Multi-Segment Foot Coordination of the Treated Clubfoot

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MULTI-SEGMENT FOOT COORDINATION OF THE TREATED CLUBFOOT

A Master’s Thesis Presented

by

AMY J. WHITED

Submitted to the Graduate School of the University of Massachusetts Amherst in partial fulfillment of the requirements for the degree of

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Department of Kinesiology
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ABSTRACT

MULTI-SEGMENT FOOT COORDINATION OF THE TREATED CLUBFOOT

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Idiopathic congenital clubfoot can be treated either operatively (comprehensive surgical release (CSR)) or conservatively (ponseti technique (PCT)). This thesis compared the mid-term outcomes after CSR and PCT treatments to a typically developing sample. A Dynamical Systems Analysis (DSA) approach and a multi-segment foot model were used to examine group differences in multi-segment foot and lower extremity kinematics, kinetics, coordination and coordination variability during walking.

Ten children with clubfoot treated with PCT and seven children with clubfoot treated with CSR were evaluated retrospectively and compared to ten typically developing children. Multi-segment foot and lower extremity kinematic (240 Hz) and kinetic (1080 Hz) data were collected while participants walked barefoot at a fixed walking velocity (1.0 m/s\(^{-1}\) ±5%). Sagittal plane metatarsophalangeal (MTP) and three-dimensional (3D) forefoot-rearfoot, ankle, knee and hip joint range of motion (ROM) during stance and 3D ankle, knee and hip peak joint moments during push-off were calculated. A modified vector coding technique was used to quantify
the multi-segment foot and lower extremity coordination and coordination variability throughout stance for forefoot-rearfoot inversion/eversion (Ff-Rf), rearfoot inversion/eversion–tibial internal/external rotation (Rf-Tib) and femur-tibia internal/external rotation (Fem-Tib) couples.

Reduced MTP and forefoot-rearfoot ROM was observed in the CSR group while the PCT group demonstrated values comparable to CTR. Sagittal plane ankle ROM was similar between groups however, the CSR group demonstrated reduced frontal plane ROM compared to PCT. Peak ankle plantar flexion moment was reduced in the last 50% of stance in the clubfoot groups. The CSR group demonstrated greater knee and hip moments compared to CTR and PCT. The PCT group demonstrated lesser peak ankle eversion, knee external rotation and knee valgus moments compared to CTR. No significant differences were observed in Ff-Rf, Rf-Tib and Fem-Tib coordination and coordination variability throughout stance between the groups.

PCT and CSR gait was characterized by restricted multi-segment foot motion and abnormal lower extremity joint moments; suggesting mild residual deformity. Despite residual deformity, the coordination and coordination variability results indicate that the PCT and CSR groups are not functionally limited and demonstrate similar multi-segment foot and lower extremity movement patterns as CTR.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT ........................................................................................................... iii</td>
</tr>
<tr>
<td>LIST OF TABLES ................................................................................................. viii</td>
</tr>
<tr>
<td>LIST OF FIGURES ............................................................................................... x</td>
</tr>
</tbody>
</table>

## CHAPTER

1. INTRODUCTION ........................................................................................................... 1

1.1 Background ........................................................................................................ 1
1.2 Statement of the Problem ................................................................................... 5
1.3 Purpose of the Study ......................................................................................... 6
1.4 Significance of the Study .................................................................................. 6
1.5 Summary ............................................................................................................ 7

2. LITERATURE REVIEW ................................................................................................... 9

2.1 Introduction ...................................................................................................... 9
2.2 Anatomy of the Clubfoot Deformity ................................................................ 10
2.3 Clubfoot Treatment .......................................................................................... 12

2.3.1 Ponseti Casting Technique ................................................................ 13
2.3.2 Comprehensive Surgical Release ..................................................... 14

2.4 Evaluation of Foot Function ............................................................................ 15

2.4.1 Kinetics .................................................................................................... 17
2.4.2 Kinematics ............................................................................................. 20
2.4.3 Evaluation of Foot Function Summary ............................................. 23

2.5 Dynamical Systems Approach to Coordination ............................................... 24

2.5.1 Foundation for Coordination Analysis ............................................... 24
2.5.2 Movement Coordination ....................................................................... 25
2.5.3 Multi-segment Foot Coordination and Vector Coding .................... 26
2.5.4 Coordination Variability ....................................................................... 28

2.6 Chapter Summary ............................................................................................ 30

3. METHODS ................................................................................................................. 32

3.1 Introduction ..................................................................................................... 32
3.2 Participants ........................................................................................................... 32
3.3 Experimental Setup .............................................................................................. 33
   3.3.1 Camera Setup ............................................................................................. 34
   3.3.2 Marker Setup ............................................................................................ 34
   3.3.3 Force Platforms ....................................................................................... 36
   3.3.4 Walking Velocity ..................................................................................... 37
3.4 Experimental Protocol .......................................................................................... 38
3.5 Data Analysis ....................................................................................................... 39
   3.5.1 Range of Motion ........................................................................................ 40
   3.5.2 Peak Moment ............................................................................................ 41
   3.5.3 Stride Parameters ..................................................................................... 41
   3.5.4 Coordination Analysis ............................................................................. 42
3.6 Statistical Analysis ............................................................................................... 44
3.7 Summary ............................................................................................................... 44

4. MULTI-SEGMENT FOOT KINEMATICS AND KINETICS OF THE TREATED CLUBFOOT ................................................................. 46
   4.1 Introduction .................................................................................................... 46
   4.2 Materials and Methods ................................................................................... 49
      4.2.1 Participants ............................................................................................ 49
      4.2.2 Experimental Setup ............................................................................. 50
      4.2.3 Protocol ................................................................................................ 50
      4.2.4 Data Reduction ..................................................................................... 54
      4.2.5 Statistical Analysis ............................................................................. 56
   4.3 Results .............................................................................................................. 57
      4.3.1 Participants ............................................................................................ 57
      4.3.2 Multi-Segment Foot Kinematics ............................................................ 58
      4.3.3 Lower Extremity Joint Kinematics ....................................................... 61
      4.3.4 Lower Extremity Joint Moments ............................................................ 65
   4.4 Discussion ........................................................................................................... 71
      4.4.1 Limitations ............................................................................................. 75
      4.4.3 Conclusion ............................................................................................ 76

5. MULTI-SEGMENT FOOT COORDINATION OF THE TREATED CLUBFOOT ................................................................................................. 78
   5.1 Introduction .................................................................................................... 78
   5.2 Materials and Methods ................................................................................... 82
5.2.1 Participants........................................................................................................82
5.2.2 Experimental Setup........................................................................................83
5.2.3 Protocol .............................................................................................................84
5.2.4 Data Reduction ...............................................................................................87
5.2.5 Statistical Analysis .........................................................................................90

5.3 Results ................................................................................................................90
5.3.1 Participants ....................................................................................................90
5.3.2 Coordination .................................................................................................91
5.3.3 Coordination Variability ..............................................................................99

5.4 Discussion ..........................................................................................................101
5.4.3 Limitations .................................................................................................106
5.4.4 Conclusion .................................................................................................107

6. SUMMARY AND FUTURE DIRECTIONS .........................................................108
6.1 Summary ..........................................................................................................108
6.2 Study Results .................................................................................................109
6.3 Future Directions ...........................................................................................113

BIBLIOGRAPHY .......................................................................................................115
### LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1: Coordination pattern categorization</td>
<td>44</td>
</tr>
<tr>
<td>4.1: Group (mean ± SD) participant characteristics for age, height and weight for the three experimental groups</td>
<td>57</td>
</tr>
<tr>
<td>4.2: Group (mean ± SD) temporal and spatial parameters for the three experimental groups</td>
<td>57</td>
</tr>
<tr>
<td>4.3: Mean ± SD values for rearfoot-forefoot joint range of motion (ROM) in the sagittal (dorsiflexion-plantar flexion), frontal (inversion-eversion) and transverse (adduction-abduction) planes during the stance phase</td>
<td>59</td>
</tr>
<tr>
<td>4.4: Mean ± SD values for hip joint range of motion (ROM) in the sagittal (flexion-extension), frontal (inversion-eversion) and transverse (adduction-abduction) planes during the stance phase</td>
<td>65</td>
</tr>
<tr>
<td>4.5: Mean ± SD values for normalized peak ankle joint moments (N·m/kg) during the last 50% of the stance phase</td>
<td>67</td>
</tr>
<tr>
<td>4.6: Mean ± SD values for normalized peak knee joint moments (N·m/kg) during the last 50% of the stance phase</td>
<td>69</td>
</tr>
<tr>
<td>4.7: Mean ± SD values for normalized peak hip joint moments (N·m/kg) during the last 50% of the stance phase</td>
<td>71</td>
</tr>
<tr>
<td>5.1: Coordination pattern categorization</td>
<td>89</td>
</tr>
<tr>
<td>5.2: Group (mean ± SD) participant characteristics for age, height and weight for the three experimental groups</td>
<td>90</td>
</tr>
<tr>
<td>5.3: Group (mean ± SD) temporal and spatial parameters for the three experimental groups</td>
<td>91</td>
</tr>
</tbody>
</table>
5.4: Mean and standard deviation (SD) forefoot-rearfoot inversion/eversion coordination pattern frequency count for control (CTR), ponseti casting technique (PCT) and comprehensive surgical release (CSR) groups for early, mid and late stance..................................................................................................................................................................93

5.5: Summary of Tukey statistical post-hoc analysis (Adj p) and effect sizes (ES) for group forefoot-rearfoot inversion/eversion coordination patterns over early, mid and late stance..................................................................................................................................................................93

5.6: Mean and standard deviation (SD) rearfoot inversion/eversion-tibial internal/external rotation coordination pattern frequency count for control (CTR), ponseti casting technique (PCT) and comprehensive surgical release (CSR) groups for early, mid and late stance ..................................................................................................................................................................95

5.7: Summary of Tukey statistical post-hoc analysis (Adj p) and effect sizes (ES) for group rearfoot inversion/eversion-tibial internal/external rotation coordination patterns over early, mid and late stance..................................................................................................................................................................96

5.8: Mean and standard deviation (SD) femur-tibia internal/external rotation coordination pattern frequency count for control (CTR), ponseti casting technique (PCT) and comprehensive surgical release (CSR) groups for early, mid and late stance..................................................................................................................................................................98

5.9: Summary of Tukey statistical post-hoc analysis (Adj p) and effect sizes (ES) for group femur-tibia internal/external rotation coordination patterns over early, mid and late stance ..................................................................................................................................................................98

5.10: Group coordination variability mean ± standard deviation (SD) and summary of Tukey statistical post-hoc analysis (Adj p) and effect sizes (ES) for group comparisons ................................................................................................................................................................100
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Severe bilateral clubfoot deformity.</td>
<td>10</td>
</tr>
<tr>
<td>2.2</td>
<td>Clubfoot deformity.</td>
<td>12</td>
</tr>
<tr>
<td>2.3</td>
<td>Total ankle power.</td>
<td>19</td>
</tr>
<tr>
<td>2.4</td>
<td>Ankle Flexion.</td>
<td>21</td>
</tr>
<tr>
<td>2.5</td>
<td>Multi-segment foot kinematics throughout the gait cycle.</td>
<td>23</td>
</tr>
<tr>
<td>2.6</td>
<td>Angle-angle diagram.</td>
<td>27</td>
</tr>
<tr>
<td>2.7</td>
<td>Loss of complexity hypothesis.</td>
<td>29</td>
</tr>
<tr>
<td>2.8</td>
<td>Pelvis and trunk axial rotation angle-angle and coordination plots</td>
<td>30</td>
</tr>
<tr>
<td>3.1</td>
<td>Bilateral lower extremity marker placement.</td>
<td>35</td>
</tr>
<tr>
<td>3.2</td>
<td>Multi-segment foot model consisting of three dimensional shank, foot, forefoot, rearfoot and a two-dimensional hallux line segment.</td>
<td>37</td>
</tr>
<tr>
<td>4.1</td>
<td>Bilateral lower extremity marker placement.</td>
<td>51</td>
</tr>
<tr>
<td>4.2</td>
<td>Multi-segment foot model consisting of three dimensional shank, foot, forefoot, rearfoot and a two-dimensional hallux line segment.</td>
<td>53</td>
</tr>
<tr>
<td>4.3</td>
<td>Metatarsophalangeal (MTP) planar joint angle in the sagittal plane during stance (0-100%) for comprehensive surgical release (CSR), ponseti casting technique (PCT) and typically developing controls (CTR).</td>
<td>58</td>
</tr>
</tbody>
</table>
4.4: Rearfoot-forefoot kinematic time series during stance (0-100%) in comprehensive surgical release (CSR), Ponseti casting technique (PCT) and typically developing controls (CTR). .................................................................60

4.5: Ankle kinematic time series during stance (0-100%) in comprehensive surgical release (CSR), Ponseti casting technique (PCT) and typically developing controls (CTR). .................................................................62

4.6: Knee kinematic time series during stance (0-100%) in comprehensive surgical release (CSR), Ponseti casting technique (PCT) and typically developing controls (CTR). .................................................................63

4.7: Hip kinematic time series during stance (0-100%) in comprehensive surgical release (CSR), Ponseti casting technique (PCT) and typically developing controls (CTR). .................................................................64

4.8: Normalized ankle joint moments (N·m/kg) during stance (0-100%) in comprehensive surgical release (CSR), Ponseti casting technique (PCT) and typically developing controls (CTR). .................................................................66

4.9: Normalized knee joint moments (N·m/kg) during stance (0-100%) in comprehensive surgical release (CSR), Ponseti casting technique (PCT) and typically developing controls (CTR). .................................................................68

4.10: Normalized hip joint moments (N·m/kg) during stance (0-100%) in comprehensive surgical release (CSR), Ponseti casting technique (PCT) and typically developing controls (CTR). .................................................................70

5.1: Bilateral lower extremity marker placement. .................................................................84

5.2: Multi-segment foot model consisting of three dimensional forefoot and rearfoot segments, and a two-dimensional hallux line segment ........................................86

5.3: Forefoot-rearfoot inversion/eversion coordination histograms (group mean + SD) for control (CTR), Ponseti casting technique (PCT) and comprehensive surgical release (CSR) group for early (0-33%), mid (34-66%) and late stance (67-100%). .................................................................92
5.4: Forefoot-rearfoot inversion/eversion coordination ensemble group mean phase angle plot for control (CTR), ponseti casting technique (PCT) and comprehensive surgical release (CSR) group during stance (0-100%). ...............94

5.5: Rearfoot inversion/eversion-tibial internal/external rotation coordination histograms (group mean + SD) for control (CTR), ponseti casting technique (PCT) and comprehensive surgical release (CSR) group for early (0-33%), mid (34-66%) and late stance (67-100%). .................................................................95

5.6: Femur-tibia internal/external rotation histograms (group mean + SD) for control (CTR), ponseti casting technique (PCT) and comprehensive surgical release (CSR) group for early (0-33%), mid (34-66%) and late stance (67-100%). ....................................................................................................................97

5.7: Coordination Variability. .........................................................................................................................99
CHAPTER 1

INTRODUCTION

1.1 Background

Idiopathic talipes equinovarus (clubfoot) is a common congenital three-dimensional (3D) deformity of the foot in newborn children that may occur unilateral or bilateral. The etiology of the deformity remains unknown; however, it has been suggested that it may be the result of genetic and environmental factors during the development of the fetus (Wynne-Davies, 1972). Clubfoot is estimated to occur in approximately three in every 1,000 live births and has a higher incidence in males than females with a ratio of 2:1 (Wynne-Davies, 1972). The initial deformity consists of four primary components: 1) equinus; 2) hindfoot varus; 3) forefoot adductus; and 4) forefoot cavus and presents a wide spectrum of severity at birth. While not painful early in life, if left untreated, affected individuals tend to walk on the lateral sides of their feet, which leads to severe discomfort and disability by adolescence. The goal of successful clinical intervention is to restore normal function or to provide alternate movement strategies by reducing or eradicating the four primary components of the deformity (Ponseti, 1992). Ideally, treatment should result in a pain-free, plantigrade foot with good flexibility that allows the patient to wear shoes without modifications (Ponseti, 1992).

