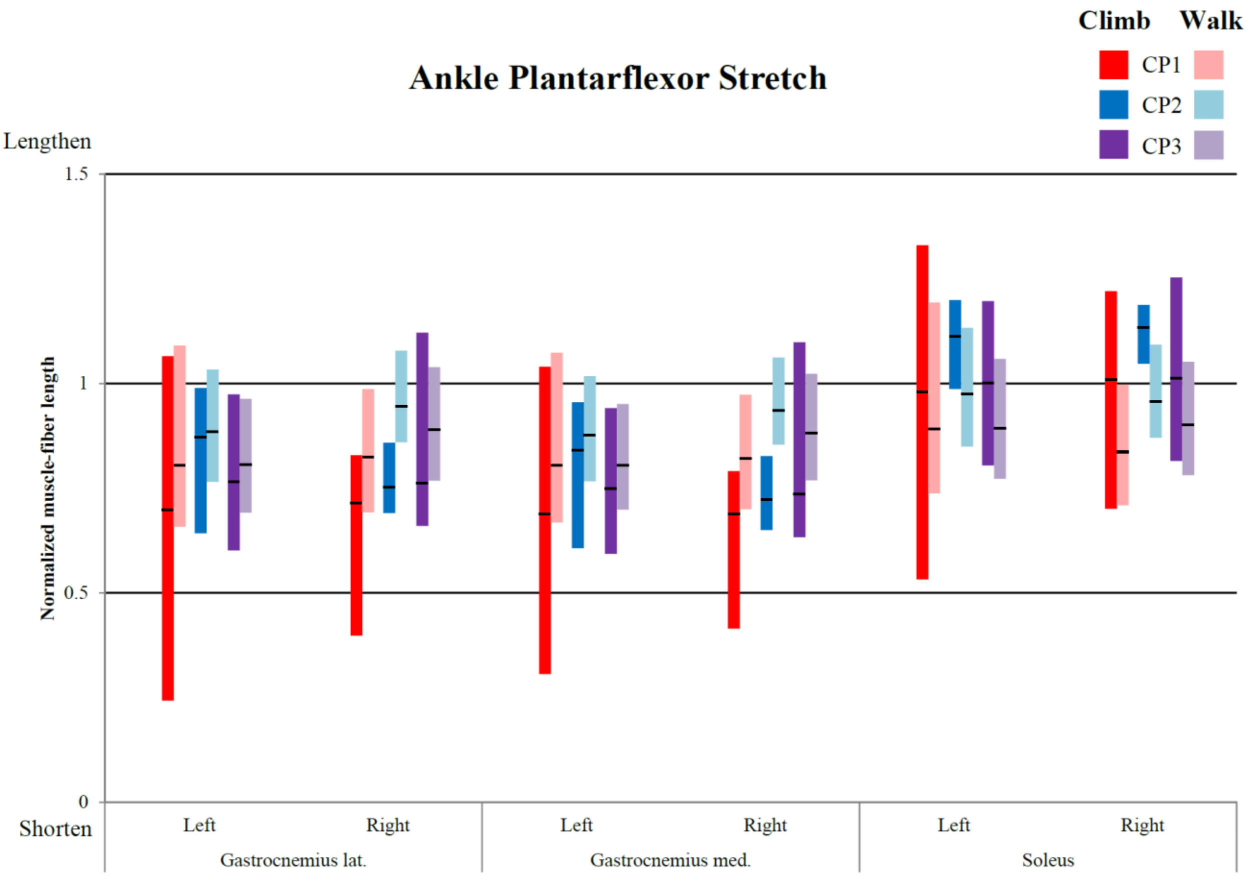

Figure 4.6. Ankle plantarflexor normalized muscle-fiber lengths. Columns represent the range (minimum to maximum) observed, while black lines indicate mean muscle-fiber length over the course of the whole climb trial. Dark colors represent climbing data, while light colors represent walking data.

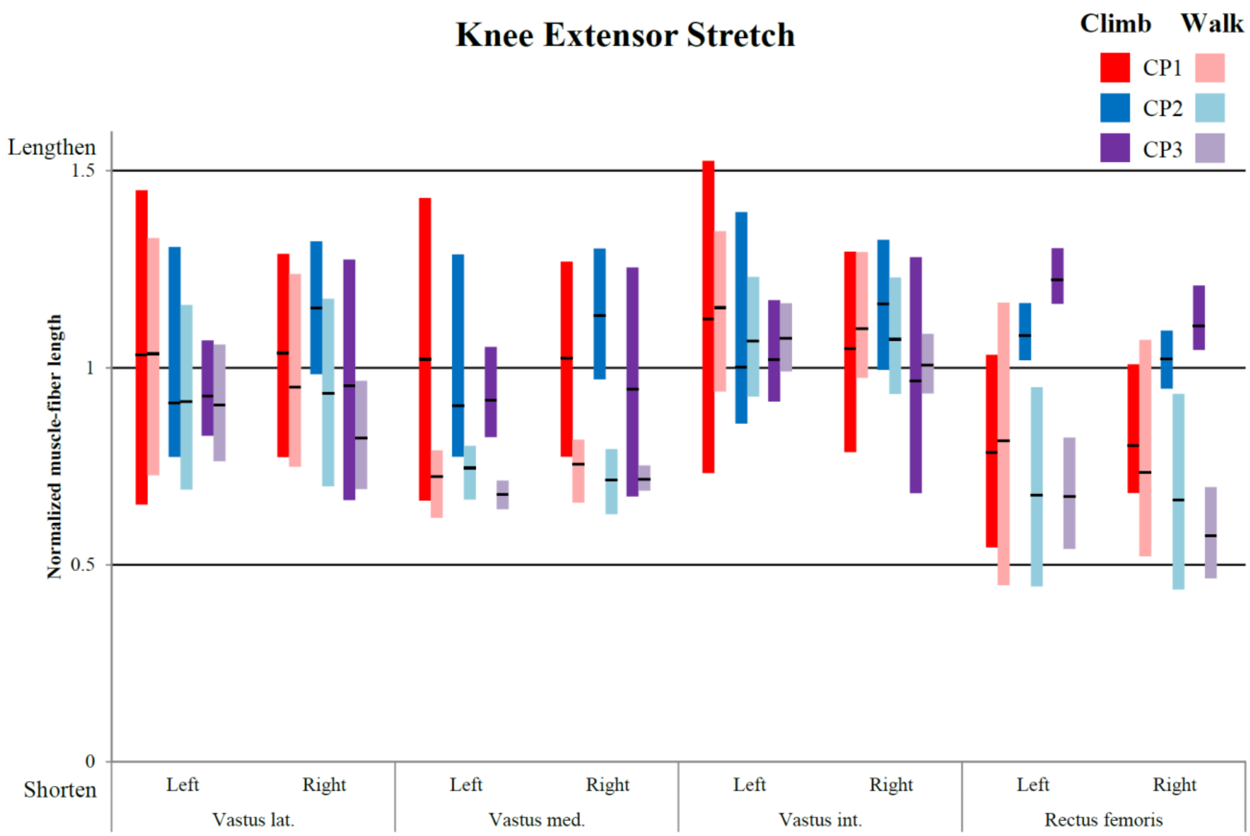

Figure 4.7. Knee extensor normalized muscle-fiber lengths. Columns represent the range (minimum to maximum) observed, while black lines indicate mean muscle-fiber length over the course of the whole climb trial. Dark colors represent climbing data, while light colors represent walking data.

Table 4.2. Mean ± SD information for CP population normalized ankle plantarflexor muscle-fiber length data. A one-tailed paired t-test was performed comparing climbing data to walking data. *p<0.05, **p<0.01, ***p<0.001.

Ankle Plantarflexors							
		CP Climb Mean Mean (±SD)	**CP Walk Mean** Mean (±SD)	**p-value**	**CP Climb Range** Mean (±SD)	**CP Walk Range** Mean (±SD)	**p-value**
Gastrocnemius lateralis	*Left*	0.778 (0.09)	0.831 (0.05)	0.097	0.514 (0.27)	0.324 (0.09)	0.099
	Right	0.743 (0.03)	0.886 (0.06)	<0.05*	0.353 (0.16)	0.261 (0.04)	0.167
Gastrocnemius medialis	*Left*	0.759 (0.08)	0.828 (0.04)	0.052	0.477 (0.22)	0.303 (0.09)	0.076
	Right	0.716 (0.02)	0.879 (0.06)	<0.05*	0.339 (0.15)	0.245 (0.03)	0.157
Soleus	*Left*	1.032 (0.07)	0.919 (0.05)	<0.01**	0.468 (0.30)	0.341 (0.10)	0.201
	Right	1.052 (0.07)	0.897 (0.06)	<0.01**	0.366 (0.20)	0.261 (0.03)	0.192
		CP Climb Min Mean (±SD)	**CP Walk Min** Mean (±SD)	**p-value**	**CP Climb Max** Mean (±SD)	**CP Walk Max** Mean (±SD)	**p-value**
Gastrocnemius lateralis	*Left*	0.496 (0.22)	0.704 (0.06)	0.090	1.010 (0.05)	1.028 (0.06)	0.185
	Right	0.584 (0.16)	0.773 (0.08)	<0.05*	0.937 (0.16)	1.034 (0.05)	0.201
Gastrocnemius medialis	*Left*	0.503 (0.17)	0.711 (0.05)	0.058	0.980 (0.05)	1.013 (0.06)	0.078
	Right	0.567 (0.13)	0.774 (0.08)	<0.05*	0.906 (0.17)	1.019 (0.05)	0.180
Soleus	*Left*	0.775 (0.23)	0.786 (0.06)	0.461	1.243 (0.08)	1.128 (0.07)	<0.05*
	Right	0.855 (0.18)	0.786 (0.08)	0.170	1.221 (0.03)	1.047 (0.05)	<0.05*

Table 4.3. Mean ± SD information for CP population normalized knee extensor muscle-fiber length data. A one-tailed paired t-test was performed comparing climbing data to walking data. *p<0.05, **p<0.01, ***p<0.001.