The two standard treatment techniques are the: 1) comprehensive surgical release (CSR); and 2) ponseti casting technique (PCT). The CSR is an invasive surgical procedure that involves the release of the posterior and medial ligaments at the ankle joint (Atar, Lehman, Grant, & Strongwater, 1992). Often CSR-treated feet require a return trip
to the operating room for a “re-do” of surgical releases, tendon lengthenings, osteotomies and selective joint fusions to correct the residual deformity. More recently, the PCT surfaced as an alternative correction method. This technique utilizes a progressive series of plaster casts to correct the inverted, supinated foot during infancy, followed by percutaneous heel cord lengthening to correct the foot equinus and anterior tibialis tendon transfers in about 15% of cases (Ponseti, 1992). After casting, a foot abduction orthosis is worn full-time for 3 months in order to prevent recurrence of the primary components of the deformity. After 3 months, it is recommended to wear the splint at night for two years (Ponseti & Campos, 2009b). Surgical intervention for clubfoot treatment in the United States decreased from 70% in 1996 to 10% in 2006 (Church et al., 2012; Zionts, Zhao, Hitchcock, Maewal, & Ebramzadeh, 2010) and currently, the vast majority of pediatric orthopedic surgeons have adopted the PCT in the United States and globally.

Reported outcomes in the literature on the effectiveness of clubfoot treatments initiated a shift toward primarily performing the PCT. Numerous studies have contributed to the assessment of clubfoot treatment outcomes; however, a closer look at the literature reveals large variability in ranges of reported positive outcomes. The PCT is reported with poor outcomes in 42-89% of cases and as many as 40% of patients treated with the PCT require some further operative treatment to correct a recurrence (Crawford & Gupta, 1996; Haft, Walker, & Crawford, 2007; Halanski, Huang, Walsh, & Crawford, 2009; Harrold & Walker, 1983; Herzenberg, Radler, & Bor, 2002; Laaveg & Ponseti, 1980). The CSR is reported with poor outcomes in 9-73% of cases and has an average reported rate of recurrent deformity in 25% of cases (Atar et al., 1992; Dobbs, Nunley, & Schoenecker, 2006; Lehman et al., 2003; Viskelety & Szepesi, 1989). Despite initial
promising results, it is now apparent that not all PCT-treated feet are free from recurrent deformity.

There remains a need to characterize the mechanisms of functional pathology present in the treated clubfoot. No studies in the past literature have analyzed the lower extremity and intra-foot coordination and coordination variability in children treated for clubfoot. Traditional biomechanical analysis in pediatric populations utilizes a single joint or single segment approach. Albeit valuable, these analyses neglect useful information in the data because single instant temporal events are identified a priori and within the gait cycle. The Dynamical Systems Analysis (DSA) approach to movement coordination differs from traditional biomechanical analyses in that it analyzes the interaction between two adjacent segments or joints.

There are two important components to analyzing a movement task when implementing a DSA approach. First, the relationship between parts of a system are of key importance and not the investigation of the parts separately (Bernstein, 1967). In this approach it is implied that the motion of one segment can influence the motion of another segment. Chang et al. (Chang, Van Emmerik, & Hamill, 2008) proposed the quantification of the coordination of the lower extremity using vector coding as a method to analyze the interactions between the segments. The coordination of two segments may be summarized through a set of operational coordination patterns: anti-phase (AP), in-phase (IP), distal phase (DP) and proximal phase (PP). AP coordination indicates the segments are rotating in opposite directions. Segments rotating in the same direction exhibit IP coordination. DP coordination indicates only the distal segment is rotating...
while the proximal segment is not. PP coordination indicates the proximal segment is rotating and the distal segment is not.

It is thought that in normal lower extremity mechanics during walking, eversion of the subtalar joint is functionally linked to internal tibial rotation and external femoral rotation. Also, inversion of the subtalar joint requires external tibial rotation and internal femoral rotation. These segment couples demonstrate AP coordination patterns during normal walking as the adjacent segments rotate in opposite directions. Deviation from these coupled motions are said to be “asynchronous” and can result in injury (Hamill, Palmer, & Van Emmerik, 2012).

As there are such a large number of degrees of freedom, variability in the organization of the segments is expected. Therefore, the second important component of analyzing a movement task using a DSA approach is the coordination variability. Coordination variability is of utmost importance as it provides a measure related to the variety of combinations used to organize the segments in order to produce a specific movement (Bernstein, 1967; Davis & Burton, 1991; Hamill et al., 2012). It has been reported that greater coordinative variability is normal for a healthy individual because there are numerous combinations of intra-segment coordination available. However, lower coordinative variability is normal for individuals with injury or disease because the number of combinations of intra-segment coordination is significantly reduced (Hamill et al., 2012; Hamill, van Emmerik, Heiderscheit, & Li, 1999; Seay, Van Emmerik, & Hamill, 2011).
The DSA approach macroscopically analyzes the many interacting mechanisms that may be responsible for the abnormal movement exhibited by feet treated with the PCT and feet treated with CSR.

1.2 Statement of the Problem

Due to the complexity of foot structure and motion, it has been difficult to fully understand the kinematics of the foot (Carson, Harrington, Thompson, O'Connor, & Theologis, 2001). In the past, much of the evaluation of clubfoot treatment outcomes has used radiographic measurements, range of motion measures, various scoring systems and questionnaires. These measures do not correlate with dynamic functioning of the foot and furthermore, they are not reliable, accurate nor reproducible methods of assessment (Cooper & Dietz, 1995; Huber & Dutoit, 2004; Ponseti, 1996).

Some biomechanical studies in the literature have used gait analysis in the investigation of clubfoot treatment outcomes (Alkjaer, Pedersen, & Simosen, 2000; Beyaert, Haumont, Paysant, Lascombes, & Andre, 2003; C. T. Davies, Kiefer, & Zernicke, 2001; El-Hawary, Karol, Jeans, & Richards, 2008; Karol, Concha, & Johnston, 1997; Karol, O'Brien, Wilson, & Johnston, Charles E., Richards, Stephen, 2005; Karol, Jeans, & ElHawary, 2009; Widhe & Berggren, 1994). However, these studies were limited to modeling the foot as a single rigid segment. The use of single-segment foot kinematics limits the acquisition of the true motion that occurs between the forefoot and the rearfoot (MacWilliams, Cowley, & Nicholson, 2003). Despite reporting the advantages of PCT over CSR, the true functional capacity of the treated clubfoot is not understood.
1.3 Purpose of the Study

The purpose of this study is examine group differences in lower extremity segmental/joint kinematics, kinetics and to determine the lower extremity coordination and coordination variability, specifically of the rearfoot and forefoot, during walking in individuals treated with either the PCT or CSR 5-7 years after treatment. We hypothesized that:

**Hypothesis 1:** There will be significant group differences (PCT vs. CSR vs. control) in rearfoot-forefoot, metatarsophalangeal (MTP), ankle, knee and hip joint range of motion (ROM) as well as significant group differences in ankle, knee and hip peak joint moments in the last 50% of stance.

**Hypothesis 2:** There will be more AP multi-segment foot coordination in the control group vs. the PCT and CSR groups.

**Hypothesis 3:** There will be more AP multi-segment foot coordination in the PCT group compared to the CSR group.

**Hypothesis 4:** There will be greater coordination variability in the control group vs. the PCT and CSR groups.

**Hypothesis 5:** There will be greater coordination variability in the PCT group compared to the CSR group.

1.4 Significance of the Study

Much of the literature on clubfoot treatment outcomes on mid-term foot function indicates the advantages of the PCT over CSR. However, many of these studies are limited by: 1) the use of methods of assessment that are not accurate, reliable or
reproducible, 2) the use of methods of assessment that do not correlate with dynamic foot function and 3) the use of single segment foot models in gait analysis research. Since the clubfoot deformity exists in the foot, an understanding of the interactions of the foot segments are of utmost importance in order to establish the effectiveness of treatment on long-term dynamic foot function (Church et al., 2012). Despite previous reports in the literature, there is very little understanding of the dynamic function of the treated clubfoot.

This study will implement new methods based on a DSA approach combined with the use of a multi-segment foot model that has not previously been applied to pediatric populations to determine the multi-segment foot coordination of treated clubfeet. Thus, evaluating the multi-segment foot coordination and coordination variability would represent a significant advancement in the understanding of the after-effects of two different treatments and the adaptations in dynamic foot function in this clinical pediatric population.

1.5 Summary

Clubfoot is a common 3D deformity of the foot in newborn children, occurring in three in every 1,000 live births (Wynne-Davies, 1972). The deformity consists of equinus, hindfoot varus, forefoot adductus and forefoot cavus and if left untreated, the deformity may lead to severe discomfort and disability later in life. The PCT and CSR are the two standard treatment methods for the clubfoot deformity. The PCT is currently the standard of care for clubfoot correction. However, despite its popularity amongst orthopedic surgeons around the world it is clear that not all PCT-treated feet are free from
recurrent deformity and that deficits in foot function do exist after treatment. The coordinative function of the treated clubfoot has yet to be characterized and may offer insight into the mechanisms of pathology.

This study will investigate group differences in lower extremity kinematics, kinetics, coordination and coordination variability, specifically of the rearfoot and forefoot, during walking in individuals treated with either the PCT or CSR 5-7 years after treatment. By utilizing methods based on a DSA approach combined with the multi-segment foot model, the results of this study will present more discerning differences in dynamic foot function between radically different treatment methods that are used to correct clubfoot in children.
CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Treatment of clubfeet has catalyzed much controversy in the literature. The etiology is unknown, the pathological anatomy is complex and long-term follow-ups are rare. The primary focus has been to compare the differences in outcome between the conservative and surgical approaches to the treatment of clubfoot to establish if one is more successful than the other. Numerous studies have contributed to the investigation of clubfoot deformity; however, it is difficult to make comparisons between these studies due to the many evaluation methods used and the variable lengths of follow-up (Huber & Dutoit, 2004; Ponseti, 1996). Additionally, many of the standard clinical methods for evaluating results do not accurately correlate with factors of good foot function (Cooper & Dietz, 1995). In order to truly understand dynamic foot function, knowledge of the interactions of the individual foot segments relative to one another is necessary.

Comparative differences between the PCT method, CSR and controls (CTR) have been investigated using traditional kinematic and kinetic perspectives. However, many of these studies were not able to quantify the interactions of the forefoot and rearfoot due to the limitations of modeling the foot as a single rigid segment. Therefore, to our knowledge, there is no comparative research on the differences in the coordinated function of the forefoot and rearfoot between feet treated with the PCT method and feet treated with CSR.
2.2 Anatomy of the Clubfoot Deformity

The foot is often divided into three functional segments: the forefoot, midfoot and rearfoot. The rearfoot represents the subtalar joint, which is comprised of the talus and calcaneus. The midfoot is comprised of the navicular, cuboid and three cuneiforms. Hindfoot refers to the rearfoot and the navicular and cuboid together. The forefoot is comprised of the metatarsals and phalanges. The clubfoot deformity is characterized by four primary components: 1) equinus; 2) hindfoot varus; 3) forefoot adductus; and 4) forefoot cavus (Ponseti, 1992). Figure 2.1 depicts the four primary components of the deformity in severe bilateral clubfeet.

Figure 2.1: Severe bilateral clubfoot deformity. Adapted from (Ponseti & Smokey, 2009)

The hindfoot is the most severely deformed component of the clubfoot (Ponseti, 1992). It is important to note that movement of the tarsal bones (bones of the rearfoot and midfoot) is mutually dependent and thus, movement of the tarsal joints occurs
concurrently. Thus, if one joint is restricted then the articulating joints are restricted as well. The tibialis posterior muscle is the primary muscle responsible for the clubfoot deformity. This muscle primarily inverts the foot and assists with plantar flexion of the foot and ankle. The tendon of the tibialis posterior divides into three components: plantar, main and recurrent. The plantar portion of its tendon inserts into the bases of the second, third and fourth metatarsals, second and third cuneiforms and lastly the cuboid. The main portion of its tendon is attached to the first cuneiform and the navicular, holding it against the medial surface of the talus (Bensahel, Huguenin, & Themar-Noel, 1983). The recurrent portion of its tendon inserts into the calcaneus. Contracture of the tibialis posterior causes the navicular and cuboid to become medially rotated and displaced in adduction and inversion. The displacement of the navicular causes it to articulate with the medial portion of the head of the talus and in some cases, with the medial malleolous (Bensahel et al., 1983; Howard & Benson, 1993; Ponseti, 1992; Ponseti & Smokey, 2009). This displacement of the navicular consequently causes the talus and the calcaneus to become medially rotated and locked in equinus (Bensahel et al., 1983; Howard & Benson, 1993). As a result, the anterior and medial surfaces of the calcaneus are forced to lie beneath the head of the talus where the posterior surface lies more transverse than normal (Howard & Benson, 1993). The abnormal displacements of the navicular, talus and calcaneus are responsible for the severe varus and equinus deformities of the hindfoot (Bensahel et al., 1983; Howard & Benson, 1993; Ponseti, 1992; Ponseti & Smokey, 2009).

The cuneiforms are directed downward and inward and thus medially displaced in front of the navicular. The forefoot is adducted as a result of the medial displacements of
the cuneiforms, cuboid and navicular; this combined with the calcaneovarus and equinus results in supination of the entire foot (Howard & Benson, 1993; Ponseti & Smokey, 2009). The cavus deformity involves greater plantarflexion of the first metatarsal compared to the fifth metatarsal. The cavus deformity is thus caused by the pronation of the forefoot relative to the rearfoot. The forefoot remains adducted but slightly less inverted in relation to the hindfoot. The result is a modestly pronated forefoot in relation to the severely supinated hindfoot; this is the cause of the cavus deformity (Ponseti, 1992; Ponseti & Smokey, 2009; Ponseti, 1997b). Figure 2.2 depicts the bony displacements in the clubfoot deformity.

Figure 2.2: Clubfoot deformity. The navicular is medially displaced causing it to articulate with the medial aspect of the head of the talus. The cuneiforms are directed downward and inward. The anterior and medial portions of the calcaneus lie underneath the talus. Adapted from (Ponseti & Campos, 2009a).

2.3 Clubfoot Treatment

Operative and non-operative are the two standard approaches for correction of a clubfoot deformity. Most orthopedists agree that an operative approach should only be considered if a non-operative approach unsuccessfully corrects the deformity (Ponseti,
1992). The two standard treatment procedures for clubfoot are the: 1) ponseti casting technique (PCT); and 2) comprehensive surgical release (CSR).

2.3.1 Ponseti Casting Technique

The PCT is initiated within the first week of life because the fibroelastic properties of the connective tissue are optimal and prolonging the plaster-cast treatment may interfere with the natural development of the foot (Ponseti & Smokey, 2009; Ponseti, 1997b). A series of five to ten well molded, thinly padded plaster casts are worn for five to twelve weeks. The casts are changed every four to seven days. In order to correct tibial torsion, toe-to-groin plaster casts are used to immobilize the knee at a right angle and the leg is externally rotated (Ponseti & Smokey, 2009).

The cavus deformity is corrected first. As mentioned previously, the cavus deformity is caused by the pronation of the forefoot with respect to the hindfoot. Thus, supinating the forefoot and dorsiflexing the first metatarsal will correct the cavus deformity (Ponseti & Smokey, 2009; Ponseti, 1997b).