Knee Extensors							
		CP Climb Mean Mean (±SD)	**CP Walk Mean** Mean (±SD)	**p-value**	**CP Climb Range** Mean (±SD)	**CP Walk Range** Mean (±SD)	**p-value**
Vastus lateralis	*Left*	0.958 (0.07)	0.892 (0.07)	<0.01**	0.524 (0.28)	0.427 (0.14)	0.169
	Right	1.048 (0.10)	0.845 (0.06)	<0.05*	0.488 (0.14)	0.388 (0.11)	0.269
Vastus medialis	*Left*	1.258 (0.19)	0.670 (0.03)	<0.01**	0.503 (0.27)	0.119 (0.05)	<0.05*
	Right	1.034 (0.09)	0.683 (0.02)	<0.05*	0.470 (0.13)	0.121 (0.05)	<0.05*
Vastus intermedius	*Left*	1.049 (0.06)	1.029 (0.04)	0.123	0.528 (0.27)	0.276 (0.11)	0.055
	Right	1.060 (0.10)	0.993 (0.04)	0.144	0.479 (0.14)	0.239 (0.09)	0.089
Rectus femoris	*Left*	1.030 (0.23)	0.676 (0.07)	0.087	0.258 (0.20)	0.471 (0.20)	<0.05*
	Right	0.977 (0.16)	0.616 (0.07)	0.056	0.213 (0.10)	0.399 (0.16)	0.068
		CP Climb Min Mean (±SD)	**CP Walk Min** Mean (±SD)	**p-value**	**CP Climb Max** Mean (±SD)	**CP Walk Max** Mean (±SD)	**p-value**
Vastus lateralis	*Left*	0.753 (0.09)	0.681 (0.04)	0.145	1.277 (0.19)	1.108 (0.13)	<0.05*
	Right	0.808 (0.16)	0.668 (0.03)	0.144	1.296 (0.02)	1.056 (0.13)	<0.05*
Vastus medialis	*Left*	0.755 (0.08)	0.601 (0.02)	<0.05*	1.258 (0.19)	0.720 (0.04)	<0.05*
	Right	0.807 (0.15)	0.616 (0.03)	0.104	1.277 (0.02)	0.738 (0.03)	<0.001***
Vastus intermedius	*Left*	0.836 (0.09)	0.892 (0.03)	0.172	1.365 (0.18)	1.169 (0.09)	<0.05*
	Right	0.822 (0.16)	0.888 (0.02)	0.281	1.301 (0.02)	1.127 (0.10)	<0.05*
Rectus femoris	*Left*	0.910 (0.32)	0.447 (0.05)	0.056	1.168 (0.14)	0.918 (0.16)	0.141
	Right	0.893 (0.19)	0.445 (0.04)	<0.05*	1.105 (0.10)	0.844 (0.18)	0.122

Hip extensor muscle data (Fig. 4.8, Table 4.4) indicated greater ROM during climbing compared to walking, with significant results for the right biceps femoris long head (BFLH) ($p < 0.05$) and left gluteus maximus ($p < 0.05$) and near significant results for the left BFLH ($p = 0.071$). Potential to maximally stretch these muscles may be obscured by the extent of knee flexion and variability observed in this group.

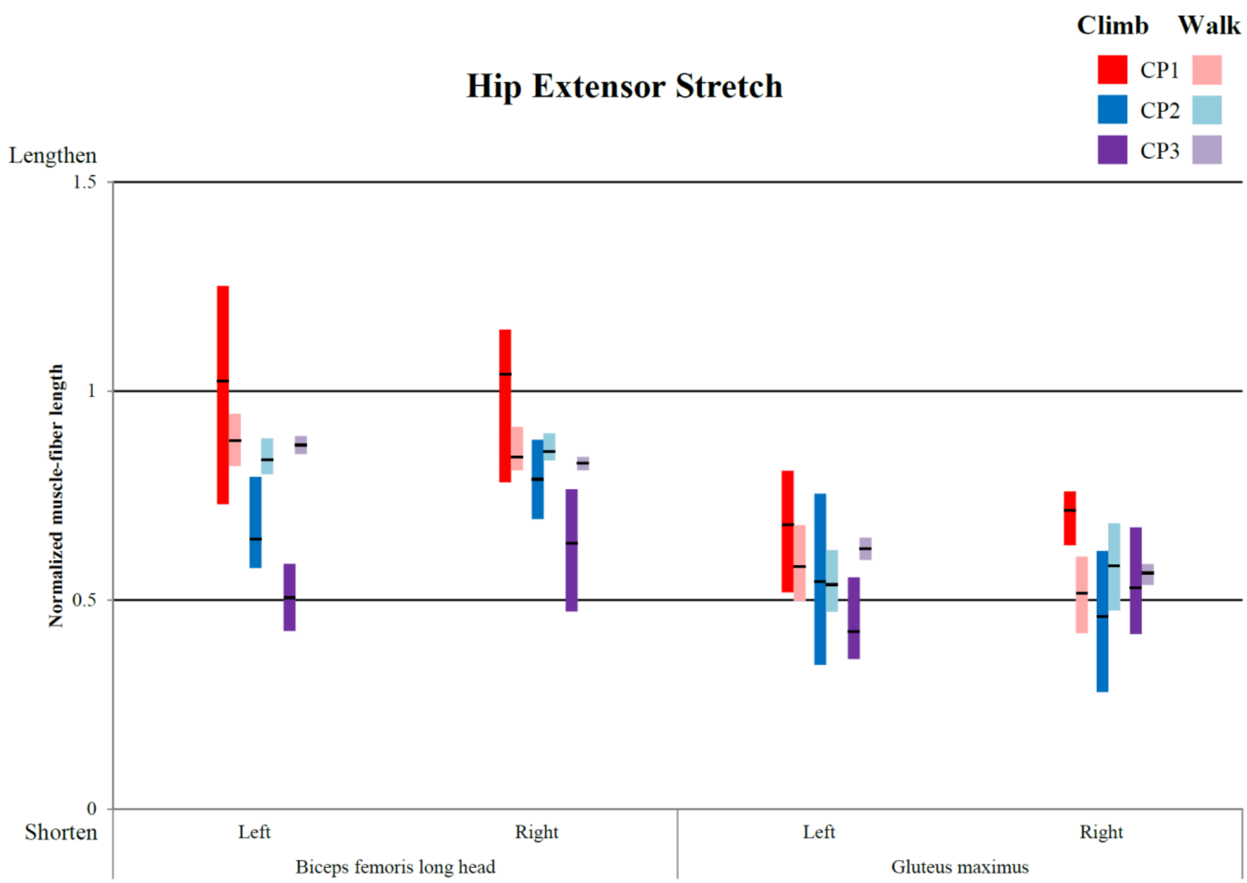

Figure 4.8. Hip extensor normalized muscle-fiber lengths. Columns represent the range (minimum to maximum) observed, while black lines indicate mean muscle-fiber length over the course of the whole climb trial. Dark colors represent climbing data, while light colors represent walking data.

For the two adductor muscles in the hip adductor group (Fig. 4.9, Table 4.5), significant lengthening of the muscle is evident in the mean and maximum muscle-fiber length comparison (see Table 4.5 for full results). Lateral movement present during the climb stride is unlikely to occur during a walk stride; in other words, this aspect of ROM is unique to the climbing wall (add. brevis: $p < 0.05$ and < 0.05; add. longus: $p = 0.081$ and 0.052). Results for the pectineus were inconclusive due to high variability in the CP population, perhaps due to its anatomy, as the pectineus has a more proximal attachment point on the femur than the two adductor muscles.

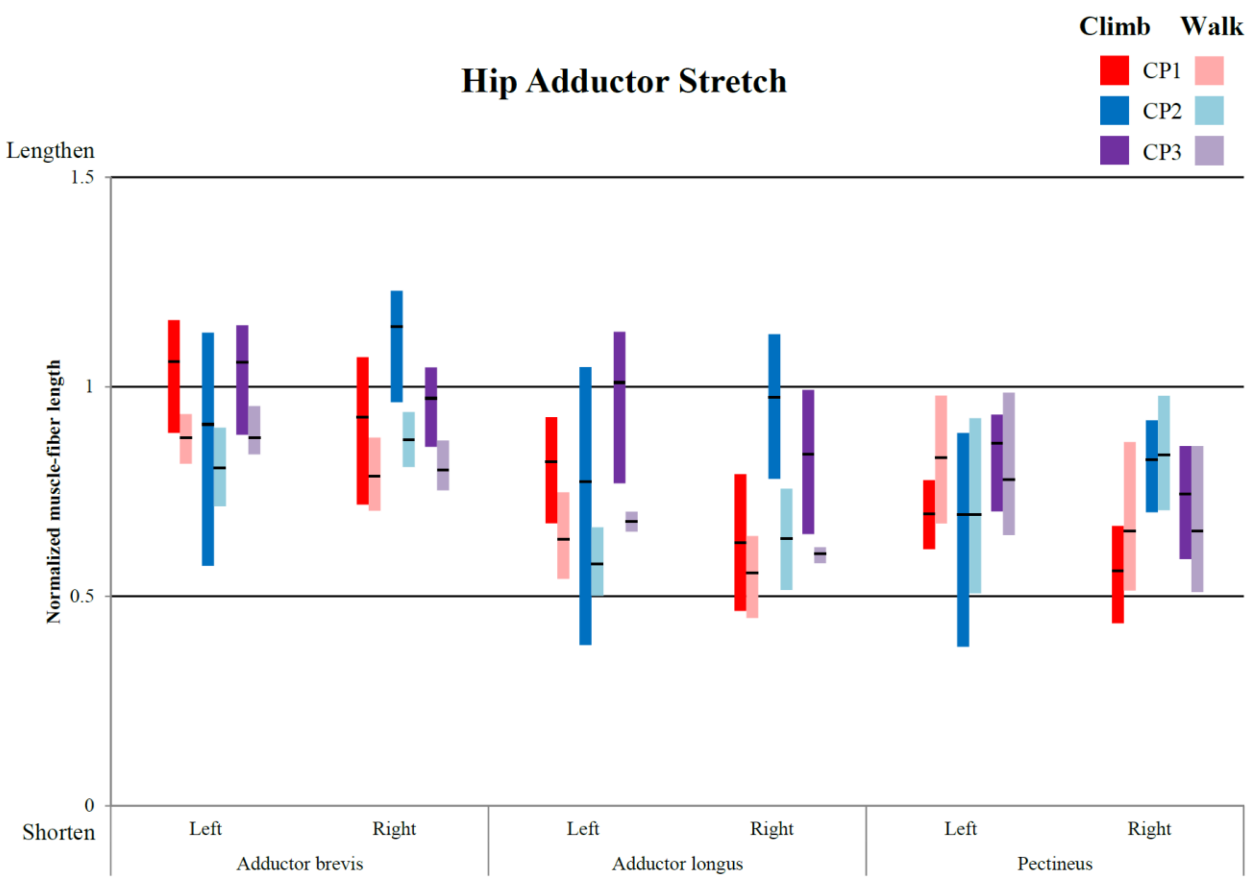

Figure 4.9. Hip adductor normalized muscle-fiber lengths. Columns represent the range (minimum to maximum) observed, while black lines indicate mean muscle-fiber length over the course of the whole climb trial. Dark colors represent climbing data, while light colors represent walking data.

Table 4.4. Mean ± SD information for CP population normalized hip extensor muscle-fiber length data. A one-tailed paired t-test was performed comparing climbing data to walking data. *p<0.05, **p<0.01, ***p<0.001.

Hip Extensors							
		CP Climb Mean Mean (±SD)	**CP Walk Mean** Mean (±SD)	**p-value**	**CP Climb Range** Mean (±SD)	**CP Walk Range** Mean (±SD)	**p-value**
Biceps femoris long head	*Left*	0.726 (0.27)	0.862 (0.02)	0.227	0.300 (0.19)	0.08 (0.04)	0.071
	Right	0.822 (0.20)	0.841 (0.01)	0.441	0.282 (0.09)	0.067 (0.04)	<0.05*
Gluteus maximus	*Left*	0.550 (0.13)	0.579 (0.04)	0.385	0.298 (0.11)	0.127 (0.07)	<0.05*
	Right	0.569 (0.13)	0.554 (0.03)	0.445	0.240 (0.11)	0.147 (0.09)	0.175
		CP Climb Min Mean (±SD)	**CP Walk Min** Mean (±SD)	**p-value**	**CP Climb Max** Mean (±SD)	**CP Walk Max** Mean (±SD)	**p-value**
Biceps femoris long head	*Left*	0.579 (0.15)	0.824 (0.02)	0.063	0.878 (0.34)	0.908 (0.03)	0.441
	Right	0.650 (0.16)	0.818 (0.01)	0.101	0.933 (0.20)	0.885 (0.04)	0.332
Gluteus maximus	*Left*	0.409 (0.10)	0.522 (0.06)	0.134	0.707 (0.13)	0.649 (0.03)	0.264
	Right	0.444 (0.18)	0.478 (0.06)	0.407	0.685 (0.07)	0.625 (0.05)	0.228

Table 4.5. Mean ± SD information for CP population normalized hip adductor muscle-fiber length data. A one-tailed paired t-test was performed comparing climbing data to walking data. *p<0.05, **p<0.01, ***p<0.001.

Hip Adductors							
		CP Climb Mean Mean (±SD)	**CP Walk Mean** Mean (±SD)	**p-value**	**CP Climb Range** Mean (±SD)	**CP Walk Range** Mean (±SD)	**p-value**
Adductor brevis	*Left*	1.008 (0.09)	0.853 (0.04)	<0.05*	0.362 (0.17)	0.140 (0.04)	<0.05*
	Right	1.014 (0.11)	0.820 (0.05)	<0.05*	0.269 (0.08)	0.141 (0.03)	<0.05*
Adductor longus	*Left*	0.867 (0.13)	0.629 (0.05)	<0.05*	0.426 (0.21)	0.139 (0.08)	0.081
	Right	0.813 (0.17)	0.597 (0.04)	0.052	0.338 (0.01)	0.158 (0.11)	0.052
Pectineus	*Left*	0.751 (0.10)	0.767 (0.07)	0.413	0.302 (0.18)	0.354 (0.06)	0.273
	Right	0.710 (0.13)	0.715 (0.11)	0.462	0.240 (0.03)	0.325 (0.05)	<0.05*
		CP Climb Min Mean (±SD)	**CP Walk Min** Mean (±SD)	**p-value**	**CP Climb Max** Mean (±SD)	**CP Walk Max** Mean (±SD)	**p-value**
Adductor brevis	*Left*	0.783 (0.18)	0.790 (0.07)	0.464	1.145 (0.02)	0.930 (0.03)	<0.01**
	Right	0.846 (0.12)	0.754 (0.05)	0.075	1.11 (0.10)	0.896 (0.04)	<0.05*
Adductor longus	*Left*	0.609 (0.20)	0.565 (0.08)	0.324	1.035 (0.10)	0.704 (0.04)	<0.05*
	Right	0.631 (0.16)	0.514 (0.07)	0.128	0.970 (0.17)	0.672 (0.07)	<0.05*
Pectineus	*Left*	0.565 (0.17)	0.608 (0.09)	0.255	0.866 (0.08)	0.963 (0.03)	0.104
	Right	0.575 (0.13)	0.576 (0.11)	0.494	0.815 (0.13)	0.715 (0.11)	0.142

4.4 Discussion and Conclusions

Climbing enables the CP population to achieve ROM not usually observed during walking, such as greater ankle dorsiflexion (longer soleus muscles), knee flexion (longer vastus muscles), hip flexion (wider ROM for the biceps femoris and gluteus maximus muscles), and hip abduction (longer adductor muscles). These muscle stretches have functional relevance over long term training, as increasing ankle dorsiflexion could help toe drag and foot clearance, and stretching the adductor muscles while activating the abductors could reduce genu valgum and improve lateral balance.

This study did not target any muscles to stretch, but rather allowed subjects to decide strategies for completing climbing strides while still supporting a significant portion of their body weight. By doing this, this study shows that climbers with CP are willing to pursue strenuous ROM even when outside of their typical routines. Examining both ROM through joint excursion angles and muscle stretch via normalized muscle-fiber length make it easier to establish cause-and-effect for obtaining certain muscle stretches. By targeting ROM proven to stretch tight muscles – e.g., allowing hip flexion while reducing knee flexion to stretch hamstring muscles – climbers could mitigate functional impairments such as crouch gait.

Future work should focus on eliciting stretch from specific muscles that have been clinically identified as problematic for the patient. By modeling stretch as done in this work and performing functional tests, researchers may identify particularly effective route designs that address different variations of CP and muscle tightness. This field of investigation would also benefit from analysis using electromyography (EMG), which could reveal information about active and passive stretch on the climbing wall, as well as the effects of spasticity on muscle length throughout a climb stride and whether climb training reduces spasticity over time. If muscle is lengthened similar to the results in this study, one would expect spastic incidences to decrease in frequency and for the subject to complete steps more quickly without a spastic response.

Upper body muscles were excluded from analysis due to limitations in scope and in motion resolution. Complex joint mechanics, such as those of the shoulder, were difficult to capture accurately and reliably, and have yet to be represented in a model without broad simplifications. The upper body should be closely examined in future studies for several reasons: joint kinematics may be more complex with less intuitive muscle stretch results; non-locomotive activities of daily living often depend on arm function; and CP populations such as hemiplegic or quadriplegic climbers could benefit from muscle lengthening alleviating rigidity and contractures that otherwise lead to joint deformities.

This study had some limitations. Climbers were for the most part permitted to pursue their own climbing strategies, leading to largely variable results making generalizations difficult – both observational and statistical. Consequently, minimal comparison between climbers occurred, with most of the analysis based on each individual climber's results. Additionally, walking data was not obtained for the TD population in the study; instead, this data was taken from a database in the clinical motion laboratory at the University of Virginia, which produces reports on CP walking and routinely compares the results to this standard data. It may be that the data for the five TD climbers in this study may vary from the data shown in the results. Finally, modeling constraints may influence the results in unexpected ways; joints are modeled using simplifying assumptions such as uniaxial or biaxial degrees of freedom for the knee and ankle joints, respectively.

In this chapter, stretching muscles was the key motivation for encouraging recreational climbing therapy among the CP population. The results are strong evidence that higher mean and maximum muscle lengths are achieved with higher ROM for many important lower limb muscles while climbing. Furthermore, changes in joint kinematics from walking to climbing were linked to changes in modeled muscle-fiber lengths, producing predictable, anatomically logical connections. This proof-of-concept removes an implementation obstacle, as clinicians with detailed anatomical knowledge should be able to easily design climbing routes without requiring extensive climbing background knowledge. Future studies should elaborate by establishing and recording all motions that lead to stretch in various muscles. This work provides a strong foundation for considering climbing as a prospective therapy that could replace traditional therapies and deliver important long-term functional benefits related to muscle length in a medium that is fun and interesting for patients.