The hindfoot varus and forefoot adductus (components of the supination of the entire foot) are corrected simultaneously by abducting the supinated foot. The goal is to simultaneously realign the calcaneocuboid, the talocalcaneonavicular, and the posterior talocalcaneal joints. By laterally displacing the navicular and cuboid, the anterior surface of the calcaneus is displaced from resting underneath the head of the talus by simultaneously abducting and evertting. Immobilization tends to loosen then tight medial and posterior tarsal ligaments. This part of the deformity is gradually corrected in five or six cast changes (Ponseti & Smokey, 2009; Ponseti, 1997b).
The hindfoot equinus is corrected next. This is the most difficult deformity to correct because the Achilles tendon tends to resist manipulation. Correction of the equinus requires dorsiflexion of the fully abducted foot. Two to three cast changes are typically applied. Often, a simple tenotomy of the Achilles tendon is required in order to fully correct the deformity (Ponseti & Smokey, 2009; Ponseti, 1997b).

After casting, a foot abduction orthosis is worn full time for three months in order to prevent recurrence of the primary components of the deformity. After three months, it is further recommended to wear at night for twenty-one and a half months (Ponseti & Smokey, 2009).

2.3.2 Comprehensive Surgical Release

The CSR technique is performed typically between 9 and 12 months of age in order to avoid fibrosis, scarring and stiffness (Ponseti, 1997b). The talonavicular and subtalar joints are the primary location of the clubfoot deformity and therefore the soft tissue releases of these two joints are the most important steps of the posteromedial release (Ashby, 1976). It is important to note that release of the soft tissue cannot correct deformed bony anatomy.

Posterior release consists of the release of the posterior capsule of the ankle, subtalar joint and lengthening of the Achilles tendon (Penny, 2005). A posterior capsulotomy is performed on the ankle and subtalar joints where the posterior talofibular and calcaneofibular ligaments are released. The Achilles tendon is lengthened by performing a Z-plasty (Ebnezar, 2010).

The medial release involves the complete release of the posterior and medial subtalar joint capsule, talonavicular joint capsulotomy, medial calcaneocuboid joint
capsulotomy, release of the knot of Henry, sectioning of the abductor hallucis, and lengthening of the posterior tibial tendon, flexor hallucis longus and flexor digitorum longus (Penny, 2005). Further, the capsules of the naviculocuneiform and first metatarsocuneiform joints are also released (Ebnezar, 2010).

2.4 Evaluation of Foot Function

A majority of the literature on the evaluation of clubfoot treatment outcomes has used radiographic measurements (Bensahel, Kuo, & Duhaime, 2003; Dobbs et al., 2006), pedobarography (Huber & Dutoit, 2004), range of motion, or by various scoring systems (Munshi, Varghese, & Joseph, 2006). Objective measures such as radiographic or range of motion measures, have not been demonstrated to correlate with pain and functioning of the foot nor have they been shown to distinguish between excellent, good or poor outcomes (Cooper & Dietz, 1995). The numerous rating scales used for the evaluation of clubfoot makes it difficult to compare results and the results are often arbitrary and unrelated to good long-term dynamic foot function. These measures do not assess the dynamics of the foot during gait and therefore, are not good measures of long term foot function nor are they reliable, accurate or reproducible methods of assessment (Huber & Dutoit, 2004; Ponseti, 1996). However, measurement of the center of pressure path via pedobarography has yielded useful results.

The center of pressure path is the location of the vertical ground reaction force resultant on the foot during gait (Brand, 2009). At heel strike, a short pronation movement of the subtalar joint is necessary in order to allow the tibia to internally rotate. This mechanism “unlocks” the knee at heel strike, allowing knee flexion to occur for
optimal shock absorption as a result of the foot striking the ground. The amount of motion at the subtalar joint at heelstrike depends on the configuration of the articulating surfaces and ligamentous support (Mann & Haskell, 1993; Salathe, Arangio, & Salathe, 1990). Restricted motion or abnormal structure of the subtalar joint, diminishes the joint’s ability to act as a “torque converter” (Smith et al., 2013). Any dysfunction at the foot and ankle could cause alterations and compensatory injuries to the proximal joints in the kinetic chain because the forefoot, rearfoot and leg are mechanically linked (Church et al., 2012; Mann & Hagy, 1980). As complete correction of the clubfoot deformity is not possible for both treatment methods it is expected that the center of pressure path of a treated clubfoot may be abnormal (Brand, Laaveg, Crowninshield, & Ponseti, 1981; Cummings, Hay, McCluskey, Mazur, & Lovell, 1994; Huber & Dutoit, 2004; Laaveg & Ponseti, 1980). Center of pressure path results have consistently shown that the treated clubfoot demonstrates a significant lateral shift (Brand et al., 1981; Huber & Dutoit, 2004; Widhe & Berggren, 1994). This of course has important implications for the kinematics and kinetics of the treated clubfoot.

Since the treatment methods fix the deformity in different ways it is expected to see differences in the kinematics and kinetics. Kinematic and kinetic data analysis of locomotion has become a routine practice in clinical gait laboratories in order to focus and optimize rehabilitation management of gait disorders (Kerrigan & Glenn, 1994). A few studies have used gait analyses to evaluate clubfoot treatment effectiveness (C. T. Davies et al., 2001; El-Hawary et al., 2008; Karol et al., 1997; Karol et al., 2005; Karol et al., 2009).
2.4.1 Kinetics

There are several kinetic differences between the treated clubfoot and the normal clubfoot. For this literature review, the focus will be on differences in ground reaction forces and joint moments in all three planes for the PCT and CSR. There is agreement in the literature that there are significant differences observed in the ground reaction forces and joint moments of the ankle, knee and hip among feet treated with PCT and with CSR from typically developing feet.

2.4.1.1 Ground Reaction Forces

The ground reaction force is the force the ground exerts on the individual during the stance phase of gait, which is equal and opposite the force the individual applies to the ground. The ground reaction force can be resolved into three orthogonal components along a three-dimensional coordinate system: 1) vertical; 2) anteroposterior; and 3) mediolateral (Hamill & Knutzen, 1995).

The maximum vertical ground reaction force was significantly lower in both PCT and CSR-treated clubfeet (Widhe & Berggren, 1994). The anteroposterior ground reaction force is the force required for propulsion and braking. Davies and colleagues (T. C. Davies, Kiefer, & Zernicke, 2001) found the CSR treated clubfoot had reduced anterior ground reaction force and reduced ankle push-off power compared to normal. The PCT group demonstrated significantly greater push-off power than the CSR group, however the PCT group demonstrated values significantly lower than normal. PCT and CSR-treated feet had a 26.9% and 45.8% reduction in ankle push-off power, respectively (Church et al., 2012). Smith and colleagues (Smith et al., 2013) found there was a significant difference ($p<0.05$) in total ankle power throughout stance between CSR-
treated clubfeet and PCT-treated clubfeet (Figure 2.3). Karol and colleagues (Karol et al., 2009) found slightly similar results in that ankle push-off power of five-year old patients was reduced by 17% in PCT-treated feet and 30% in CSR-treated feet. The lack of ankle push-off power may be attributed to several factors that have important implications for the kinetic chain. Ankle range of motion is restricted due to joint stiffness. This prevents the subtalar joint from rapidly plantar flexing during pre-swing to push-off the ground (Smith et al., 2013). Torque acting around the ankle is reduced from weak musculature of the gastrocsoleus. It has been suggested that loss plantar flexion power and a reduction in gastrocsoleus strength is due to lengthening of the Achilles tendon (Karol et al., 1997). Lastly, overall abnormal foot structure could inhibit the effective transfer of forces through the mechanically linked forefoot, rearfoot and leg to more proximal segments (Smith et al., 2013).

Both treatment methods demonstrated an increased lateral ground reaction force when compared to normal (C. T. Davies et al., 2001; Widhe & Berggren, 1994). As mentioned previously, dynamic foot pressure data has shown increased stress along the fifth metatarsal (Aronson & Puskarich, 1990) and a lateral shift of the center of pressure (Widhe & Berggren, 1994) in the treated clubfoot.
2.4.1.2 Joint Moments

A joint moment is defined as the tendency of a force to cause a rotation about a joint axis. A moment may be calculated by multiplying the magnitude of the force with the perpendicular distance between the joint and the line of action of the force (moment arm). The net joint moment is the sum of individual moments produced by ground reaction forces, joint reaction forces and muscle and soft tissue forces. PCT and CSR-treated feet result in decreased ankle joint moments during stance in numerous studies at various lengths of follow up (Alkjaer et al., 2000; Church et al., 2012; C. T. Davies et al., 2001; Karol et al., 2009). The CSR-treated clubfeet exhibit decreased ankle adduction moments (C. T. Davies et al., 2001). Peak ankle plantar flexor moments are lower in the CSR group than normal (Beyaert et al., 2003). CSR-treated clubfeet demonstrate increased knee and hip moments when compared to controls at long term follow-ups (Alkjaer et al., 2000; C. T. Davies et al., 2001). Specifically, the CSR- treated clubfeet exhibit increased knee valgus moments and decreased knee varus moments (C. T. Davies
et al., 2001). An internal knee extension moment was shown to be higher in the CSR group compared to the CTR group at maximal knee flexion (Beyaert et al., 2003).

### 2.4.2 Kinematics

There is agreement in the literature that the treated clubfoot results in functional deficits in motion, most strikingly at the ankle (Church et al., 2012; C. T. Davies et al., 2001; El-Hawary et al., 2008; Karol et al., 1997).

A recent study by Church et al. (Church et al., 2012) examined the kinematics and kinetics of children treated for unilateral clubfoot by the PCT and CSR at an average follow up of 9.2 years. Church et al. (Church et al., 2012) found both the PCT and CSR-treated clubfeet demonstrate decreased ankle sagittal plane range of motion. CSR-treated clubfeet were found to have significantly decreased ankle plantar flexion peak angles (7.8° ± 6.5°) during gait compared to normal children (14.4°± 4.5°) (Church et al., 2012; C. T. Davies et al., 2001) whereas PCT-treated clubfeet demonstrate values closer to normal. Smith and colleagues (Smith et al., 2013) found similar results for reduced ankle plantar flexion angles in the PCT and CSR-treated clubfeet at long-term follow up (Figure 2.4.2.1), however no reduction of ankle dorsiflexion was found for either treatment group. Karol et al. (Karol et al., 1997) suggest that increased dorsiflexion during stance is suggested to be due to mild calcaneus deformity. Previously published studies report reduced sagittal plane range of motion at the ankle with diminished push-off power in the sagittal plane (Aronson & Puskarich, 1990; Church et al., 2012; C. T. Davies et al., 2001; Karol et al., 1997; Karol et al., 2009).
CSR-treated feet demonstrated reduced sagittal plane range of motion of the knee (Karol et al., 1997). CSR-treated feet demonstrated increased knee varus angles, decreased knee valgus angles and increased knee internal rotation (C. T. Davies et al., 2001).

CSR-treated clubfeet demonstrated increased hip external rotation during the support phase of stance while PCT-treated clubfeet exhibited values closer to normal (Church et al., 2012). Karol and colleagues found that PCT-treated feet demonstrated external hip rotation throughout stance (Karol et al., 2009). Church and colleagues (Church et al., 2012) found CSR-treated feet to have significantly less externally rotated foot progression angles than normal feet (p<0.01) and significant residual internal foot rotation (p<0.01). It has been suggested that increased external rotation of the hip in the CSR-treated clubfeet is a compensatory mechanism for internal rotation of their tibia and foot (Church et al., 2012). However, Smith and colleagues (Smith et al., 2013) found CSR-treated clubfeet to demonstrate persistent hip internal rotation throughout the gait. 

Figure 2.4: Ankle Flexion. Adapted from (Smith et al., 2013).
cycle when compared to control feet (p<0.001). They also found CSR-treated clubfeet to have more externally rotated foot progression angles at pre-swing than normal feet (p<0.001). The difference in hip rotation between the two studies may be due to the varying lengths of follow up.

Few studies in the literature have reported the multi-segment foot kinematics of the treated clubfoot. Smith and colleagues (Smith et al., 2013) reported a plantar flexion shift in hindfoot kinematics and a dorsiflexion shift in forefoot kinematics throughout the gait cycle for PCT and CSR-treated feet. Specifically, hindfoot ROM decreased from terminal stance to pre-swing. See Figure 2.5. It was suggested that the abnormal kinematics of the hindfoot and forefoot of the PCT and CSR-treated clubfeet was responsible for the appearance of normal ankle dorsiflexion throughout the stance phase (Smith et al., 2013). Multi-segment foot kinematics demonstrated reduced rearfoot varus/valgus range of motion in both PCT and CSR-treated feet (Church et al., 2012).
Figure 2.5: Multi-segment foot kinematics throughout the gait cycle. Adapted from (Smith et al., 2013).

2.4.3 Evaluation of Foot Function Summary

Radiographic, range-of-motion measurements and various scoring systems do not assess the dynamics of the foot during gait. These methods are therefore not good measures of long-term dynamic foot function nor are they reliable, accurate or
reproducible methods of assessment. However, kinematic and kinetic analysis of the treated clubfoot has offered insight into treatment outcome.

In summary, the literature on traditional kinematic and kinetic analyses of clubfoot has provided definitive results that clearly distinguish between clubfoot groups and healthy controls and between treatment methods. However, these studies have not lead to a clearer understanding of the pathological mechanisms that exist during walking in the feet treated with the PCT and the feet treated with CSR. It is therefore necessary to use more sensitive analyses to investigate the contributing factors that interact to produce the pathological mechanisms in order to assess the differences in treatment methods on dynamic foot function.

2.5 Dynamical Systems Approach to Coordination

Traditional biomechanical analysis in pediatric populations has focused on sagittal plane ankle, knee and hip angles and moments. In the foot, researchers have used single joint or single segment approach. Albeit valuable, these analyses neglect useful information in the data because single instant temporal events are identified a priori and within the gait cycle. The DSA approach macroscopically analyzes the many interacting mechanisms that may be responsible for the abnormal movement exhibited by feet treated with the PCT and feet treated with CSR.

2.5.1 Foundation for Coordination Analysis

The DSA approach differs in that it reflects the changes of joint or segment angular rotations relative to another joint or segment. Patterns of relative motion of the
segments of interest may be quantified by representing the system in a state space that is based on an angle-angle relative motion plot. For example, instead of plotting the angular displacements of the right thigh, $x$, and right shank, $y$, as a function of time, the angular displacement values for the thigh and shank may be plotted as coordinates of a point in the $x$-$y$ plane. This $(x,y)$ point is referred to as a state. As the thigh-shank angular displacement changes throughout the gait cycle, the point $(x,y)$ will form a curve in this plane. The state space of the system is the portion of the plane that represents all physically possible movements or postures and represents the relevant variables that characterize the behavior of the system (Callahan, 1995; Van Emmerik, Miller, & Hamill, 2013). The states in this proposed study will be typically developing (CTR), PCT-treated foot and CSR-treated foot.

2.5.2 Movement Coordination

Movement coordination is described as the mastering of redundant degrees of freedom of a system into a controllable unit (Bernstein, 1967). Reducing the number of redundant degrees of freedom to a more controllable level is accomplished by formation of coordinative structures between the neurons, muscles and joints. Each coordinative structure may function alone, however components of the structure may become functionally linked by forming temporary “couplings” that integrate to satisfy the movement task (Bernstein, 1967; Turvey, 1990).

For the purpose of this study, “coupling” refers to the interaction between segments or joints. It is implied that the motion of one segment can influence the motion of another segment. In normal lower extremity mechanics during walking, eversion of the subtalar joint is functionally linked to internal tibial rotation and external femoral
rotation. Also, inversion of the subtalar joint requires external tibial rotation and internal femoral rotation. Deviation from these coupled motions are said to be “asynchronous” and can result in injury (Hamill et al., 2012).

According to the Russian movement scientist Nicolai Bernstein, there are two important components to analyzing a movement. First, it is the relationship between parts of a system that are of key importance and not only the investigation of the parts separately. This is due to the fact that the numerous degrees of freedom of the body may be organized in a large number of ways in order to produce the same coordination pattern. As there are such a large number of degrees of freedom, variability in the formation of these coordinative structures seems to be inevitable. Therefore, the second important component is that variability is of utmost importance as it provides a measure related to the variety of combinations used to maintain the coordinative structures (Bernstein, 1967; Davis & Burton, 1991; Hamill et al., 2012). For the purpose of this study, we will investigate coordination variability as an indicator of the possible differences in dynamic function between the typically developing, PCT-treated and CSR-treated feet.

2.5.3 Multi-segment Foot Coordination and Vector Coding

Single segment foot models are inaccurate for clinical decision making for patients with foot impairments. With recent advances in the accuracy and resolution of motion capture systems it is now possible to track a large number of foot segments during gait. The multi-segment foot model quantifies the dynamic, intrinsic motion of the foot and has been used to quantify foot deformity in a variety of diagnoses (Church et al., 2012). Therefore, a multi-segment approach is essential in order to analyze the
coordination of the lower extremity in the treated clubfoot, since the deformity affects the movements of the joints of the foot.

The coordination between the rearfoot and the forefoot is more complicated than previously described. Chang et al. (Chang et al., 2008) proposed the quantification of the coordination of the rearfoot-forefoot using vector coding as a method to analyze the interactions between the foot segments. This approach utilizes segment angle-angle plots to assess the relative motion between the angular time series of two joints or segments. The coordination of two segments may be inferred by calculating a coupling angle between consecutive data points in the segment angle-angle plots. Coupling angles are calculated from vectors connecting two consecutive time points (Figure 2.6) (Chang et al., 2008). The coordinative patterns between the two segments may be summarized through a set of operational terms: in-phase (IP), anti-phase (AP), distal phase (DP) and proximal phase (PP).

Figure 2.6: Angle-angle diagram of the intralimb thigh-leg angular relative motion in the sagittal plane during walking. i represents consecutive data points in the cycle and \( \gamma_i \) represents the coupling angle. Adapted from (Van Emmerik et al., 2013).
2.5.4 Coordination Variability

When performing a repetitive movement in a multiple degree of freedom system, variability in the performance of the movement is to be expected. Iterations of the movement will result in slightly varied patterns of motion of each body segment. Therefore, coordination variability pertains to the range of coordinative patterns that the body displays while performing a movement task. Coordination variability may be quantified as the between-trial or between-gait cycle standard deviation of the movement (Van Emmerik et al., 2013).

The functional role of coordinative variability may be emphasized by using a DSA perspective in the investigation of overuse injuries. In a study by (Hamill et al., 1999), coordinative variability was assessed in individuals with and without knee pain. It was reported that greater coordinative variability was normal for a healthy individual. However, lower coordinative variability was normal for individuals with knee pain. Hamill et al. (Hamill et al., 1999) proposed that the healthy individual had the potential for higher coordinative variability because there were numerous combinations of intra-segment coordination available. However, in an injured individual, the number of combinations is reduced and thus the coordinative variability is significantly reduced. The loss of available degrees of freedom and resulting loss of variability due to injury or disease is explained by the loss of complexity hypothesis based on the work of (Lipsitz, 2002). This hypothesis is demonstrated in Figure 2.7. In a similar study, tibial stress fractures in female runners were compared to healthy, matched controls (Hamill, Haddad, Milner, & Davis, 2005). It was concluded that the coordination variability in the injured limb was significantly less than in the non-injured limb. There was no difference in
coordination variability between limbs of the control subjects. Further, it has been demonstrated that coordinative variability measures are able to discriminate between injured and non-injured groups. In a study by Seay et al. (Seay et al., 2011), coordinative variability measures demonstrated a distinction between runners with low back pain (LBP group), those recovered from low back pain (RES group), and those who never experienced low back pain (CTR group). Exemplar pelvis-trunk angle-angle plots and the resulting coupling angles are demonstrated in Figure 2.8. These findings suggest that longitudinal coordinative variability research can help determine the progress of recovery from an injury or the progression towards an injured state (Hamill et al., 2012).

Figure 2.7: Loss of complexity hypothesis. (a) Reductions in available degrees of freedom over time are associated with reductions in variability (b). Injury or disease may occur when reductions in degrees of freedom and variability reach a critical threshold. Adapted from (Van Emmerik et al., 2013).
Figure 2.8: Pelvis and trunk axial rotation angle-angle and coordination plots of one participant from each group. ‘+’ demonstrates the beginning of the gait cycle and the arrow demonstrates the direction of progression. CTR-control; RES- resolved back pain; LBP- low back pain. Adapted from (Seay et al., 2011)

2.6 Chapter Summary

The clubfoot deformity is characterized by four primary components: 1) equinus; 2) hindfoot varus; 3) forefoot adductus; and 4) forefoot cavus (Ponseti, 1992). The PCT and CSR are the two standard treatment procedures for the clubfoot deformity. The PCT utilizes a progressive series of well-molded plaster casts and gentle manipulations to correct the inverted, supinated foot during infancy, followed by percutaneous heel cord lengthening to correct the foot equinus and post casting orthotics (Ponseti, 1992). The
CSR is an invasive surgical procedure that involves the release of the posterior and medial ligamentous structures surrounding the ankle joint (Atar et al., 1992).

Differences in foot function outcome between the two techniques have been evaluated using a variety of methods. Much of the literature on the evaluation of clubfoot treatment effectiveness has used radiographic measurements, pedobarography, range of motion, or by various scoring systems. These measures do not assess the dynamics of the foot during gait therefore are not good measures of long term foot function nor are they reliable, accurate or reproducible methods of assessment. However, center of pressure path results have consistently shown that the treated clubfoot demonstrates a significant lateral shift and thus has important implications for the kinematics and kinetics of the treated clubfoot.

The literature has established that kinetic and kinematic differences exist between treatment techniques and normal feet. Therefore, it is to be expected that there may be differences in coordination patterns and coordination variability of the lower extremity segments between treatment groups and normal. The main components that are of key importance in the analysis of a movement in the DSA approach is the relationship between parts of a system and the variability of the motions. This study will utilize a multi-segment foot model and vector coding technique to analyze the interactions between the foot segments.
CHAPTER 3  

METHODS  

3.1 Introduction  

The purpose of this study was to quantify segmental/joint kinematics and kinetics and to determine the lower extremity coordination and coordination variability, specifically of the rearfoot and forefoot, during walking in individuals treated with either the PCT or CSR 5-7 years after treatment.  

3.2 Participants  

An “a priori” sample size calculation assuming a medium effect size (ES=0.5), yielded a necessary sample of n=12-16 in order to achieve statistical significance for the collected variables ($\alpha$=0.05, $\beta$=0.20). The sample size calculation was based on specific primary variables from multiple sources (Chang et al., 2008; Church et al., 2012; Heiderscheit, Hamill, & Caldwell, 2000). Based on these calculations, we should have used 15 participants in each of the three groups of children. However, because of the difficulty in recruiting clubfoot participants, we used 10 in each of the two groups and 7 in the other group. The three groups consisted of: 1) children with a primary diagnosis of unilateral idiopathic clubfoot treated with the PCT; 2) children with a primary diagnosis of unilateral Idiopathic clubfoot treated with the CSR; and 3) typically developing children with no history of clubfoot age matched with the experimental groups. The children previously treated for clubfoot were 5-7 years post treatment. This range in years post-treatment was chosen because the last CSR procedure was done 7 years ago at Shriners Hospitals for Children in Springfield, MA.
The children with clubfoot were recruited from the clubfoot outpatient clinic at Shriners Hospitals for Children in Springfield, MA. The same doctor treated all children with clubfoot. The typically developing children were recruited from a local school system, the siblings of patients with clubfoot at Shriners Hospitals for Children, and the children of employees and friends of employees of Shriners Hospitals for Children and the University of Massachusetts Amherst. Participants were to be able to walk at least 50 feet without assistance or pain and able to comply with instructions to be included in this study. Participants were excluded if further treatment for clubfoot was anticipated, pain at time of data collection, current use of braces/orthoses or if there was a history of other major orthopedic deformities or surgeries.

Children with clubfoot were prescreened through review of their electronic medical record to assess eligibility. All participants read and signed an age appropriate assent form and the guardian of the participant read and signed the informed consent. The parent/guardian completed a Physical Activity Readiness Questionnaire (PAR-Q) and completed a lower extremity injury history.

### 3.3 Experimental Setup

Several different measurement systems were used to collect kinematic and kinetic data necessary to complete this study. All collections took place in the Motion Analysis Laboratory at the Shriners Hospitals for Children in Springfield, MA.
3.3.1 Camera Setup

Ten infrared cameras (Vicon T40S, Vicon, Centennial, CO) sampled at 240 Hz were used to collect the 3D kinematic data. The cameras surrounded the walkway over which the participants walked and were placed such that each marker on the participant was visible in at least two cameras. A calibration of the camera system was performed using a known-distance T-wand with an L-bracket placed at the lab coordinate system origin.

3.3.2 Marker Setup

The participants were fitted with 51 retro-reflective markers that were tracked by the ten infrared cameras. 10 mm diameter reflective markers were placed bilaterally on the participant to track the motion of the lower extremities and pelvis (Dierks, Manal, Hamill, & Davis, 2011). Reflective markers were placed on the pelvis at the right anterior superior iliac spine, right iliac crest, and the L5-S1 interspace and bilaterally at the sites of: the medial and lateral malleoli, the medial and lateral femoral condyles and greater trochanters (Figure 3.1). The anatomical coordinate systems were developed from the position of these markers. Reflective markers were securely placed bilaterally on the participant’s thigh and leg using clusters of four non-colinear markers on rigid plates. The anatomical markers of the pelvis also served as tracking markers.
Reflective markers (8 mm diameter) were also fixed to the skin of the foot (bilateral) according to a multi-segment foot model (Leardini et al., 2007). Foot motion was measured with a multi-segment foot model that allowed the calculation of the position and orientation of four (assumed) rigid segments: 1) shank: tibia and fibula, 2) foot: all bones, 3) rearfoot: calcaneus, 4) forefoot: five metatarsal bones. The proximal phalanx of the hallux, was taken as an independent line segment. Coordinate system constructions for the shank, foot, rearfoot, forefoot and hallux line segment were right-handed, and were constructed according to the original model (Figure 3.2). Forefoot and rearfoot segments were constructed from anatomically placed skin markers (Leardini et al., 2007) (first metatarsal (FM), second metatarsal (SM), head (H), base (B), peroneal tubercle (PT), sustenaculum tali (ST), calcaneus (CA)). The forefoot’s origin was located at SMB and the X-axis was the projection of the line joining SMB and SMH on the transverse plane passing through the origin and FMH and VMH. The forefoot’s Y-axis
was orthogonal to X and lied in this transverse plane. The forefoot’s Z-axis was orthogonal to the XY plane. The rearfoot’s origin was located at CA and the X-axis was aligned to a midpoint between ST and PT. The rearfoot’s Y-axis was aligned to a transverse plane defined by rearfoot X-axis and the ST. The rearfoot’s Z-axis was orthogonal to the rearfoot’s XY plane. The shank was defined by the medial and lateral femoral epicondyles (proximal segment definition markers) and the medial and lateral malleoli (distal segment definition markers). Clusters of four markers were fixed to the distal-lateral shank. The static positions of the four cluster markers were associated with the segment definition markers and thus, the cluster markers were used to track shank movements. The origin of the shank was located at the midpoint between the medial and lateral malleoli (Y-axis oriented to medial malleolus; Z-axis oriented proximally to midpoint between medial and lateral femoral epicondyles; Y-axis was orthogonal to Y and Z, and oriented to the anterior direction (line of walking progression)).

Pilot data demonstrated the inter-day and inter-trial reliability of the multi-segment foot model on children ages 8-10 during walking using the Coefficient of Multiple Correlation (Ferrari, Cutti, & Cappello, 2010). The coefficient ranged from 0.88 to 0.99 for the flexion-extension, abduction-adduction and internal-external rotation angles. A coefficient of 0.5 is considered sufficient for repeatability of measurement.

### 3.3.3 Force Platforms

In order to collect the kinetic data, the walkway was embedded with two force platforms (AMTI, Watertown, MA). Force data were sampled at 1080 Hz and was
collected via Vicon Nexus Software (Vicon, Centennial, CO) on the same computer as the motion capture data. Thus, the force and motion capture data were synchronized in time.

Figure 3.2: Multi-segment foot model consisting of three dimensional shank, foot, forefoot, rearfoot and a two-dimensional hallux line segment (Leardini et al., 2007). Transverse planes (dash-dot triangles) and X- and Y-axes (solid arrows) on these planes are shown, corresponding Z-axes pointing proximally. b) Lateral view of the shank and foot. c) Medial view of the shank and foot. Head of the proximal phalanx of the hallux (PM), first metatarsal (FM), second metatarsal (SM), head (H), base (B), peroneal tubercle (PT), sustenaculum tali (ST), calcaneus (CA), lateral malleolus (LM) and medial malleolus (MM).

3.3.4 Walking Velocity

Walking velocity was measured using two infrared timing gates at a known distance apart, connected to an electronic clock.
3.4 Experimental Protocol

This study consisted of one data collection session involving a full gait analysis. Initially, the participant was familiarized to the protocol and the guardian of the participant read and signed the informed consent, completed a PAR-Q and completed a lower extremity injury history. Demographics were collected to evaluate differences in age, weight, and sex. Participants read and signed an age appropriate assent form.

An explanation and practice of the walking procedure was given before the gait analysis protocol so that the participant had a clear understanding of the experimental protocol. Prior to the motion capture trials, a barefoot neutral standing calibration trial (feet, shoulders, and hips pointed straight in the walking direction) was captured. One complete stride of the left and right lower extremities per walking trial was captured. Participants then completed two barefoot walking conditions for the kinematic and kinetic data collection: 1) preferred walking velocity; and 2) fixed walking velocity at 1.0 m/s-1 (±5%). A successful trial was one in which the participant contacted the force platform at the required locomotor velocity. At least five complete strides of the left and right lower extremities were captured for each condition.

A Visual Analog Scale (VAS) based on a 10 mm range was used to evaluate participant pain during the study. If the participant complained of pain in excess of 8 mm on a 10 mm scale during study procedures, the visit was to be discontinued and a recommendation was to be made for the participant to visit his primary care physician as follow up.
3.5 Data Analysis

The primary dependent variables to test our first hypotheses were: 1) sagittal plane range of motion (ROM) of the metatarsal-phalangeal (MTP) joint; 2) 3D joint ROM of the forefoot-rearfoot, ankle, knee and hip and 3) 3D peak ankle, knee and hip joint moments in the last 50% of stance. Secondary outcomes consisted of: 1) stride length; 2) stride time; 3) stance time; and 4) dual limb support time.

The primary dependent measures to test the 2nd and 3rd hypotheses included the coordination pattern frequency count values of the: 1) forefoot-rearfoot inversion/eversion coupling (Ff-Rf); 2) rearfoot inversion/eversion-tibial internal/external rotation coupling (Rf-Tib); and 3) femur-tibia internal/external rotation (Fem-Tib). The primary dependent measures to test the 4th and 5th hypotheses included the coordination variability of the segment coordination couplings of interest.