Chapter 5: Impact of Climb Training on Functional Measurements

5.1 Introduction and Background

The efficacy of a physical therapy as measured by functional tests and ability to carry out daily activities of living is of paramount interest to orthopedic doctors, clinicians, and therapists. Functional measurements can be difficult to determine, especially in the case of patients with cerebral palsy (CP) where the variety and severity of symptoms resists categorization. Nevertheless, there are metrics, often based on qualitative judgments, commonly used by clinicians to assign a medical status to a patient's condition, such as the Gross Motor Function Classification System (GMFCS) or the Gross Motor Function Measure (GMFM). These tools are certainly useful for orienting a patient and his or her family to the types of challenges they can expect and the assistive equipment that may address the patient's needs. In the past two decades, however, as surgical interventions and assistive technology have become more sophisticated, the demand for quantitative data has increased.

While biomechanists and clinicians may extrapolate information from their expertise and observations, experimental data and modeling provide precise tools to ascertain specific causes of functional gaps between CP and typically developed (TD) populations or to predict outcomes of an intervention. Using models of patients incorporating experimental data has led to new conclusions absent from those based upon clinical observation alone: the results of muscle transfer surgery on patient balance can be modeled; the impact of cocontraction can be investigated empirically; 3D gait analysis can quantify increased functional abilities after strength training; and so on (Damiano & Abel, 1998; Damiano, Martellotta, Sullivan, Granata, & Abel, 2000; Mansouri et al., 2016). It has become both simpler to extract information about patient improvement from data and more difficult to choose from the growing array of methods and evaluations.

This chapter explores two types of functional measurements pre- and post-climb training for the subjects with CP: walking gait analysis and balance evaluation. The focus on range of motion (ROM), stretch, and strength in the preceding chapters motivated the choice to perform 3D gait analysis of each subject during walking, as well as stabilograms for balance evaluation. The former allows a close look at joint angles, while the latter is an indirect examination of the functional impact of potential shifts in strength and stretch.

5.2 Methods

5.2.1 Collection and Analysis of Walking Gait

All subjects with CP underwent a walking gait evaluation in the Kluge Children Rehabilitation Center facilities at the University of Virginia before and after the climbing protocol. Reflective marker positions placed on bony lower limb landmarks on subjects were tracked by an eight Vicon camera system (Vicon Motion Systems Ltd., Oxford, UK). Two force plates embedded in the laboratory floor measured heel strike and toe off forces when possible; for two out of three subjects, kinetics analysis was impractical due to crutch use during walking. For the first collection, markers were placed by an experienced clinician, whereas study researchers placed markers for the second collection. Any corrections that were applied (i.e., removing pelvic tilt measurement bias from hip flexion measurements) were performed using the clinically applied marker set as standard. Within the Vicon Nexus software, a lower body model was constructed for each trial that allowed calculation of lower body joint angles. Average joint angles over 100% gait cycle were taken for six trials per session per subject. For each walking session, a clinical gait report was generated using Excel plug-ins.

5.2.2 Collection and Analysis of Postural Steadiness Test

Before climbing, all subjects were asked to undergo a postural steadiness test, colloquially known in the clinical field as the stand and sway test, which serves as a measure of balance and neuromuscular control during a static pose. Subjects stood on a horizontal force plate (Bertec Corp., Columbus, OH) for 30 seconds at a time for three different trials; forces and torques in the global xyz orientations were collected. This test was repeated upon the conclusion of the climbing study in order to examine any potential differences in balance performance.

For this test, a 95% confidence ellipse (CE) area was calculated using principal component analysis (Oliveira, Simpson, & Nadal, 1996), which find the principal axis by minimizing residual error in a direction orthogonal to the fitted regression line. The lengths of the major and minor axes of the CE were determined using the equations

$$(4.1) \quad l_{major} = z\,\sigma_{major}$$

$$(4.2) \quad l_{minor} = z\,\sigma_{minor}$$

where σ_{major} and σ_{minor} are the standard deviations in the respective directions of the primary axes and z is the z-value that corresponds to the desired confidence level (i.e., z = 1.96 for a confidence level of 95%). The directions of the primary axes were found by computing the covariance matrix of the COP data; that matrix's first eigenvector and eigenvalue are the direction and variance, respectively, of the major axis, while the second eigenvector and eigenvalue correspond to the minor axis direction and value. These two axes are orthogonal to each other. The area of the ellipse is given by the equation

$$(4.3) \quad Area = \pi ab$$

where a and b are the major and minor axes. Less sway and higher stability during the test should result in smaller area calculations.

A paired t-test was computed, where the first nominal variable is each subject with CP, the second nominal variable is before/after differences in the measurement variable, and the measurement variable is the calculated CE area. To test the null hypothesis (i.e., the true mean difference is zero), the difference between each pair of observations was calculated, then averaged to find the mean difference *d*. The standard error of the mean difference (Eq. 5.4) was calculated and used to find the t-statistic, given by Eq. 5.5.

$$(5.4) \quad SE(d) = \frac{s_d}{\sqrt{n}}$$

$$(5.5) \quad T = \frac{d}{SE(d)}$$

A table was used to compare calculated T to the t_{n-1} distribution, which gave the p-value for the paired t-test.

5.3 Results

5.3.1 Walking Gait

The walking gait results for ankle dorsiflexion, knee flexion, hip flexion, and hip adduction for all three subjects are plotted in Figure 5.1a-c (right side only). Six independent strides were averaged to find the joint angles.

CP1

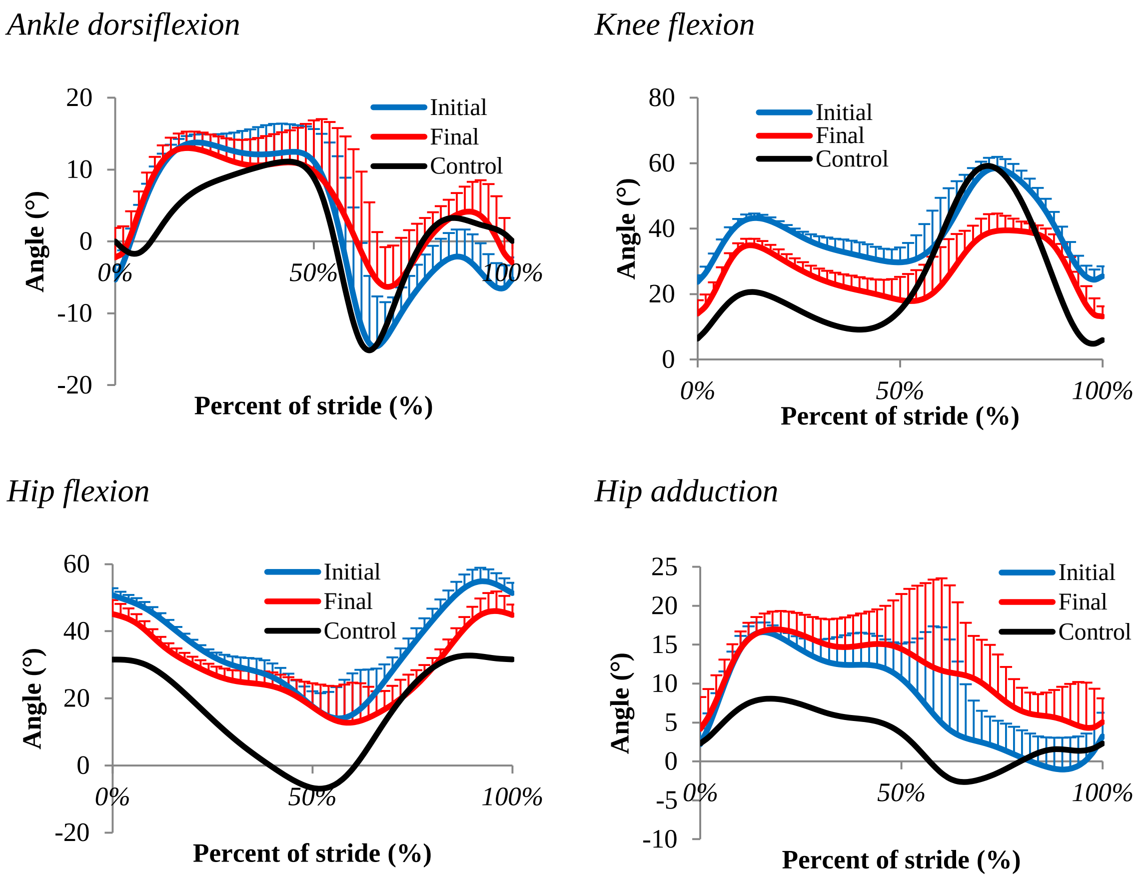

Figure 5.1. Joint angle measurements (right side) for subject CP1. Blue is the baseline result, and red represents the results of the same test post-climbing protocol. Standard deviation is included to show variation within each set of trials averaged to obtain all curves.

CP2

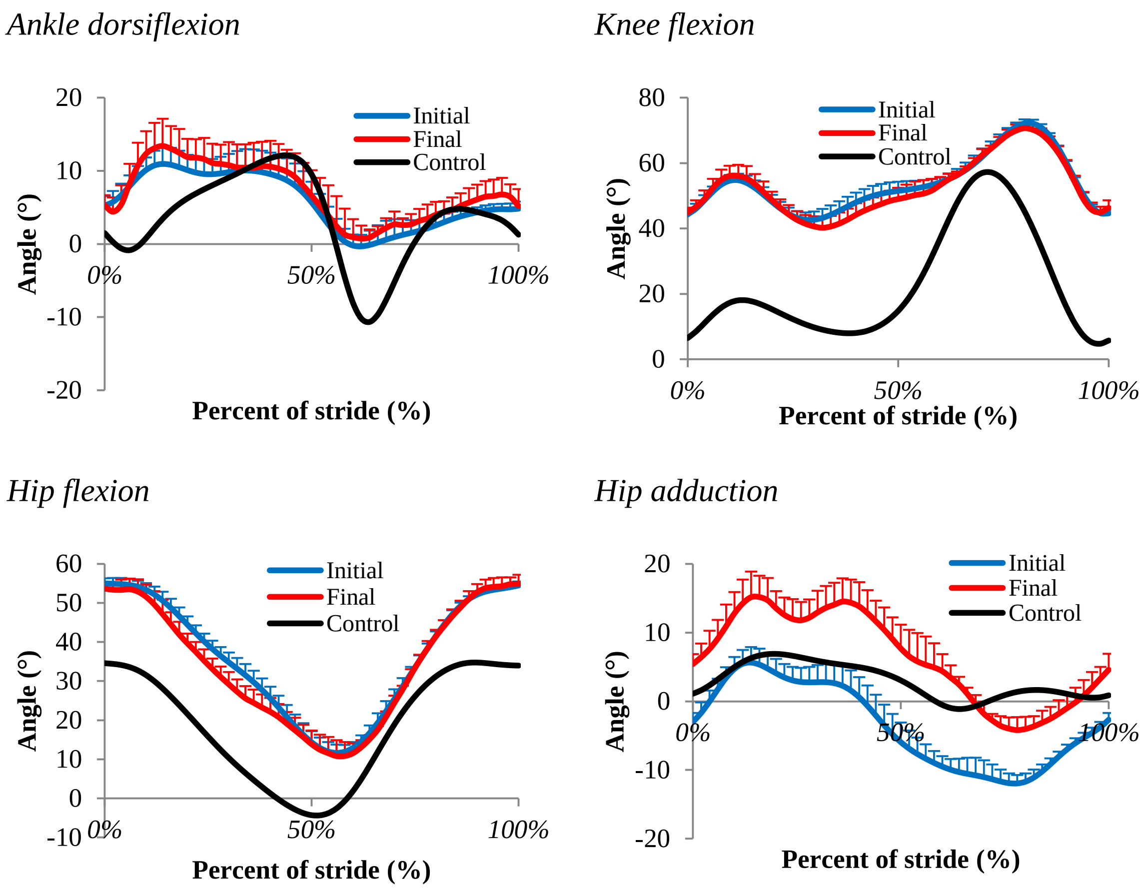

Figure 5.2. Joint angle measurements (right side) for subject CP2. Blue is the baseline result, and red represents the results of the same test post-climbing protocol. Standard deviation is included to show variation within each set of trials averaged to obtain all curves.

CP3

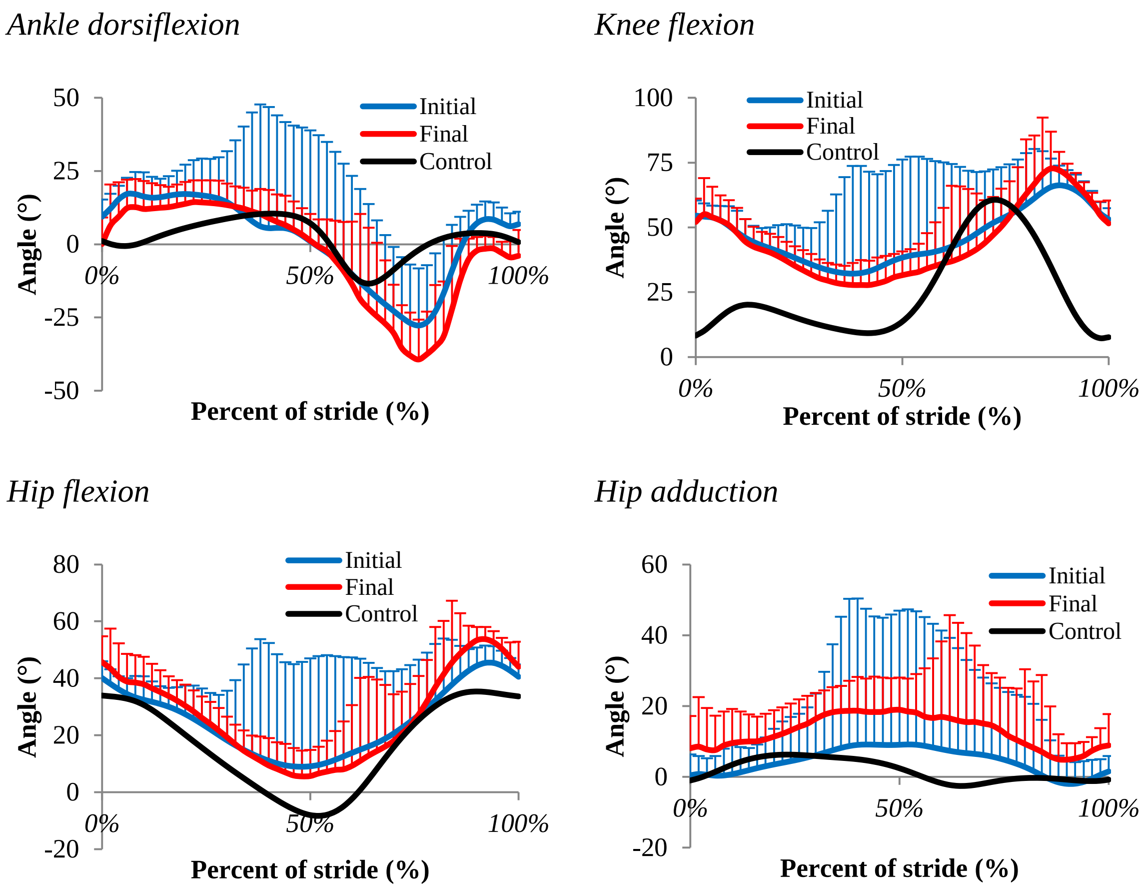

Figure 5.3. Joint angle measurements (right side) for subject CP3. Blue is the baseline result, and red represents the results of the same test post-climbing protocol. Standard deviation is included to show variation within each set of trials averaged to obtain all curves.

Table 5.1. Comparison of initial and final results. RMSE was calculated for both initial results and final curve results relative to control curve. Smaller RMSE values indicate that the associated curve is statistically closer to the control population overall. Mean difference between the final and initial results were calculated; positive values indicate that the initial mean of the joint angle is smaller, while negative values indicate that the final mean of the joint angle is smaller.

Ankle dorsiflexion			
Subject	*RMSE (Initial/Control)*	*RMSE (Final/Control)*	*Mean difference (°)*
CP1	4.95	5.07	+2.56
CP2	4.87	5.67	+1.23
CP3	11.3	14.5	-4.86
Knee flexion			
Subject	*RMSE (Initial/Control)*	*RMSE (Final/Control)*	*Mean difference (°)*
CP1	17.3	12.7	-11.5
CP2	33.2	32.2	-0.94
CP3	27.5	27.1	-2.15
Hip flexion			
Subject	*RMSE (Initial/Control)*	*RMSE (Final/Control)*	*Mean difference (°)*
CP1	19.5	14.6	-6.46
CP2	18.8	16.7	-1.86
CP3	21.0	24.0	+1.57
Hip adduction			
Subject	*RMSE (Initial/Control)*	*RMSE (Final/Control)*	*Mean difference (°)*
CP1	5.69	8.90	+3.80
CP2	7.49	5.73	+9.85
CP3	7.70	13.2	+8.40

Table 5.2. Mean ± SD information for CP population walking data, pre- and post-climb. A one-tailed paired t-test was performed comparing the two data sets. *p<0.05, **p<0.01, ***p<0.001.

	Ankle dorsiflexion	**Knee flexion**	**Hip flexion**	**Hip adduction**
MEAN (°)				
Pre-climb *Mean (SD)*	3.33 (2.2)	46.26 (7.6)	32.21 (6.0)	2.76 (5.7)
Post-climb *Mean (SD)*	3.10 (5.2)	42.23 (13.5)	30.39 (3.5)	10.42 (3.8)
p-value	**0.463**	**0.199**	**0.283**	**<0.05***
RANGE (°)				
Pre-climb *Mean (SD)*	28.17 (16.8)	32.76 (2.9)	40.20 (3.5)	15.45 (3.8)
Post-climb *Mean (SD)*	26.62 (18.8)	33.33 (8.8)	40.58 (6.4)	16.93 (3.6)
p-value	**0.361**	**0.460**	**0.470**	**0.359**
MINIMUM (°)				
Pre-climb *Mean (SD)*	-14.21 (13.7)	32.86 (9.5)	11.56 (2.6)	-4.98 (6.1)
Post-climb *Mean (SD)*	-14.14 (20.0)	27.61 (13.6)	10.86 (1.9)	1.43 (4.9)
p-value	**0.495**	**0.094**	**0.105**	**<0.01****
MAXIMUM (°)				
Pre-climb *Mean (SD)*	13.96 (3.1)	65.52 (6.9)	51.76 (5.5)	10.47 (5.6)
Post-climb *Mean (SD)*	12.47 (1.3)	60.95 (18.6)	51.4 (4.8)	18.4 (4.1)
p-value	**0.307**	**0.298**	**0.477**	**0.092**

All three climbers showed no relevant changes in ankle dorsiflexion; RMSE values did not suggest that post-climbing data matched the control curve more closely than pre-climbing data (see Table 5.1, Ankle dorsiflexion). Additionally, there were no significant differences (see Table 5.2). CP3 was able to achieve better stride consistency (reduced deviation) post-climbing.