For all experimental groups, data were collected bilaterally and for both walking velocity conditions (preferred and fixed), but once the data collection stage was complete for the entire study, only the fixed walking velocity condition (1.0 m/s ±5%) and the affected limb were analyzed for all experimental groups and for all variables of interest. For CTR participants and bilateral clubfoot participants, the right limb was selected as the affected limb. Marker positions were tracked using Vicon Nexus software (Vicon, Centennial, CO). Kinematic and kinetic data were filtered using a fourth order, zero-lag Butterworth digital low-pass filter with a cutoff frequency of 6 Hz and 30 Hz, respectively. Model building and further data processing were performed in Visual 3D
analysis software (C-Motion Inc., Germantown, MD). Bilateral 3D joint angles and moments for the ankle, knee and hip were calculated. Joint angles were calculated following the right-hand rule with respect to the proximal segment using a Cardan YXZ rotation sequence, a sequence representing abduction/adduction (X), flexion/extension (Y) and axial rotation (Z) (Cole, Nigg, Ronsky, & Yeadon, 1993). 3D segment angles for the thigh, shank, rearfoot and forefoot were also calculated. Segment angles were calculated relative to the laboratory coordinate system (X-line of walking progression; Y-medio-lateral; Z-vertical) using a Cardan YXZ rotation sequence. Segment angles were interpolated and normalized to 101 data points for each stance phase. A sagittal plane MTP joint angle (dorsi/plantar flexion) derived by computing the angle between two vectors lying in the XZ plane, represented by the first metatarsal head, base and hallux markers. Stance was identified using the vertical ground reaction force data and a 15 N threshold. Visual 3D joint angles were normalized to angles obtained in the standing calibration position. Ground reaction force, kinematic and anthropometric data were combined using a Newton-Euler inverse dynamics procedure to calculate 3D joint moments for the hip, knee and ankle (Bresler & Frankel, 1950). The joint moments in this investigation will be reported as internal resultant moments. Joint angles and moments and segment angles were interpolated and time scaled to 100% of stance.

3.5.1 Range of Motion

To test the primary dependent variables for the first hypothesis, 3D forefoot-rearfoot, ankle, hip and knee joint and sagittal plane MTP joint range of motion (ROM)
were determined. To determine the ROM during the stance phase for each variable of interest, the minimum value was subtracted from the maximum value for each stance phase in all planes and averaged across five stance phases for each affected limb. Group ROM averages and standard deviations were calculated by including all stance phases per group in all planes of motion.

3.5.2 Peak Moment

Peak moment about each axis for each joint was determined as the largest moment (either positive or negative) during the push-off phase of the support period. Push-off was determined as occurring in the last 50% of support.

3.5.3 Stride Parameters

The stride parameters of interest consisted of: 1) stride length; 2) stride time; 3) stance time; and 4) dual limb support time. Stride parameters were calculated using Visual 3D software (C-Motion Inc., Germantown, MD). Stride length was defined as the distance between successive points of initial contact (heelstrike) of the same foot. Stride time was defined as the time between successive points of heelstrike of the same foot. Stance time was defined as the time between heelstrike and toe-off of the same foot. Dual limb support time was defined as the time between heelstrike of one foot and toe-off of the contralateral foot. Group stride parameter averages were determined by averaging across all stance phases for each limb per group for each walking velocity. Group standard deviation values were also calculated.
3.5.4 Coordination Analysis

A custom MATLAB program was written to calculate coupling (coordination) angles for the Ff-Rf, Rf-Tib and Fem-Tib couples using a modified vector coding technique (Chang et al., 2008). Segment angle-angle plots were generated over the complete stride cycle. A vector drawn between two adjacent time points on the angle-angle plot for leg-thigh and leg-foot coordination was used to derive the coupling angles (γ) in all three planes of movement. Coupling angles were calculated by:

\[ \gamma_{j,i} = \tan^{-1} \left( \frac{y_{j,i+1} - y_{j,i}}{x_{j,i+1} - x_{j,i}} \right) \]

Where 0 ≤ γ ≤ 360°, i is a percent stance of the jth trial, and “i,j+1” and “i, j” are subscripts of the x and y coordinates. Coupling angles were determined relative to the right horizontal and calculated by the vertical, horizontal, and 45° diagonals of a unit circle. Coupling angles were categorized into one of four coordination patterns: in-phase (IP), anti-phase (AP), proximal phase (PP), and distal phase (DP). Segments rotating in the same direction exhibited IP coordination and were indicated by a coupling angle of 202.5° ≤ γ < 247.5° (coupling angle lies on the positive diagonal). AP coordination indicated the segments were rotating in opposite directions and was signified by a coupling angle of 0 ≤ γ < 22.5°, 157.5° ≤ γ < 202.5° (horizontally directed coupling angle). Exclusive proximal segment rotation (PP) indicated the proximal segment was rotating and the distal segment was not. PP was designated by a coupling angle of 0 ≤ γ < 22.5°, 157.5° ≤ γ < 202.5°, 337.5° ≤ γ ≤ 360° (horizontally directed coupling angle). Exclusive distal segment rotation (DP) indicated only the distal segment was rotating while the proximal
segment was not. This coordination pattern was designated by a coupling angle of $67.5^\circ \leq \gamma < 112.5^\circ$, $247.5^\circ \leq \gamma < 292.5^\circ$ (vertically directed). The coupling angles for five stances were calculated for each participant.

Because the vector coding parameters were directional data, circular statistics were used to calculate the circular mean and standard deviation of the coupling angles over early (0-33%), mid-(34-67%) and late stance (68-100%) across the five trials for each participant (Batschelet, 1981). The circular standard deviation of the coupling angle across the five trials per participant was used to determine the between-trial coordination variability. Coordination patterns were inferred by categorizing the mean coupling angle of each participant into 45° bins of a 360° unit circle (Table 3.1) (Chang et al., 2008). Frequency count values of each coordination pattern were derived by counting the number of occurrences AP, IP, DP and PP for each couple throughout early, mid- and late stance for each participant. The arithmetic mean of the frequency count values were calculated to obtain group coordination frequency counts values for early, mid- and late stance.

The arithmetic mean of the mean coupling angle for each participant was calculated to obtain the group mean phase angles for each speed. The arithmetic standard deviation of the group averaged mean coupling angle was calculated to obtain the group coordination variability.
Table 3.1: Coordination pattern categorization

<table>
<thead>
<tr>
<th>Coordination Pattern</th>
<th>Coupling angle definitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anti-phase</td>
<td>112.5° ≤ γ &lt; 157.5°, 292.5° ≤ γ ≤ 337.5°</td>
</tr>
<tr>
<td>In-phase</td>
<td>22.5° ≤ γ ≤ 67.5°, 202.5° ≤ γ ≤ 247.5°</td>
</tr>
<tr>
<td>Proximal phase</td>
<td>0° ≤ γ &lt; 22.5°, 157.5° ≤ γ ≤ 202.5°, 337.5° ≤ γ ≤ 360°</td>
</tr>
<tr>
<td>Distal phase</td>
<td>67.5° ≤ γ &lt; 112.5°, 247.5° ≤ γ &lt; 292.5°</td>
</tr>
</tbody>
</table>

3.6 Statistical Analysis

A one-way analysis of variance (ANOVA) was used to compare the kinematic, kinetic, coordination and coordination variability primary dependent variables between groups. A criterion alpha level of 0.05 was used for all statistical tests. A post hoc Tukey test was employed where it was appropriate. Effect sizes (ES) were calculated between the groups for the dependent variables to supplement the interpretation of statistically significant results. ES is estimated as the difference between two means over a pooled variance and thus was used to assess the clinical relevance of a difference between means. Typically when comparing two means within biological systems, an ES greater than 0.5 represents clinically relevant differences (Cohen, 1988).

3.7 Summary

The purpose of this study is examine group differences in lower extremity segmental/joint kinematics, kinetics and to determine the lower extremity coordination and coordination variability, specifically of the rearfoot and forefoot, during walking in individuals treated with either the PCT or CSR 5-7 years after treatment. To accomplish this, kinetic and kinematic data were collected and compared between groups. Kinematic
data will be used to conduct coordination analyses of the multi-segment and lower extremity segments that will be compared between groups. This study will be the first study to characterize the coordination patterns and quantify the coordination variability of the multi-segment foot and lower extremity segments during walking in typically-developing children and in children with a clubfoot. As there is still not a clear understanding of the biomechanical and functional differences, of the foot specifically, between PCT, CSR and CTR feet; the results of this study will demonstrate the outcomes of dynamic foot function to differentiate how individuals treated with PCT or CSR have adapted in response to the radically different interventions. This information will provide a scientific basis for the development of targeted treatments and rehabilitation strategies for clubfoot.
CHAPTER 4
MULTI-SEGMENT FOOT KINEMATICS AND KINETICS OF THE TREATED CLUBFOOT

4.1 Introduction

Clubfoot is a common congenital three-dimensional (3D) deformity of the foot occurring in approximately three in every 1,000 live births (Wynne-Davies, 1972). The initial deformity consists of four primary components: 1) equinus; 2) hindfoot varus; 3) forefoot adductus; and 4) forefoot cavus and presents a wide spectrum of severity at birth (Dobbs et al., 2004). Correction of the deformity may be achieved by surgical and/or non-surgical intervention where the goal of successful clinical intervention is to restore function or to provide alternate movement strategies for pain-free gait (Ponseti, 1992).

There are two primary treatments that are used to correct clubfoot: 1) comprehensive surgical release (CSR); and 2) Ponseti casting technique (PCT). CSR is an invasive surgical procedure that involves the release of the posterior and medial ligamentous structures surrounding the ankle joint. CSR-treated feet report poor outcomes in 9-73% of cases and twenty-five percent of patients have a recurrent deformity that requires additional surgical releases, tendon lengthenings, osteotomies and selective joint fusions to correct the residual deformity (Atar et al., 1992; Lehman et al., 2003; Lehman, 1980; Viskelety & Szepesi, 1989). Long-term follow up based on various grading systems, radiographs, passive range of motion scores and questionnaires report increased pain and functional limitations, stiffness, weakness and premature arthritis in CSR-treated feet (Dobbs et al., 2006; Herzenberg et al., 2002).
PCT utilizes a progressive series of well-molded long-leg plaster casts, percutaneous heel cord lengthening and at least two years of a foot abduction orthosis (Ponseti, 1997a; Ponseti & Smokey, 2009). PCT-treated feet report poor outcomes in 42-89% of cases (Crawford & Gupta, 1996; Haft et al., 2007; Halanski et al., 2009; Harrold & Walker, 1983; Herzenberg et al., 2002; Laaveg & Ponseti, 1980). Long-term follow-up studies reveal that as many as forty percent of patients require further operative treatment to correct a recurrence and, when compared to typically-developing feet, PCT-treated feet report an increased prevalence of osteoarthritis, lower SF-36 physical functioning subscores and restricted motion at the foot, ankle and knee (Crawford & Gupta, 1996; Haft et al., 2007; Halanski et al., 2009; Harrold & Walker, 1983; Herzenberg et al., 2002; Laaveg & Ponseti, 1980).

Treatment of clubfeet has catalyzed much controversy in the literature. The etiology is unknown, the pathological anatomy is complex and long-term follow-ups are rare. Currently, the PCT is the standard of care for clubfoot correction due to the noninvasive approach and promising clinical and functional outcomes compared to CSR (Ponseti, 1992; Zionts et al., 2010). Numerous studies have contributed to the assessment of clubfoot treatment outcomes; however, a comprehensive literature search reveals large variability in ranges of reported positive outcomes. It is difficult to make comparisons between these studies due to varying lengths of follow-up, assessment methods used, primary outcome selection and levels of severity of the initial deformity. Many of the assessment methods used do not accurately correlate with dynamic function and additionally, are not reliable, accurate nor are reproducible methods of functional assessment (Huber & Dutoit, 2004; Ponseti, 1996).
Several studies in the literature have made attempts to objectively assess the functional status of children treated for clubfoot using gait analysis (Alkjaer et al., 2000; Beyaert et al., 2003; Church et al., 2012; C. T. Davies et al., 2001). Compared to typically-developing children, PCT and CSR-treated feet demonstrate reduced sagittal plane ankle and knee range of motions (Church et al., 2012; C. T. Davies et al., 2001; Smith et al., 2013). The treated clubfeet also demonstrate lesser ankle joint moments but greater knee and hip moments (Alkjaer et al., 2000; Church et al., 2012; C. T. Davies et al., 2001; Karol et al., 2009). PCT-treated feet consistently demonstrate values more closely to typically-developing feet than CSR-treated feet in all kinematic and kinetic comparisons. Although valuable, these studies were limited to modeling the foot as a single rigid segment and do not provide accurate information about the dynamic function of the foot.

Since the forefoot, rear foot and leg are mechanically linked, residual deformity or any dysfunction at the foot and ankle could be responsible for compensatory movement strategies and alterations to the proximal joints in the kinetic chain (Church et al., 2012; Mann & Hagy, 1980). Few studies have reported the multi-segment foot kinematics of the treated clubfoot. Reduced range of motion (ROM) of the rearfoot in relation to the tibia has been reported in CSR-treated feet (Smith et al., 2013). Although informative, these studies have not led to a clear understanding of the biomechanical and functional differences, of the foot segments specifically, between PCT-treated feet, CSR-treated clubfeet and typically developing-feet.
Therefore, the purpose of this study was to examine group differences in multi-segment foot and lower extremity kinematics and kinetics during walking in individuals treated with either the PCT or CSR 5-7 years after treatment compared to a healthy non-involved group (CTR). We hypothesized that there will be significant group differences (PCT vs. CSR vs. CTR) in rearfoot-forefoot, metatarsophalangeal (MTP), ankle, knee and hip joint ROM as well as significant group differences in ankle, knee and hip peak joint moments in the last 50% of stance.

4.2 Materials and Methods

4.2.1 Participants

The New England and University of Massachusetts Amherst Institutional Review Boards approved the study. All participants were between 5 and 21 years, able to walk at least fifty feet without assistance or pain and were able to comply with instructions. Participants were evaluated retrospectively and were assigned to one of three groups: 1) participants with a history of a clubfoot treated with the PCT; 2) participants with a history of a clubfoot treated with the CSR; and 3) typically-developing participants with no history of a clubfoot. Clubfoot inclusion criteria included a primary diagnosis of idiopathic congenital Talipes Equinovarus and a minimum follow-up (post-treatment) of 5 years. All children seen as patients in the outpatient orthopedic clinic at Shriners Hospitals for Children in Springfield, MA were pre-screened through review of electronic medical records to assess eligibility. Children that fit the criteria and were treated with
either the PCT or CSR were contacted. CTR participants had no history of a clubfoot and were recruited from employees and friends of employees of Shriners Hospitals for Children in Springfield, MA. Prior to participation, all participants read and signed an age appropriate consent form and completed a Modified Physical Activity Readiness, Lower Extremity Injury History and Demographics questionnaire (completed with the help of parents/guardians). Participants were excluded if further treatment for clubfoot was anticipated, pain at time of data collection, current use of braces/orthoses or if there was a history of other major orthopedic deformities or surgeries.

4.2.2 Experimental Setup

3D kinematic and kinetic data were collected using ten infrared cameras (Vicon T40S, Vicon, Centennial, CO) sampled at 240 Hz and two embedded force platforms (AMTI, Watertown, MA) sampled at 1080 Hz. Walking velocity was measured using two infrared timing gates at a known distance apart, connected to an electronic clock. Kinematic and kinetic data were collected on the same computer and were thus synchronized in time.

4.2.3 Protocol

Anthropometric data were measured before the gait analysis was conducted. Reflective markers (10 mm diameter) were then placed bilaterally to track the motion of the lower extremities and pelvis (Dierks et al., 2011). Reflective markers were placed on the pelvis at the right anterior superior iliac spine, right iliac crest, and the L5-S1
interspace and bilaterally at the sites of: the medial and lateral malleoli, the medial and lateral femoral condyles and greater trochanters (Figure 4.1). The anatomical coordinate systems were developed from the position of these markers. Additional tracking markers were placed using clusters of four markers on the femur and shank. The anatomical markers of the pelvis also served as tracking markers.

![Figure 4.1: Bilateral lower extremity marker placement.](image)

Reflective markers (8 mm diameter) were also fixed to the skin of the foot (bilateral) according to a multi-segment foot model (Leardini et al., 2007). Pilot data demonstrated the inter-day and inter-trial reliability of the multi-segment foot model on children ages 8-10 during walking using the Coefficient of Multiple Correlation (Ferrari, Cutti, & Cappello, 2010). The coefficient ranged from 0.88 to 0.99 for the flexion-extension, abduction-adduction and internal-external rotation angles. A coefficient of 0.5 is considered sufficient for repeatability of measurement. The multi-segment foot model allowed the calculation of the position and orientation of four (assumed) rigid segments: 1) shank: tibia and fibula, 2) foot: all bones, 3) rearfoot: calcaneus, 4) forefoot: five
metatarsal bones. The proximal phalanx of the hallux, was taken as an independent line segment. Coordinate system constructions for the shank, foot, rearfoot, forefoot and hallux line segment were right-handed, and were constructed according to the original model (Leardini et al., 2007) (Figure 4.2).

Forefoot and rearfoot segments were constructed from anatomically placed skin markers (Leardini et al., 2007) (first metatarsal (FM), second metatarsal (SM), head (H), base (B), peroneal tubercle (PT), sustenaculum tali (ST), calcaneus (CA)). The forefoot’s origin was located at SMB and the X-axis was the projection of the line joining SMB and SMH on the transverse plane passing through the origin and FMH and VMH. The forefoot’s Y-axis was orthogonal to X and lied in this transverse plane. The forefoot’s Z-axis was orthogonal to the XY plane. The rearfoot’s origin was located at CA and the X-axis was aligned to a midpoint between ST and PT. The rearfoot’s Y-axis was aligned to a transverse plane defined by rearfoot X-axis and the ST. The rearfoot’s Z-axis was orthogonal to the rearfoot’s XY plane. The shank was defined by the medial and lateral femoral epicondyles (proximal segment definition markers) and the medial and lateral malleoli (distal segment definition markers). Clusters of four markers were fixed to the distal-lateral shank. The static positions of the four cluster markers were associated with the segment definition markers and thus, the cluster markers were used to track shank movements. The origin of the shank was located at the midpoint between the medial and lateral malleoli (Y-axis oriented to medial malleolus; Z-axis oriented proximally to midpoint between medial and lateral femoral epicondyles; Y-axis was orthogonal to Y and Z, and oriented to the anterior direction (line of walking progression)).
Figure 4.2: Multi-segment foot model consisting of three dimensional shank, foot, forefoot, rearfoot and a two-dimensional hallux line segment (Leardini et al., 2007). Transverse planes (dash-dot triangles) and X- and Y-axes (solid arrows) on these planes are shown, corresponding Z-axes pointing proximally. b) Lateral view of the shank and foot. c) Medial view of the shank and foot. Head of the proximal phalanx of the hallux (PM), first metatarsal (FM), second metatarsal (SM), head (H), base (B), peroneal tubercle (PT), sustenaculum tali (ST), calcaneus (CA), lateral malleolus (LM) and medial malleolus (MM).

With the retroreflective markers affixed to the lower extremities, a barefoot neutral standing calibration trial (feet, shoulders, and hips pointed straight in the walking direction) was captured. Prior to the kinematic and kinetic data collection, participants were given instructions for the walking procedures and were able to perform practice walking trials. Participants then completed two barefoot walking conditions: 1) preferred walking velocity; and 2) fixed walking velocity at 1.0 m/s-1 (±5%). A successful trial was one in which the participant contacted the force platform at the required locomotor
velocity. At least five complete strides of the left and right lower extremities were captured for each condition.

A Visual Analog Scale (VAS) based on a 10 mm range was used to evaluate participant pain during the study. If the participant complained of pain in excess of 8 mm on a 10 mm scale during study procedures, the visit was to be discontinued and a recommendation was to be made for the participant to visit his primary care physician as follow up.

4.2.4 Data Reduction

For all experimental groups, data were collected bilaterally and for both walking velocity conditions (preferred and fixed), but once the data collection stage was complete for the entire study, only the fixed walking velocity condition (1.0 m/s-1 ±5%) and the affected limb were analyzed for all experimental groups and for all variables of interest. For CTR participants and bilateral clubfoot participants, the right limb was selected as the affected limb. Marker positions were tracked using Vicon Nexus software (Vicon, Centennial, CO). Kinematic and kinetic data were filtered using a fourth order, zero-lag Butterworth digital low-pass filter with a cutoff frequency of 6 Hz and 30 Hz, respectively. Model building and further data processing were performed in Visual 3D analysis software (C-Motion Inc., Germantown, MD). Bilateral 3D joint angles and moments for the ankle, knee and hip were calculated. Joint angles were calculated following the right-hand rule with respect to the proximal segment using a Cardan YXZ rotation sequence, a sequence representing abduction/adduction (X), flexion/extension.
(Y) and axial rotation (Z) (Cole et al., 1993). A sagittal plane MTP joint angle (dorsi/plantar flexion) derived by computing the angle between two vectors lying in the XZ plane, represented by the first metatarsal head, base and hallux markers. Stance was identified using the vertical ground reaction force data and a 15 N threshold. Visual 3D joint angles were normalized to angles obtained in the standing calibration position. Ground reaction force, kinematic and anthropometric data were combined using a Newton-Euler inverse dynamics procedure to calculate 3D joint moments for the hip, knee and ankle (Bresler & Frankel, 1950). Joint angles and moments were interpolated and time scaled to 100% of stance.

4.2.4.1 Range of Motion

To test the primary variables for our hypothesis, 3D forefoot-rearfoot, ankle, knee, and hip joint and sagittal plane MTP joint range of motion (ROM) were determined. To determine the ROM during the stance phase for each variable of interest, the minimum value was subtracted from the maximum value for each stance phase in all planes and averaged across five stance phases for each affected limb. Group ROM averages and standard deviations were calculated by including all stance phases per group in all planes of motion.
4.2.4.2 Peak Moment

Peak moment about each axis for each joint was determined as the largest moment (either positive or negative) during the push-off phase of the support period. Push-off was determined as occurring in the last 50% of support.

4.2.4.3 Stride Parameters

The stride parameters of interest consisted of: 1) stride length; 2) stride time; 3) stance time; and 4) dual limb support time. Stride parameters were calculated using Visual 3D software (C-Motion Inc., Germantown, MD). Stride length was defined as the distance between successive points of initial contact (heelstrike) of the same foot. Stride time was defined as the time between successive points of heelstrike of the same foot. Stance time was defined as the time between heelstrike and toe-off of the same foot. Dual limb support time was defined as the time between heelstrike of one foot and toe-off of the contralateral foot. Group stride parameter averages were determined by averaging across all stance phases for each limb per group for each walking velocity. Group standard deviation values were also calculated.

4.2.5 Statistical Analysis

A one-way analysis of variance (ANOVA) was used to compare the kinematic and kinetic primary dependent variables between groups. A criterion alpha level of 0.05 was used for all statistical tests. A post hoc Tukey test was employed where it was appropriate. Effect sizes were calculated between the groups for the dependent variables.
to supplement the interpretation of statistically significant results. Effect sizes greater than 0.5 represent clinically relevant differences between two means (Cohen, 1988).

4.3 Results

4.3.1 Participants

A summary of participant information revealed that there were no significant differences between groups for age and weight however, the CSR group had significantly greater body mass than CTR (adj. p=0.019) and PCT (adj. p= 0.01) groups (Table 4.1). No significant differences were observed between CTR, PCT and CSR groups for temporal and spatial parameters (Table 4.2).

Table 4.1: Group (mean ± SD) participant characteristics for age, height and weight for the three experimental groups (CTR: control; PCT: ponseti casting technique; CSR: comprehensive surgical release).

<table>
<thead>
<tr>
<th>Group (mean ± SD)</th>
<th>CTR (n=10)</th>
<th>PCT (n=10)</th>
<th>CSR (n=7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>11.92 ± 5.05</td>
<td>12.54 ± 3.99</td>
<td>16.08 ± 3.90</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.48 ± 0.19</td>
<td>1.48 ± 0.10</td>
<td>1.71 ± 0.19</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>46.46 ± 18.96</td>
<td>56.87 ± 31.05</td>
<td>76.79 ± 34.05</td>
</tr>
</tbody>
</table>

Table 4.2: Group (mean ± SD) temporal and spatial parameters for the three experimental groups (CTR: control; PCT: ponseti casting technique; CSR: comprehensive surgical release).

<table>
<thead>
<tr>
<th>Group (mean ± SD)</th>
<th>CTR</th>
<th>PCT</th>
<th>CSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Affected Stance Time (sec)</td>
<td>0.651 ± 0.113</td>
<td>0.630 ± 0.076</td>
<td>0.699 ± 0.112</td>
</tr>
<tr>
<td>Unaffected Stance Time (sec)</td>
<td>0.648 ± 0.107</td>
<td>0.647 ± 0.081</td>
<td>0.712 ± 0.106</td>
</tr>
<tr>
<td>Double Limb Support Time (sec)</td>
<td>0.107 ± 0.038</td>
<td>0.099 ± 0.022</td>
<td>0.131 ± 0.036</td>
</tr>
<tr>
<td>Affected Step Length (m)</td>
<td>0.542 ± 0.065</td>
<td>0.542 ± 0.059</td>
<td>0.563 ± 0.057</td>
</tr>
<tr>
<td>Unaffected Step Length (m)</td>
<td>0.539 ± 0.061</td>
<td>0.536 ± 0.043</td>
<td>0.572 ± 0.075</td>
</tr>
<tr>
<td>Stride Length (m)</td>
<td>1.081 ± 0.123</td>
<td>1.054 ± 0.101</td>
<td>1.136 ± 0.127</td>
</tr>
</tbody>
</table>
4.3.2 Multi-Segment Foot Kinematics

MTP dorsi/plantar flexion ROM was significantly lower in CSR participants than PCT (adj p=0.02, ES=0.66) and CTR participants (adj p = <0.01, ES=0.77). There were no significant differences in MTP dorsi/plantar flexion ROM between the PCT and CTR groups; however, the overall movement pattern of the PCT group consisted of greater dorsiflexion in early and midstance (~10-65%) but less dorsiflexion prior to push-off (Fig. 4.3).

![Figure 4.3: Metatarsophalangeal Angle](image)

The clubfoot groups demonstrated reduced rearfoot-forefoot ROM during stance compared to the typically-developing group (Table 4.3) (Fig. 4.4). Specifically, CSR participants had significantly less rearfoot-forefoot dorsi/plantar flexion ROM than PCT (adj p=0.03, ES=0.66) and CTR participants (adj p=0.02, ES=0.71). In addition, CSR and PCT participants had less add/abduction ROM compared to CTR participants.
during stance. No significant differences were found in rearfoot-forefoot inversion/eversion ROM between the three groups during the stance phase.

Table 4.3: Mean ± SD values for rearfoot-forefoot joint range of motion (ROM) in the sagittal (dorsiflexion-plantar flexion), frontal (inversion-eversion) and transverse (adduction-abduction) planes during the stance phase. Summary of Tukey statistical post-hoc analysis (adj p) and effect sizes (ES). Significance between groups at p-value<0.05 and large difference between group means (ES>0.8): bold text.

<table>
<thead>
<tr>
<th>Rearfoot-Forefoot Angle</th>
<th>ROM°</th>
<th>Group Comparison</th>
<th>p value</th>
<th>Effect Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dorsiflexion-plantar flexion</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTR</td>
<td>14.3 ± 3.4</td>
<td>CTR, PCT</td>
<td>0.99</td>
<td>0.00</td>
</tr>
<tr>
<td>PCT</td>
<td>14.3 ± 4.0</td>
<td>CTR, CSR</td>
<td><strong>0.02</strong></td>
<td>0.71</td>
</tr>
<tr>
<td>CSR</td>
<td>11.8 ± 3.6</td>
<td>PCT, CSR</td>
<td><strong>0.03</strong></td>
<td>0.66</td>
</tr>
<tr>
<td>Inversion-eversion</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTR</td>
<td>5.1 ± 3.7</td>
<td>CTR, PCT</td>
<td>0.84</td>
<td>0.10</td>
</tr>
<tr>
<td>PCT</td>
<td>4.6 ± 3.3</td>
<td>CTR, CSR</td>
<td>0.32</td>
<td>0.37</td>
</tr>
<tr>
<td>CSR</td>
<td>3.8 ± 3.4</td>
<td>PCT, CSR</td>
<td>0.62</td>
<td>0.24</td>
</tr>
<tr>
<td>Adduction-abduction</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTR</td>
<td>6.9 ± 2.7</td>
<td>CTR, PCT</td>
<td>&lt;0.01</td>
<td>0.76</td>
</tr>
<tr>
<td>PCT</td>
<td>3.1 ± 2.1</td>
<td>CTR, CSR</td>
<td>&lt;0.01</td>
<td><strong>1.70</strong></td>
</tr>
<tr>
<td>CSR</td>
<td>3.0 ± 1.9</td>
<td>PCT, CSR</td>
<td>0.99</td>
<td>0.05</td>
</tr>
</tbody>
</table>
Figure: 4.4: Rearfoot-forefoot kinematic time series during stance (0-100%) in comprehensive surgical release (CSR), Ponseti casting technique (PCT) and typically developing controls (CTR). Mean angles in the (a) sagittal, (b) frontal and (c) transverse planes.
4.3.3 Lower Extremity Joint Kinematics

No significant differences were found in the sagittal and frontal plane ankle joint ROM. However, PCT participants exhibited significantly greater adduction-abduction ankle joint ROM in the transverse plane compared to CTR participants during stance (adj p=0.01, ES=0.52) and CSR participants demonstrated significantly less transverse ankle joint ROM compared to PCT participants (adj p=0.01, ES=1.09). There were no significant differences in transverse ankle joint ROM between CSR and CTR groups. Overall, the ankle joint movement patterns of CSR, PCT and CTR groups were similar during stance (Fig. 4.5). CSR individuals exhibited significantly greater knee flexion-extension ROM than PCT individuals during stance (adj p=0.05, ES=0.60). There were no significant differences between CSR and CTR participants or PCT and CTR participants in sagittal plane knee ROM. However, PCT participants exhibited significantly greater knee varus-valgus ROM than CTR participants (adj p= <0.01, ES=0.55). The CSR group had more knee varus-valgus ROM than the CTR group. It is worth mentioning, while the difference between CSR and CTR knee varus-valgus ROM was not statistically significant; an effect size of 0.64 indicates a clinically relevant difference between the two groups (Cohen, 1988). Qualitatively, the overall movement patterns of the knee in the transverse plane differed between groups (Fig. 4.6) however, no significant differences were found in knee internal/external rotation ROM between the three groups during stance. In general, CSR, PCT and CTR participants demonstrated qualitatively similar movement patterns of the hip in the sagittal, frontal and transverse planes during stance (Fig. 4.7). Only frontal plane hip joint ROM was significantly different between
groups during stance, where CSR participants exhibited significantly greater hip adduction-abduction ROM than PCT participants (adj p= 0.02, ES= 0.58; Table 4.4).

Figure 4.5: Ankle kinematic time series during stance (0-100%) in comprehensive surgical release (CSR), ponseti casting technique (PCT) and typically developing controls (CTR). Mean angles in the (a) sagittal, (b) frontal and (c) transverse planes.
Figure 4.6: Knee kinematic time series during stance (0-100%) in comprehensive surgical release (CSR), Ponseti casting technique (PCT) and typically developing controls (CTR). Mean angles in the (a) sagittal, (b) frontal and (c) transverse planes.
Figure 4.7: Hip kinematic time series during stance (0-100%) in comprehensive surgical release (CSR), ponseti casting technique (PCT) and typically developing controls (CTR). Mean angles in the (a) sagittal, (b) frontal and (c) transverse planes.
Table 4.4: Mean ± SD values for hip joint range of motion (ROM) in the sagittal (flexion-extension), frontal (inversion-eversion) and transverse (adduction-abduction) planes during the stance phase. Summary of Tukey statistical post-hoc analysis (Adj p) and effect sizes (ES). Significance between groups at p-value <0.05 and large difference between group means (ES>0.8): bold text.