CP1 knee flexion was markedly less crouched post-climbing, ranging approximately 10-20° less and averaging 11.5° less overall, and closer to matching TD walking compared to the baseline according to RMSE values (see Table 5.1, Knee flexion). CP2 and CP3 did not demonstrate similar improvement, although CP3 was able to achieve better stride consistency (reduced deviation) post-climbing. As a group, minimum knee flexion achieved was somewhat decreased post-climb ($p = 0.094$).

For CP1 hip flexion, a slight statistical improvement towards the control curve was observed with an average of 6.46° less hip flexion post-climbing (see Table 5.1, Hip flexion). CP2 and CP3 did not demonstrate significant improvements on this level, although CP3 stride deviation was again reduced. As a group, there was slightly lower minimum hip flexion ($p = 0.105$).

This CP population was observed to have considerable change in hip adduction. All three subjects had increased adductions of 3.80, 9.85, and 8.40° respectively. CP1 and CP3 moved away from the control curve, increasing RMSE values (see Table 5.1, Hip adduction), but CP2 jumped from over-abduction to over-adduction relative to the control curve. CP3 reduced variability in stride once again. There were significant or near significant increases in mean angle ($p < 0.05$), minimum angle ($p < 0.01$), and maximum angle ($p = 0.092$).

5.3.2 Postural Steadiness Test

The postural steadiness test results for all three subjects are plotted in Figure 5.4. The best 10 second interval was selected from each subject for analysis. Generally, CE area numbers corresponded qualitatively to perceived subject motor function. The pre- and post-climbing confidence ellipse areas were similar for subjects CP1 (initial 273.5 mm^2, final 283.1 mm^2) and CP2 (initial 198.9 mm^2, final 144.3 mm^2), with an increase in CE area for subject CP3 (initial 373.9 mm^2, final 778.4 mm^2), although this result was skewed by persistent fidgeting from CP3 despite verbal encouragement.

For n = 3, the one-tailed paired t-test comparing the initial and final areas yielded $p = 0.246$, meaning no statistically significant difference could be discerned. Comparing major and minor axes from initial to final measurements resulted in $p = 0.222$ for the major axis and $p = 0.472$ for the minor axis, meaning there were no statistically significant differences for this data either.

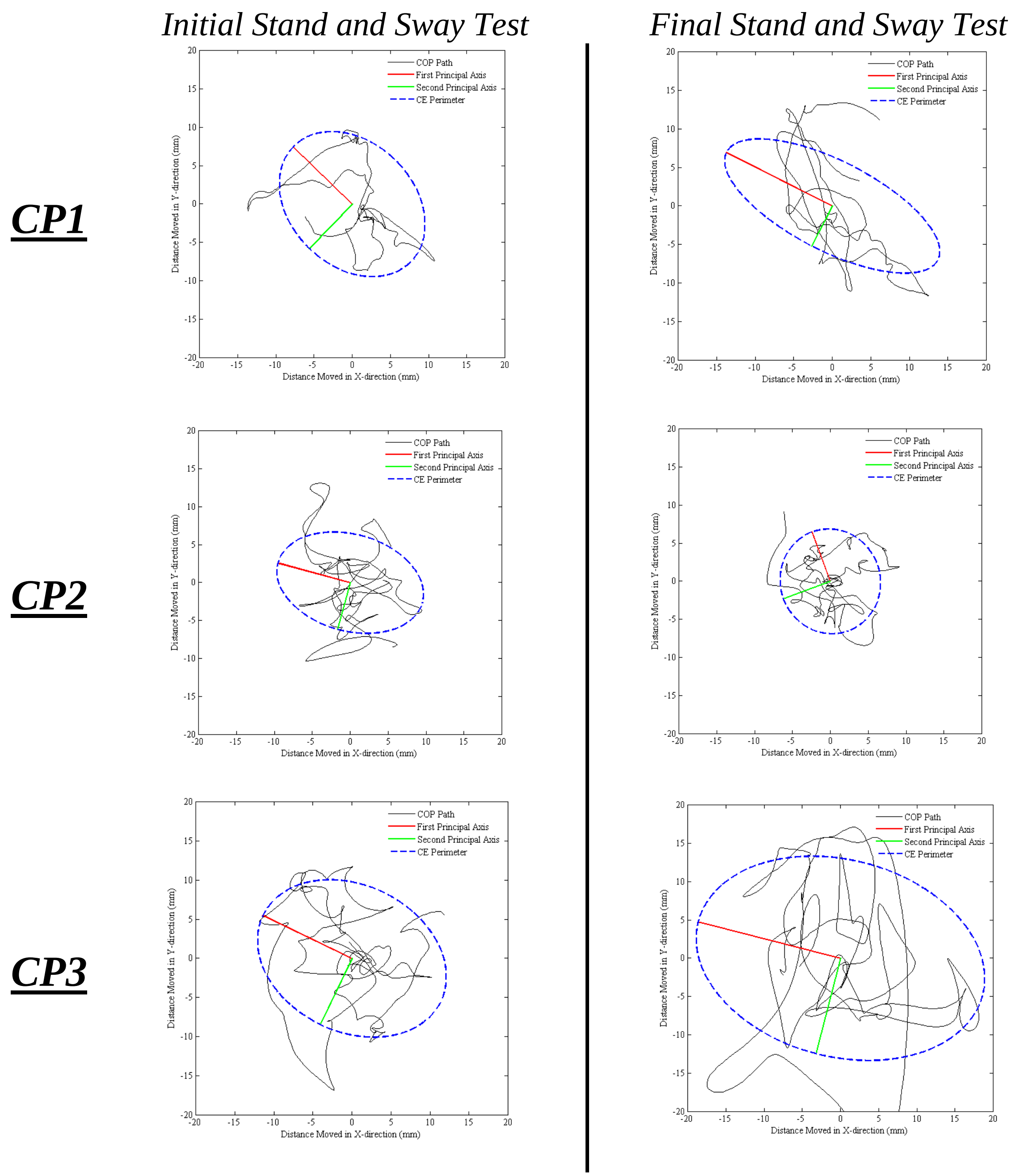

Figure 5.4. CE comparison of three CP subjects before-and-after climbing protocol. The principal axes were calculated using the Oliveira method (Oliveira et al., 1996).

5.4 Discussion and Conclusion

Even with limited training, some differences were noted in walking comparisons pre- and post-climbing. For CP1, decreased knee crouch and hip flexion were observed, moving the subject to a more neutral, energetically desirable position during the gait cycle. Crouch gait, a common movement characteristic for individuals with CP, is a frequent focus in physical therapy and surgical procedures, as it negatively impacts walking endurance and can lead to knee joint deformities. CP1 ankle dorsiflexion prior to climbing was already close to the control curve; therefore, inconsequential changes from pre- to post-climbing were a positive result. For CP2, very little difference was seen for ankle dorsiflexion, knee flexion, and hip flexion. This result could be due to the subject's use of crutches and her habitual rhythm to achieve stable locomotion; her stride deviation was the smallest in the group. For CP3, results were also similar pre- and post-climbing, perhaps due to her use of crutches, but she was able to reproduce walking joint kinematics more consistently after climbing. Reduced deviation could be a sign of improved coordination and/or strength, as a deficiency in either leads to erratic gait cycles.

All three subjects had an increase in hip adduction. In Ch. 4, hip abduction during climbing led to adductor muscle stretch. It is unclear whether these results are due to marker artifact, since hip adduction can be easily skewed by small shifts in marker positioning on clothing. If the results are reliably accurate, does this mean stretching hip adductor muscle make it more likely for individuals to adduct more? Should strengthening of the hip abductors be targeted in order to prevent excess adduction rather than stretching the adductors? Further research is required in order to investigate this important question.

The stand-and-sway balance test was inconclusive. It was difficult to obtain subject balance at their peak potential; subjects tended to fidget and talk during collection despite verbal instructions. Regardless of performance, the study would benefit from a larger sample size. Other tests may be more useful in describing fundamental functional changes, such as dynamometer testing to gauge strength through direct force and torque measurements and passive stretch tests to measure the direct ROM of the individual.

There may have been additional impacts due to climbing not measured by this study. The upper body was omitted from scrutiny because the CP population had diplegic tendencies. However, it may be that the strength of the upper arms or grip increased. Upper body ROM and dexterity could have also increased; tests such as the Bruininks-Oseretsky Test of Motor Proficiency, the Jebsen-Taylor Test of Hand Function, Assisting Hand Assessment, and many other tests proposed by upper body movement researchers may reveal changes in function (Gordon, Schneider, Chinnan, & Charles, 2007). Other work should look at electromyography (EMG) for both the upper and lower body and seek out possible neuromuscular changes as a result of climb training. This information could reveal which muscles are adapting as a result of climbing and whether spasticity is reduced or eliminated as a result of muscle stretch seen on the climbing wall.

Other research involving movement rehabilitation have emphasized high frequency and varying intensity of participation in the therapy in order to yield significant results. For example, studies examining constraint-induced movement therapy and task-specific therapies for stroke patients found that combinations of high-intensity work for 30-45 minutes and low-intensity work for 5-6 hours daily over the course of two weeks led to improved motor function, dexterity, and usage of affected limbs – even among patients assumed to have plateaued in their recovery (Page, Gater, & Bach-Y-Rita, 2004). In this study, subjects participated weekly in climbing sessions that lasted 45 minutes for six weeks (including the two data collections); current hypotheses in the motor rehabilitation field imply that they should participate daily in climbing for several weeks to see real improvements. While beyond the scope of this pilot study, this intensive regimen should be the next step in establishing climbing as a potential recreational therapy.

Psychological benefits have not been measured in this study, although parent and physical therapist testimonies with anecdotes attesting to its positive influence can be found in Appendix A.1. Because the idea of using climbing as a physical therapy is predicated on the appeal of climbing to young patients with CP, it would be useful to confirm the emotional impact of climbing. This could be strong evidence to steer clinicians towards implementing climbing into their facilities or recommending climbing as an option for physical recreation over other activities.