<table>
<thead>
<tr>
<th>Hip Angle</th>
<th>Group Comparison</th>
<th>p value</th>
<th>Effect Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexion-extension</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTR</td>
<td>33.8 ± 7.0</td>
<td>CTR, PCT</td>
<td>0.15</td>
</tr>
<tr>
<td>PCT</td>
<td>31.5 ± 4.4</td>
<td>CTR, CSR</td>
<td>0.33</td>
</tr>
<tr>
<td>CSR</td>
<td>31.8 ± 2.6</td>
<td>PCT, CSR</td>
<td>0.98</td>
</tr>
<tr>
<td>Adduction-abduction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTR</td>
<td>4.9 ± 4.0</td>
<td>CTR, PCT</td>
<td>0.79</td>
</tr>
<tr>
<td>PCT</td>
<td>4.7 ± 3.7</td>
<td>CTR, CSR</td>
<td>0.07</td>
</tr>
<tr>
<td>CSR</td>
<td>7.5 ± 6.0</td>
<td>PCT, CSR</td>
<td>0.02</td>
</tr>
<tr>
<td>Internal-external rotation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTR</td>
<td>6.7 ± 5.0</td>
<td>CTR, PCT</td>
<td>0.79</td>
</tr>
<tr>
<td>PCT</td>
<td>5.9 ± 4.2</td>
<td>CTR, CSR</td>
<td>1.00</td>
</tr>
<tr>
<td>CSR</td>
<td>6.6 ± 4.5</td>
<td>PCT, CSR</td>
<td>0.83</td>
</tr>
</tbody>
</table>

4.3.4 Lower Extremity Joint Moments

CSR and PCT individuals exhibited lesser ankle plantar flexion and eversion peak joint moments in the last 50% of stance than CTR individuals (Fig. 4.8) (Table 4.5). No significant differences were found in ankle plantar flexion and eversion peak joint moments between CSR and PCT individuals in the last 50% of stance. PCT participants demonstrated significantly reduced ankle adduction peak values than CTR (adj p= <0.01, ES=0.50) and CSR (adj p= <0.01, ES= 1.00) participants. These values were not significantly different between CSR and CTR groups. Overall, clubfoot individuals exhibited deficits in peak ankle plantar flexion, eversion and adduction joint moments in the last 50% of stance than typically developing controls.
Figure 4.8: Normalized ankle joint moments (N·m/kg) during stance (0-100%) in comprehensive surgical release (CSR), ponseti casting technique (PCT) and typically developing controls (CTR). Ensemble mean joint moments in the (a) sagittal, (b) frontal and (c) transverse planes.
Table 4.5: Mean ± SD values for normalized peak ankle joint moments (N·m/kg) during the last 50% of the stance phase. Summary of Tukey statistical post-hoc analysis (Adj p) and effect sizes (ES). Significance between groups at p-value<0.05 and large difference between group means (ES>0.8): bold text.

<table>
<thead>
<tr>
<th>Ankle Moment</th>
<th>N·m/Kg</th>
<th>Group Comparison</th>
<th>p value</th>
<th>Effect Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plantar flexion peak</td>
<td>CTR -1.30 ± 0.09</td>
<td>CTR, PCT</td>
<td>&lt;0.01</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>PCT -0.99 ± 0.16</td>
<td>CTR, CSR</td>
<td>&lt;0.01</td>
<td>1.24</td>
</tr>
<tr>
<td></td>
<td>CSR -1.07 ± 0.28</td>
<td>PCT, CSR</td>
<td>0.255</td>
<td>0.36</td>
</tr>
<tr>
<td>Eversion peak</td>
<td>CTR 0.27 ± 0.10</td>
<td>CTR, PCT</td>
<td>&lt;0.01</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>PCT 0.17 ± 0.07</td>
<td>CTR, CSR</td>
<td>&lt;0.01</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td>CSR 0.19 ± 0.08</td>
<td>PCT, CSR</td>
<td>0.77</td>
<td>0.27</td>
</tr>
<tr>
<td>Adduction peak</td>
<td>CTR 0.10 ± 0.02</td>
<td>CTR, PCT</td>
<td>&lt;0.01</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>PCT 0.06 ± 0.03</td>
<td>CTR, CSR</td>
<td>0.45</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>CSR 0.09 ± 0.03</td>
<td>PCT, CSR</td>
<td>&lt;0.01</td>
<td>1.00</td>
</tr>
</tbody>
</table>

In general, CSR, PCT and CTR participants demonstrated qualitatively similar knee joint moment production patterns in the sagittal, frontal and transverse planes throughout stance; however, the differences in magnitudes are apparent (Fig. 4.9). CSR individuals exhibited greater knee flexion and valgus joint moments during the stance phase than PCT and CTR individuals (Table 4.6). PCT and CTR peak knee flexion moments were not significantly different nor where CSR and CTR peak knee valgus moments. However, it is worth mentioning that there was a clinically significant difference between CSR and CTR peak knee valgus moments during pushoff (ES=0.68). PCT individuals demonstrated significantly lower peak valgus and external rotation knee moments than CTR (adj p= <0.01, ES= 0.47; adj p= <0.01, ES=0.46) and CSR (adj p= <0.01, ES= 1.44; adj p= <0.01, ES= 2.00) individuals.
Figure 4.9: Normalized knee joint moments (N·m/kg) during stance (0-100%) in comprehensive surgical release (CSR), ponseti casting technique (PCT) and typically developing controls (CTR). Ensemble mean joint moments in the (a) sagittal, (b) frontal and (c) transverse planes.
Table 4.6: Mean ± SD values for normalized peak knee joint moments (N·m/kg) during the last 50% of the stance phase. Summary of Tukey statistical post-hoc analysis (Adj p) and effect sizes (ES). Significance between groups at p-value<0.05 and large difference between group means (ES>0.8): bold text.

<table>
<thead>
<tr>
<th>Joint Moment</th>
<th>Group Comparison</th>
<th>p value</th>
<th>Effect Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexion peak</td>
<td>CTR</td>
<td>-0.19 ± 0.13</td>
<td>CTR, PCT</td>
</tr>
<tr>
<td></td>
<td>PCT</td>
<td>-0.14 ± 0.10</td>
<td>CTR, CSR</td>
</tr>
<tr>
<td></td>
<td>CSR</td>
<td>-0.28 ± 0.10</td>
<td>PCT, CSR</td>
</tr>
<tr>
<td>Valgus peak</td>
<td>CTR</td>
<td>-0.21 ± 0.046</td>
<td>CTR, PCT</td>
</tr>
<tr>
<td></td>
<td>PCT</td>
<td>-0.13 ± 0.08</td>
<td>CTR, CSR</td>
</tr>
<tr>
<td></td>
<td>CSR</td>
<td>-0.26 ± 0.10</td>
<td>PCT, CSR</td>
</tr>
<tr>
<td>External rotation peak</td>
<td>CTR</td>
<td>0.08 ± 0.03</td>
<td>CTR, PCT</td>
</tr>
<tr>
<td></td>
<td>PCT</td>
<td>0.05 ± 0.02</td>
<td>CTR, CSR</td>
</tr>
<tr>
<td></td>
<td>CSR</td>
<td>0.08 ± 0.01</td>
<td>PCT, CSR</td>
</tr>
</tbody>
</table>

Qualitative differences CSR, PCT and CTR joint moments about the hip during stance are presented in Fig. 4.10. Peak flexion joint moments about the hip in the last 50% of stance were significantly less in PCT individuals than CTR individuals (adj p= <0.01, ES= 0.26); whereas CSR values were not significantly different than PCT or CTR values (Table 4.7). There was however, a clinically relevant difference between PCT and CSR peak flexion joint moments (ES= 0.54) In addition, PCT individuals demonstrated significantly lower peak hip abduction joint moments than CTR (adj p= <0.01, ES= 0.26) and CSR (adj p= <0.01, ES= 1.48) individuals. CSR and CTR peak abduction joint moments in the last 50% of stance were not significantly different although, it is important to note there was a clinically relevant effect (ES=0.50). No significant differences were found in peak hip external
rotation moments but clinically relevant differences existed between CTR and PCT individuals (ES=0.55) as well as, CTR and CSR individuals (ES=1.00).

Figure 4.10: Normalized hip joint moments (N·m/kg) during stance (0-100%) in comprehensive surgical release (CSR), Ponseti casting technique (PCT) and typically developing controls (CTR). Ensemble mean joint moments in the (a) sagittal, (b) frontal and (c) transverse planes.
Table 4.7: Mean ± SD values for normalized peak hip joint moments (N·m/kg) during the last 50% of the stance phase. Summary of Tukey statistical post-hoc analysis (adj p) and effect sizes (ES). Significance between groups at p-value<0.05 and large difference between group means (ES>0.8): bold text.

<table>
<thead>
<tr>
<th></th>
<th>N·m/Kg</th>
<th>Group Comparison</th>
<th>p value</th>
<th>Effect Size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexor Peak</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTR</td>
<td>0.53 ± 0.12</td>
<td>CTR, PCT</td>
<td>&lt;0.01</td>
<td>0.26</td>
</tr>
<tr>
<td>PCT</td>
<td>0.41 ± 0.16</td>
<td>CTR, CSR</td>
<td>0.37</td>
<td>0.45</td>
</tr>
<tr>
<td>CSR</td>
<td>0.48 ± 0.10</td>
<td>PCT, CSR</td>
<td>0.11</td>
<td>0.54</td>
</tr>
<tr>
<td>Abductor Peak</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>CTR</td>
<td>-0.74 ± 0.13</td>
<td>CTR, PCT</td>
<td>&lt;0.01</td>
<td>0.35</td>
</tr>
<tr>
<td>PCT</td>
<td>-0.52 ± 0.16</td>
<td>CTR, CSR</td>
<td>0.34</td>
<td>0.50</td>
</tr>
<tr>
<td>CSR</td>
<td>-0.69 ± 0.07</td>
<td>PCT, CSR</td>
<td>&lt;0.01</td>
<td>1.48</td>
</tr>
<tr>
<td>External rotation Peak</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTR</td>
<td>0.07 ± 0.04</td>
<td>CTR, PCT</td>
<td>0.13</td>
<td>0.55</td>
</tr>
<tr>
<td>PCT</td>
<td>0.04 ± 0.07</td>
<td>CTR, CSR</td>
<td>0.21</td>
<td><strong>1.00</strong></td>
</tr>
<tr>
<td>CSR</td>
<td>0.04 ± 0.02</td>
<td>PCT, CSR</td>
<td>1.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

4.4 Discussion

There is still not a clear understanding of the biomechanical and functional differences, of the foot specifically, between PCT, CSR and CTR feet. In an effort to add to this body of literature, the purpose of this study was to examine group differences in lower extremity kinematics and kinetics during walking in individuals treated with either PCT or CSR 5-7 years after treatment compared to a healthy non-involved control group. Before the data collection, it was hypothesized that there would be significant group differences (PCT vs. CSR vs. CTR) in rearfoot-forefoot, MTP, ankle, knee and hip joint ROM as well as significant group differences in ankle, knee and hip peak joint moments during pushoff. In the current study, PCT and CSR treated clubfeet 5-7 years post-treatment, without pain and not anticipating further interventions demonstrate nearly
normal movement in the lower extremity. Despite having good overall function, restricted midfoot and MTP joint motion and abnormal lower extremity joint moments were the main characteristics of the gait of children with a clubfoot treated by PCT or CSR.

CSR-treated feet at 10 years follow-up (Karol et al., 1997) and adults with PCT-treated feet (Cooper & Dietz, 1995) are reported to have deficits in foot and ankle ROM during the stance phase of walking. The current study found few multi-segment foot and lower extremity ROM values that were significantly different compared with typically developing feet however, mild deviations suggestive of residual deformity were observed for both PCT and CSR groups.

Although previous studies using gait analysis have reported reduced sagittal ankle ROM in treated clubfeet (Church et al., 2012; T. C. Davies et al., 2001; El-Hawary et al., 2008; Karol et al., 2009; Mindler, Kranzl, Lipkowski, Ganger, & Radler, 2014; Theologis, Harrington, Thompson, & Benson, 2003a), the current study observed ankle dorsi/plantar flexion ROM values that were similar between all groups. While differences in ROM were not significant, a trend towards decreased ankle plantar flexion was observed throughout stance in CSR-treated feet. A more detailed evaluation of the multi-segment foot kinematics identified reduced sagittal plane ROM of the rearfoot-forefoot joint where mean values for the PCT group were nearly identical to the CTR group. Overall, the PCT group demonstrated greater midfoot and MTP joint flexibility than the CSR group. The multi-segment foot results revealed reduced midfoot and MTP joint
ROM in CSR-treated feet while the PCT-treated feet demonstrated values comparable to typically-developing feet.

Previous studies have reported diminished sagittal plane ankle pushoff power in the treated clubfoot (Aronson & Puskarich, 1990; Church et al., 2012; C. T. Davies et al., 2001; Karol et al., 1997; Karol et al., 2009; Theologis, Harrington, Thompson, & Benson, 2003b). Church et al. (2012) reported a 45.8% reduction in CSR treated feet and 26.9% reduction in sagittal plane ankle pushoff power compared to healthy controls. While ankle power was not reported in the current study, perhaps the most consistent abnormal finding of this study was the reduced ankle plantar flexion moment in the last 50% of stance in the clubfoot groups. As the ankle dorsiflexes, the net internal ankle plantarflexor moment implies reduced ability of the plantarflexor muscles to absorb power and to control tibial motion as the ankle dorsiflexes through midstance. In addition, a reduced ability to eccentrically contract to generate sufficient power for pushoff. Reduced midfoot ROM and MTP dorsiflexion at pushoff may be suggestive of pathological plantar fascia and reduced muscular strength in PCT and CSR treated clubfeet. MTP dorsiflexion is necessary for a stable and rigid foot at pushoff as it facilitates plantar fascia tightening (Bojsen-Moller, 1979). Previous studies have consistently reported plantarflexor muscular strength in PCT and CSR individuals (Alkjaer et al., 2000; Aronson & Puskarich, 1990; Church et al., 2012; T. C. Davies et al., 2001; Karol et al., 1997). The multi-segment foot kinematic results of our study also showed PCT-treated clubfeet demonstrated an overall, more adducted movement pattern of the forefoot relative to the rearfoot which is in agreement with Theologis et al.
(Theologis et al., 2003b). In addition, the overall sagittal plane MTP joint movement pattern of the PCT group consisted of greater dorsiflexion from 10-65% of stance but less dorsiflexion prior to push-off compared to CTR and CSR movement patterns. While ROM was not statistically different from CTR or CSR, the PCT participants’ overall different multi-segment foot kinematics may be suggestive of residual deformity. It has been suggested that abnormal forefoot and rearfoot kinematics are compensatory movement strategies and are responsible for the appearance of normal sagittal plane ankle kinematics (Smith et al., 2013).

The current study found few deviations from normal in the ROM of the proximal joints which is in disagreement with some previous studies (Alkjaer et al., 2000; Church et al., 2012; C. T. Davies et al., 2001; Karol et al., 1997; Smith et al., 2013). However, compared to PCT, CSR individuals demonstrated significantly reduced frontal plane ankle ROM as well as significantly more sagittal knee and frontal hip ROM. While these values did not differ from normal, it may be suggested that the PCT and CSR groups differ in terms of functional anatomy and organization of the segments. PCT and CSR lower extremity ROM measures were overall, not significantly different from CTR. The results of this study did find abnormal joint moments at the ankle, knee and hip. A consistent finding that is in agreement with literature, is that the CSR group demonstrated greater knee and hip moments compared to CTR and PCT (Alkjaer et al., 2000; Beyaert et al., 2003; Church et al., 2012; T. C. Davies et al., 2001), suggesting alteration of movement strategies. It is important to note that the CSR group had significantly greater body mass than both the PCT and CTR groups. While body mass and body height were
accounted for in the joint moment calculations it is possible that the significant differences detected may be attributed to the CSR group’s greater mass. In addition, the PCT individuals demonstrated diminished peak ankle eversion, knee external rotation and knee valgus moments compared to CTR individuals.