Ultimately the results shown in this chapter take a step in articulating fundamental shifts in functional abilities for the subjects in the study. Climbing may yield functional benefits to children with CP, but more study is required; the information presented in this chapter is only the tip of the iceberg. This work is important both to ensure that clinicians steer their patients to therapies that are strongly supported by a body of evidence, as well as to demonstrate climbing's feasibility as a therapy so that it is implemented in more and more facilities to maximize patient access.

Chapter 6: Conclusion

6.1 Summary

The main goals of this thesis were as follows:

1. Demonstrate any differences between a cerebral palsy (CP) population and a typically developed (TD) population during climbing
2. Quantify climbing strength for the CP population and potential improvement over time, as well as their stretch/range of motion (ROM) compared to that achieved during walking
3. Investigate potential functional differences before and after participating in climb sessions

By probing the basic questions accompanying these goals, this thesis sought to establish recreational rock climbing as a legitimate alternative to traditional physical therapies for children with CP.

Comparing the CP and TD populations revealed apparent differences in body weight support. The CP population relied on an approximate average of four times greater body weight support from belay than their TD peers, most of the difference seen in lower limb support. This finding was not surprising given that all three climbers with CP exhibited diplegic CP. After training on the climbing wall, all three climbers made positive progress to varying but definite degrees of success, making a strong case that coordinated, quadrupedal body weight support is feasible and can be improved even for a population with innate deficits in coordination and strength. Direct measurements of strength were not collected for this study to investigate functional measurements, and indirect measurements – i.e., the stand and sway test – were inconclusive, suggesting a need for more intense/frequent therapy and a fuller array of functional tests.

The CP and TD populations demonstrated only a few significant differences in mean muscle stretch during similar steps, proving that climbers with CP were immediately capable of similar or greater muscle lengths compared to their TD peers. However, the TD population was able to demonstrate greater ROM in most cases. When comparing the stretch/ROM between walking and climbing for the CP population, it became clear that climbing elicited unique stretch from many significant lower limb muscles, usually with a wider range and/or a higher mean length. These results suggest that climbers with CP can achieve significant stretch on the wall rather than on the ground, and that training for greater ROM can be encouraged by manipulating placement of climbing grips. In post-functional measurements, reduced variability in kinematics for one climber and decreased crouch for another climber hint at greater rewards possible with more extensive climb training.

6.2 Broader Impact

The field of biomechanics applied to human rock climbing is still emerging; this thesis is the first work to study a clinical population on the climbing wall and collect inverse kinematics and dynamics data. Not only does it contribute to human biomechanics knowledge, it is also a step forward in the growing clinical movement to augment or even supplant traditional physical therapies with activities and sports made more accessible through technology and innovation (Damiano, 2006; Pin et al., 2006; Sakzewski, Ziviani, & Boyd, 2014; Savelsbergh, Ledebt, Smorenburg, & Deconinck, 2013).

Building models of climbers based on experimental data to glean insights on efficiency and performance is a new concept starting only half a decade prior to this thesis (Zirker, 2011). This thesis has added to its biomechanical analysis techniques by performing the first analysis on heightened climbing walls: eighteen rather than eight feet tall. The additional technical challenges such as tracking motion over a larger area and assigning forces from six force plates to four limbs were met to construct models with the capacity for multiple strides.

Innovating ways to engage children in their physical therapy is appealing to clinicians, because the patients are more likely to put forth effort, participate more often, and become personally invested in the activity. As a child that required countless speech therapy and audiology sessions following a deaf diagnosis, the author can personally empathize with children who find their respective therapy dull or annoying even if they intellectually understand the motivation for doing it. This thesis proposes a novel idea that can inspire children to exercise in ways that can aid their movement, and in a medium that can be easily controlled by physical therapists through selective placement of climbing grips and routes and belay rope support.

6.3 Limitations of Thesis

Much of the strength investigation and discussion in this thesis hinged on direct measurements, but one challenge was to separate strength benefits from neuromuscular learning and strategic realizations on the part of the climbers. Are reductions in belay rope support because the climbers were stronger, or did they just have improved spatial awareness and planning? Better functional tests will be crucial to delineating these intertwined factors. With respect to ROM and muscle stretch, the limitations of the results were contingent on the accuracy of the models utilized. For ROM, the knee joint was assumed to be uniaxial, and the ankle joint was modeled as biaxial. For muscle stretch, the model did not take into account individual physiological differences in muscle attachment points, tendon-to-muscle length ratios, and other biomechanical constants. However, even with the inherent limitations of modeling, it was a valuable tool in showing logical ROM and muscle stretch resulting from climb strides.

6.4 Future Work

This thesis delves into new territory, and there is a lot of unexplored ground to cover. One limitation of the study was the small CP population; a larger number of subjects would provide greater statistical power to the insights seen here and perhaps reveal more or modified information. In addition, a future study designed to train climbers on a daily basis for several weeks is imperative, as more significant changes in functional measures should be apparent to prove climbing's therapeutic capabilities. Another question worth answering follows: can targeted functional improvements be made based on specific climbing wall configuration choices? If so, this information could be assembled into an instructional reference for clinicians to add another dimension of therapy personalization into their plans for their patients.

In this thesis only the lower limbs were evaluated (as appropriate for patients with diplegia), but the analytical framework is already in place to examine data-driven models of the upper body. As a quadrupedal sport, climbing is unique by engaging all four limbs at once, which could be an advantage point when offering activities to children; further investigation should confirm upper body stretch and strength benefits. Extending this further, fine motor control such as grasping objects may benefit as a result of climbing, a hypothesis that warrants a deeper look but requires better motion capture resolution and more complex modeling. Selecting a greater variety of functional tests and direct measurements of ROM and strength in the future (i.e., dynamometer testing and passive stretch evaluation) would likely produce more quantitative evidence that climbing is beneficial for children with CP.

Two other aspects of CP – coordination and spasticity – were not directly addressed in this work. Climbing may prove to positively influence these factors as well, since coordinating the limbs simultaneously may be good neuromuscular training and spasticity controlled for with deliberate pacing of each climb. Using electromyography (EMG) and motion entropy measures to quantify spasticity and coordination could reveal further benefits due to climbing.

6.5 Final Remarks

Beyond the scientific merits of this study which encourage further exploration into recreational rock climbing therapy, true satisfaction came from working closely with children with CP and enabling them to achieve greater heights (literally and figuratively) than ever before. As evidenced by testimonies in Appendix A.1, both children and parents were happy to join a fun activity that felt less like work and more like play. The children in this study visibly grew in confidence, from initial apprehension and concern over possible failure to excitement, self-determination of ambitious goals, and pride upon completion of difficult maneuvers or steps. This thesis focused on reaping physical benefits from climbing, but climbing can also enrich its participants socially and emotionally in ways that traditional physical therapies cannot hope to match, particularly in the case of children. The author hopes that these analyses and ideas provide a solid foundation upon which to build better, more intuitive therapies for children with movement disorders.

Appendix

A.1 Climbing Therapy Testimonies

A.1.1 Parent Testimony

A written statement volunteered by the parents of a subject with cerebral palsy:

"We are the parents of a child with cerebral palsy who has been a subject in John Miller's study on rock-climbing as therapy. We first met John when our daughter went for a gait study at Kluge. She can walk with crutches, but cannot walk independently (except for a few steps). We've been working on weekly PT [physical therapy] and she's been getting PT at school. Therapy is kind of a drag for her as it takes her away from 'normal' child activities and limits the time she gets to play. We had decided to forgo therapy after school and have been doing 'activities' instead (primarily swimming, also horse riding and yoga), with periodic intensive therapy sessions. John's study was perfect for this.

"We still anticipated resistance to the 'idea' of having to go out and climb ([our daughter] loves being at home!). This was never the case. Right from the start [she] loved going climbing. She set goals for herself before each session and came home proudly telling us when she'd met them. When we watch her climb we see some specific things that the exercise provides:

- She doesn't have to worry about balance and can use her upper body strength that she has developed from walking with crutches, so there is a high level of success. She does not experience the frustration she feels during regular therapy.
- She has to lift her feet to clear the footholds. Foot drag is a huge issue for her and she works on it with each hold she passes.

- She has to open her hips to get close enough to the wall to climb effectively. Since she has been climbing she can sit comfortably in a cross-legged position. She sits that way by choice now; this has not been the case previously.
- She is HAPPY! Okay, she has always been a sunny personality, but this has definitely added to her joyfulness.

“John has kindly offered to continue weekly climbing beyond the study period. We are grateful for that and hope that the therapy will be made available for many more children and adults with similar impairments as John is clearly onto something valuable.”

A.1.2 Clinical Testimony

A written statement from a subject’s physical therapist:

“In the short period of time that [John Miller] worked on climbing with [the subject], she benefited greatly from the rock wall climbing sessions with [John]. The change in her is better than physical prowess: she gained confidence, bravery, and perseverance. [The subject’s] take on new challenges and novel activities prior to your program was one of reluctance and fear, accompanied with lots of tears. [The subject], since participating with your program has progressed to being willing, even eager sometimes, to take on a new challenge.

“This newfound emotional maturity has opened so many doors for her and has given her so much more self-confidence, that our 2x/week PT sessions together at school are much more productive and fun.

“You are on to something great, so keep up your fabulous work!”

A.2 Joint Torques during Climbing

Joint torque required for climbers with CP were obtained from custom models constructed in the LifeMOD plug-in for MSC.Adams.

Ankle and knee flexion torques, normalized by mass (kg)

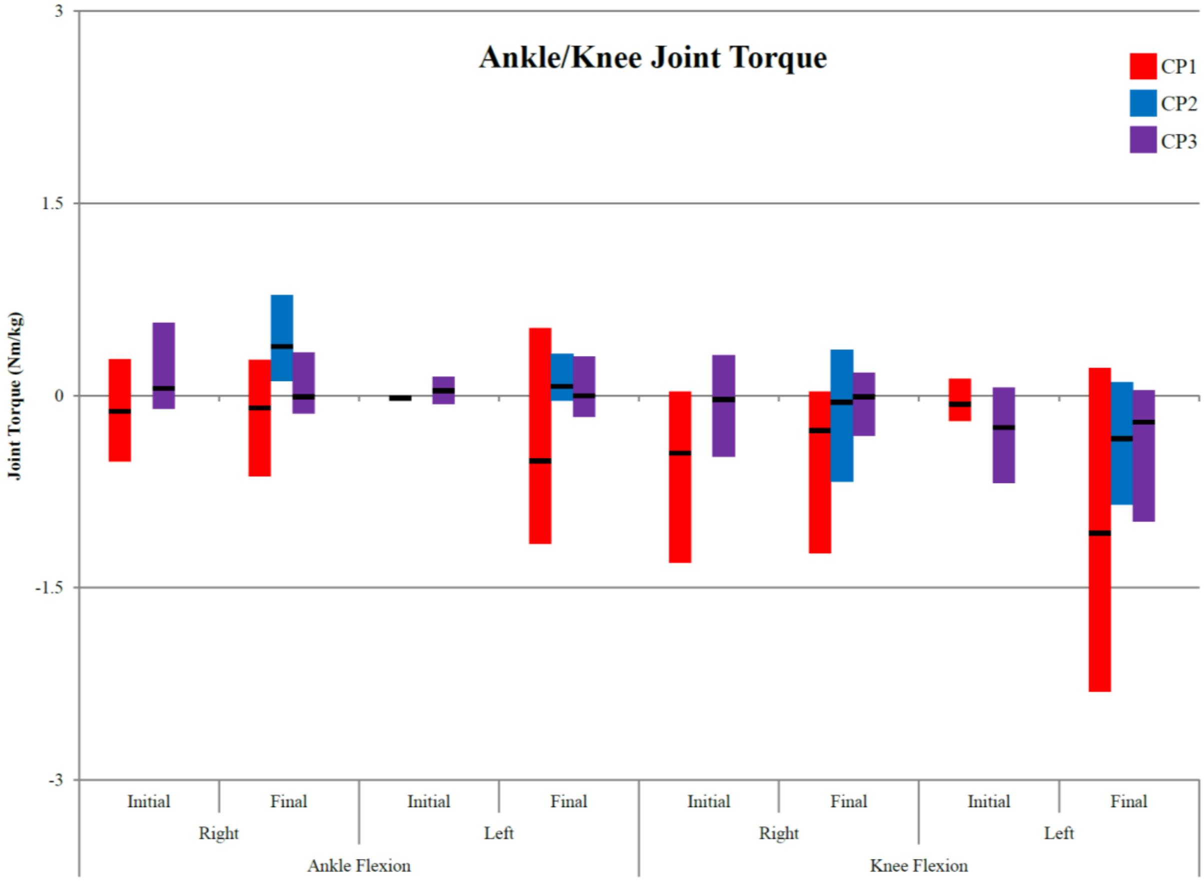

Figure A.2.1. The data shown is from the most lateral, most vertical step for subjects with CP. Modeled joint torques for the ankle in the flexion (sagittal) plane and the knee in the flexion (sagittal) plane.

Hip flexion and adduction torques, normalized by mass (kg)

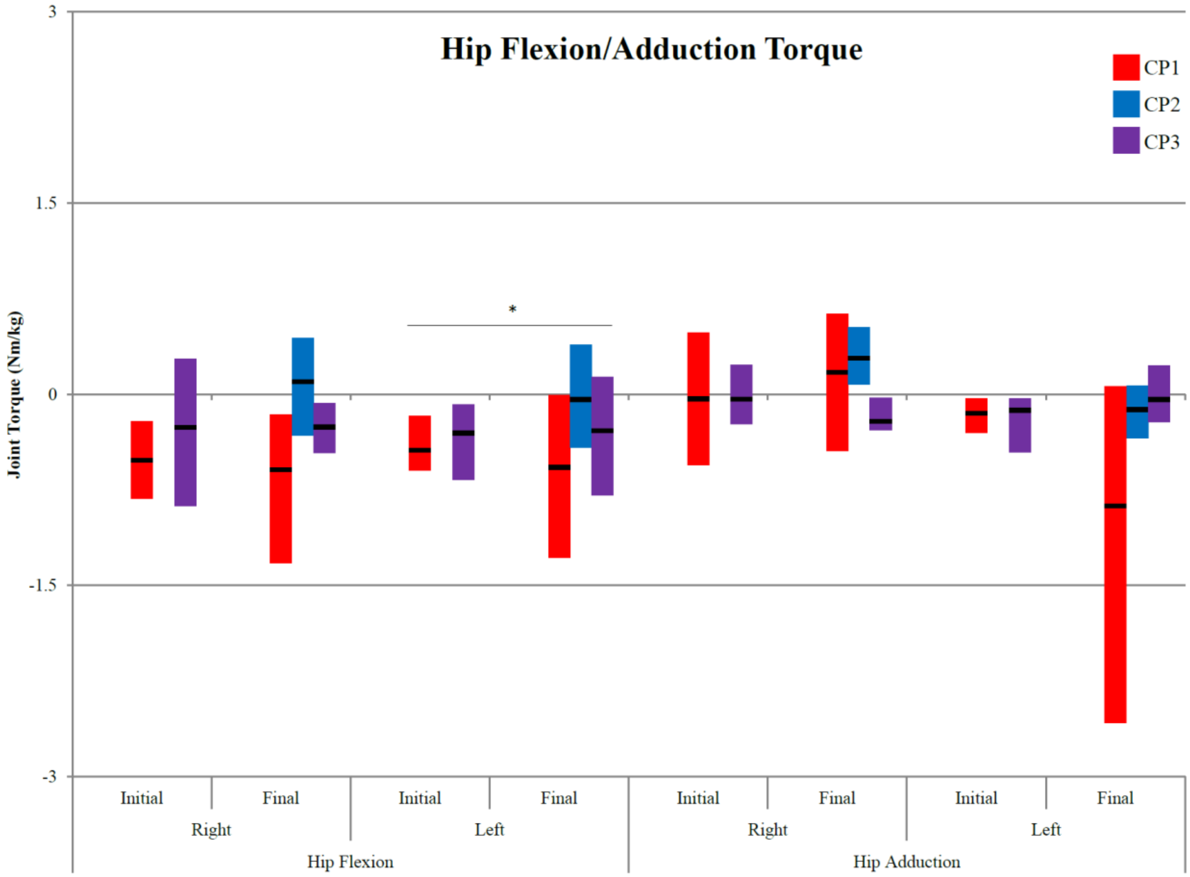

Figure A.2.2. The data shown is from the most lateral, most vertical step for subjects with CP. Modeled joint torques for the hip in the flexion (sagittal) plane and the hip in the adduction (frontal) plane.

Table A.2.1. Mean ± SD joint torque information for the CP initial and final climb sessions. [1]Data for CP2 was omitted from the initial climb session due to a data collection error. *p<0.05, **p<0.01, ***p<0.001.

	CP Initial Group Mean (±SD)[1]	**CP Final Group Mean (±SD)**	**p-value**
MEAN			
Right ankle flexion torque	-0.033 (0.13)	0.094 (0.26)	0.378
Left ankle flexion torque	0.0091 (0.04)	-0.145 (0.32)	0.224
Right knee flexion torque	-0.241 (0.30)	-0.111 (0.14)	0.216
Left knee flexion torque	-0.159 (0.13)	-0.538 (0.47)	0.264
Right hip flexion torque	-0.389 (0.18)	-0.250 (0.35)	0.272
Left hip flexion torque	-0.371 (0.10)	-0.300 (0.27)	0.290
Right hip adduction torque	-0.037 (0.0007)	0.0803 (0.26)	0.473
Left hip adduction torque	-0.138 (0.017)	-0.345 (0.46)	0.287
MAXIMUM			
Right ankle flexion torque	0.425 (0.20)	0.466 (0.28)	0.247
Left ankle flexion torque	0.071 (0.10)	0.387 (0.12)	0.156
Right knee flexion torque	0.171 (0.20)	0.188 (0.17)	0.252
Left knee flexion torque	0.095 (0.049)	0.119 (0.088)	0.329
Right hip flexion torque	0.034 (0.35)	0.071 (0.32)	0.300
Left hip flexion torque	-0.124 (0.06)	0.173 (0.20)	<0.05*
Right hip adduction torque	0.359 (0.18)	0.377 (0.35)	0.415
Left hip adduction torque	-0.032 (0.0019)	0.119 (0.094)	0.137
MINIMUM			
Right ankle flexion torque	-0.309 (0.29)	-0.217 (0.38)	0.162
Left ankle flexion torque	-0.0489 (0.021)	-0.451 (0.61)	0.221
Right knee flexion torque	-0.889 (0.58)	-0.736 (0.46)	0.116
Left knee flexion torque	-0.439 (0.34)	-1.378 (0.81)	0.205
Right hip flexion torque	-0.846 (0.043)	-0.701 (0.54)	0.469
Left hip flexion torque	-0.633 (0.051)	-0.829 (0.43)	0.194
Right hip adduction torque	-0.393 (0.23)	-0.215 (0.26)	0.375
Left hip adduction torque	-0.379 (0.11)	-1.045 (1.33)	0.284

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