Residual internal foot progression has been found in previous studies, most commonly in surgically corrected clubfeet (Asperheim, Moore, Carroll, & Dias, 1995; Church et al., 2012; Theologis et al., 2003b; Yngve, 1990). In the current study, PCT individuals exhibited a trend towards increased forefoot adduction, as well as internal tibial and femoral rotation throughout stance. Theologis et al. (Theologis et al., 2003b) attributed significant internal foot rotation to forefoot adduction or hindfoot rotation in relation to the tibia. While the multi-segment foot and lower extremity ROM values were overall similar to CTR, a closer look at the ensemble mean joint angles reveals results suggestive of residual internal foot progression in the PCT group.

4.4.2 Limitations

Classification of the severity of the initial deformity was not available for all clubfoot participants included in this study and therefore, it was not possible to compare the pre-treatment severity of the deformities.

In addition, the children with clubfoot recruited for this study were pain-free, able to walk at least fifty feet without assistance, not currently using braces/orthoses and not anticipating further clubfoot treatment. The inclusion and exclusion criterion used in the current study potentially characterizes a group of PCT and CSR participants with good
clinical and functional results 5-7 years post-treatment. Many of the gait analysis studies in the literature did not include clubfoot participants with this criteria and multi-segment foot kinematics were not quantified. As the lower extremity kinematic results of the current study were in disagreement with those previously reported, the differing results might be explained by the fact that our clubfoot participants had milder residual deformities the movement of the more proximal lower extremity joints were not influenced. Thus, the results of this study may not be indicative of all PCT and CSR-treated clubfeet 5-7 years post-treatment.

4.4.3 Conclusion

The motion of the foot is complex and understanding the position and orientation of the foot segments during walking is integral to assessing the effectiveness of treatment on long-term foot function. There is a lack of reliable, reproducible, and accurate objective measures of dynamic function 5-7 years after clubfoot treatment. In an effort to add to this body of literature, the purpose of this study was to examine group differences in multi-segment foot and lower extremity kinematics and kinetics during walking in individuals treated with either PCT or CSR 5-7 years after treatment compared to a healthy non-involved control group. A multi-segment foot model was used to measure the position and orientation of the segments of the foot which has been previously evaluated for its reliability in children. In the current study, PCT and CSR treated clubfeet 5-7 years post-treatment, without pain and not anticipating further interventions demonstrate nearly normal movement in the lower extremity. Despite having good
overall function, restricted midfoot and MTP joint motion and abnormal lower extremity joint moments were the main characteristics of the gait of children with a clubfoot treated by PCT or CSR. The current study has shown that not all PCT-treated clubfeet are free from recurrent deformity.
CHAPTER 5

MULTI-SEGMENT FOOT COORDINATION OF THE TREATED CLUBFOOT

5.1 Introduction

Clubfoot is a common congenital three-dimensional (3D) deformity of the foot occurring in approximately three in every 1,000 live births (Wynne-Davies, 1972). The initial deformity consists of four primary components: 1) equinus; 2) hindfoot varus; 3) forefoot adductus; and 4) forefoot cavus and presents a wide spectrum of severity at birth (Dobbs et al., 2004). Correction of the deformity may be achieved by surgical and/or non-surgical intervention where the goal of successful clinical intervention is to restore function or to provide alternate movement strategies for pain-free gait (Ponseti, 1992).

Comprehensive surgical release (CSR) is an invasive surgical procedure that involves the release of the posterior and medial ligament structures surrounding the ankle joint. Twenty-five percent of CSR-treated feet have a recurrent deformity and require additional surgical releases, tendon lengthenings, osteotomies and selective joint fusions to correct the residual deformity (Atar et al., 1992; Lehman et al., 2003; Lehman, 1980; Viskelety & Szepesi, 1989). Long-term follow up based on various grading systems, radiographs, passive range of motion scores, and gait analyses report increased pain and functional limitations, stiffness, weakness and premature arthritis in CSR-treated feet (Dobbs et al., 2006; Herzenberg et al., 2002).

The Ponseti casting technique (PCT) utilizes a progressive series of well-molded longleg plaster casts, percutaneous heel cord lengthening and at least two years of a foot
abduction orthosis (Ponseti, 1997a; Ponseti & Smokey, 2009). Longer-term follow-up studies reveal that as many as forty percent of patients treated with the PCT require further operative treatment to correct a recurrence and, when compared to typically-developing feet, PCT-treated feet report an increased prevalence of osteoarthritis, lower SF-36 physical functioning subscores and restricted motion at the foot, ankle and knee (Crawford & Gupta, 1996; Haft et al., 2007; Halanski et al., 2009; Harrold & Walker, 1983; Herzenberg et al., 2002; Laaveg & Ponseti, 1980). Despite the PCT’s short-term promising results, long-term follow up studies suggest that not all PCT-treated feet are free from recurrent deformity and deficits in dynamic function remain. There remains a need to characterize the underlying mechanisms that contribute to the differences in dynamic foot function of the treated clubfoot.

Currently, the PCT is the standard of care for clubfoot correction due to its non-invasive approach and superior clinical and functional reported outcomes over CSR (Ponseti, 1992; Zionts et al., 2010). Despite the PCT’s popularity amongst orthopedic surgeons around the world, there is controversy over the effectiveness of the PCT on dynamic foot function later in life and whether CSR may be a more beneficial approach to clubfoot correction.

The complexity of the foot’s structure and motion has made it difficult to achieve a thorough understanding of foot kinematics (Carson et al., 2001). Some biomechanical studies in the literature have used traditional gait analysis in the investigation of clubfoot treatment and dynamic foot function. Common results in the literature for PCT and CSR-treated clubfeet are residual foot internal rotation, limited rearfoot inversion/eversion,
limited ankle plantar/dorsiflexion and reduced ankle power generation at pushoff (Alkjaer et al., 2000; Beyaert et al., 2003; C. T. Davies et al., 2001; Karol et al., 1997; Karol et al., 2009; Widhe & Berggren, 1994). Compared to healthy controls, reported differences in lower extremity kinematics in PCT and CSR-treated feet are increased hip external rotation, limited knee flexion/extension and increased knee varus and internal rotation throughout stance (Church et al., 2012; C. T. Davies et al., 2001; Karol et al., 1997). Although informative, these studies have not led to a clear understanding of the underlying mechanisms that contribute to the biomechanical and functional differences between PCT-treated clubfeet, CSR-treated clubfeet and typically developing-feet. Traditional biomechanical measures identify single instant temporal events a priori and neglect useful information by leaving much of the data unused. A Dynamical Systems Analysis (DSA) Approach to movement coordination differs from traditional biomechanical analyses in that it analyzes the interaction between two adjacent segments or joints instead of analyzing each segment separately (Robertson, Caldwell, Hamill, Kamen, & Whittlesey, 2013). In this approach, it is implied that the motion of one segment can influence the motion of another segment. Chang et al. (Chang et al., 2008) proposed the quantification of the coordination of the lower extremity using a modified vector coding technique as a method to analyze the interactions between the segments. The coordination of two segments may be summarized through a set of operational coordination patterns: anti-phase (AP), in-phase (IP), distal phase (DP) and proximal phase (PP). AP coordination indicates the segments are rotating in opposite directions. Segments rotating in the same direction exhibit IP coordination. DP coordination
indicates only the distal segment is rotating while the proximal segment is not. PP coordination indicates the proximal segment is rotating and the distal segment is not (Chang et al., 2008).

In normal lower extremity mechanics, at heel strike, subtalar eversion is functionally linked to internal tibial rotation and external femoral rotation. This mechanism “unlocks” the knee and allows the knee to flex for optimal shock absorption at heel strike (Mann & Haskell, 1993; Salathe et al., 1990). Deviation from these coupled motions may result in injury or joint degeneration due to asynchronous coupled motions (Hamill et al., 2012). In addition to the pattern of coupled segment movement, the variability of the organization of the segments is the second main component of the DSA approach to coordination. The presence of variability in the assessment of coordination changes due to treatment may be a strong indicator of residual pathology as coordination variability provides a metric related to the range of available combinations of intra-segment coordination used during walking (Bernstein, 1967; Davis & Burton, 1991; Hamill et al., 2012). Reduced coordination variability has been associated with a decline in function due to the availability of fewer ways to organize the segments during movement (Hamill et al., 2012; Hamill et al., 1999; Seay et al., 2011). Differences in coordination variability may provide information regarding the level of pathology in PCT and CSR-treated clubfeet. Investigation of the coordination of the multi-segment foot and lower extremity segment movements during walking is necessary to understand the impact of treatment and to characterize differences in dynamic foot function.
Therefore, the purpose of this study was to determine the multi-segment foot and lower extremity coordination and coordination variability, specifically of the forefoot and rearfoot relationship, during walking in individuals treated with either PCT or CSR 5-7 years after treatment compared to a healthy non-involved control group. It was hypothesized that the control group would exhibit greater AP multi-segment foot coordination, indicating normal foot motion, than the two treatment groups and the PCT group would exhibit more AP multi-segment foot coordination than the CSR group. In addition, it was hypothesized that there would be greater lower extremity coordination variability in the control group than the treatment groups. Further, it was hypothesized that there would be greater coordination variability in the PCT group, indicating a trend towards normal foot motion, than in the CSR group.

5.2 Materials and Methods

5.2.1 Participants

The New England and University of Massachusetts Amherst Institutional Review Boards approved the study. All participants were between 5 and 21 years, able to walk at least fifty feet without assistance or pain and were able to comply with instructions. Participants were evaluated retrospectively and were assigned to one of three groups: 1) Participants with a history of a clubfoot treated with the Ponseti casting technique (PCT: n=10); 2) Participants with a history of a clubfoot treated with the Comprehensive Surgical Release (CTR: n=7); and 3) Typically developing participants with no history of
a clubfoot (CTR: n=10). Clubfoot inclusion criteria included a primary diagnosis of idiopathic congenital Talipes Equinovarus and a minimum follow-up (post-treatment) of 5 years. All children seen as patients in the outpatient orthopedic clinic at Shriners Hospitals for Children in Springfield, MA were pre-screened through review of electronic medical records to assess eligibility. Children that fit the criteria and were treated with either the PCT or CSR were contacted. CTR participants had no history of a clubfoot and were recruited from employees and friends of employees of Shriners Hospitals for Children in Springfield, MA. Prior to participation, all participants read and signed an age appropriate consent form and completed a Modified Physical Activity Readiness, Lower Extremity Injury History and Demographics questionnaire (completed with the help of parents/guardians). Participants were excluded if further treatment for clubfoot was anticipated, current use of braces/orthoses or if there was a history of other major orthopedic deformities or surgeries.

### 5.2.2 Experimental Setup

3D kinematic and kinetic data were collected using ten infrared cameras (Vicon T40S, Vicon, Centennial, CO) sampled at 240 Hz and two embedded force platforms (AMTI, Watertown, MA) sampled at 1080 Hz. Walking velocity was measured using two infrared timing gates at a known distance apart, connected to an electronic clock. Kinematic and kinetic data were collected on the same computer and were thus synchronized in time.
5.2.3 Protocol

Anthropometric data were measured before the gait analysis was conducted. Reflective markers were then placed bilaterally to track the motion of the lower extremities and pelvis (Dierks et al., 2011). Reflective markers were placed on the pelvis at the right anterior superior iliac spine, right iliac crest, and the L5-S1 interspace and bilaterally at the sites of: the medial and lateral malleoli, the medial and lateral femoral condyles and greater trochanters (Figure 5.1). The anatomical coordinate systems were developed from the position of these markers. Additional tracking markers were placed using clusters of four markers on the femur and shank. The anatomical markers of the pelvis also served as tracking markers.

![Figure 5.1: Bilateral lower extremity marker placement.](image)

Reflective markers (8 mm diameter) were also fixed to the skin of the foot (bilateral) according to a multi-segment foot model (Leardini et al., 2007). Pilot data demonstrated the inter-day and inter-trial reliability of the multi-segment foot model on children ages 8-10 during walking using the Coefficient of Multiple Correlation (Ferrari,
Cutti, & Cappello, 2010). The coefficient ranged from 0.88 to 0.99 for the flexion-extension, abduction-adduction and internal-external rotation angles. A coefficient of 0.5 is considered sufficient for repeatability of measurement. The multi-segment foot model allowed the calculation of the position and orientation of four (assumed) rigid segments: 1) shank: tibia and fibula, 2) foot: all bones, 3) rearfoot: calcaneus, 4) forefoot: five metatarsal bones. The proximal phalanx of the hallux, was taken as an independent line segment. Coordinate system constructions for the shank, foot, rearfoot, forefoot and hallux line segment were right-handed, and were constructed according to the original model (Leardini et al., 2007) (Figure 5.2).

Forefoot and rearfoot segments were constructed from anatomically placed skin markers (Leardini et al., 2007) (first metatarsal (FM), second metatarsal (SM), head (H), base (B), peroneal tubercle (PT), sustenaculum tali (ST), calcaneus (CA)). The forefoot’s origin was located at SMB and the X-axis was the projection of the line joining SMB and SMH on the transverse plane passing through the origin and FMH and VMH. The forefoot’s Y-axis was orthogonal to X and lied in this transverse plane. The forefoot’s Z-axis was orthogonal to the XY plane. The rearfoot’s origin was located at CA and the X-axis was aligned to a midpoint between ST and PT. The rearfoot’s Y-axis was aligned to a transverse plane defined by rearfoot X-axis and the ST. The rearfoot’s Z-axis was orthogonal to the rearfoot’s XY plane. The shank was defined by the medial and lateral femoral epicondyles (proximal segment definition markers) and the medial and lateral malleoli (distal segment definition markers). Clusters of four markers were fixed to the distal-lateral shank. The static positions of the four cluster markers were associated with
the segment definition markers and thus, the cluster markers were used to track shank movements. The origin of the shank was located at the midpoint between the medial and lateral malleoli (Y-axis oriented to medial malleolus; Z-axis oriented proximally to midpoint between medial and lateral femoral epicondyles; Y-axis was orthogonal to Y and Z, and oriented to the anterior direction (line of walking progression)).

Figure 5.2: Multi-segment foot model consisting of three dimensional forefoot and rearfoot segments, and a two-dimensional hallux line segment. Forefoot and rearfoot segments were constructed from anatomically placed skin markers (Leardini et al., 2007) (first metatarsal (FM), second metatarsal (SM), head (H), base (B), peroneal tubercle (PT), sustenaculum tali (ST), calcaneus (CA)). The rearfoot’s origin was located at CA and the X-axis was aligned to a midpoint between ST and PT. The rearfoot’s Y-axis was aligned to a transverse plane defined by rearfoot X-axis and the ST. The rearfoot’s Z-axis was orthogonal to the rearfoot’s XY plane. The forefoot’s origin was located at SMB and the X-axis was the projection of the line joining SMB and SMH on the transverse plane passing through the origin and FMH and VMH. The forefoot’s Y-axis was orthogonal to X and lies in this transverse plane. The forefoot’s Z-axis was orthogonal to the XY plane. Transverse planes (dash-dot triangles) and X- and Y-axes (solid arrows) on these planes are shown, corresponding Z-axes pointing proximally. b) Lateral view of the shank and foot. A rigid plate set with four markers was fixed to the lateral shank (lateral malleolus (LM)). c) Medial view of the shank and foot (medial malleolus (MM)).
With the retroreflective markers affixed to the lower extremities, a barefoot neutral standing calibration trial (feet, shoulders, and hips pointed straight in the walking direction) was captured. Prior to the kinematic and kinetic data collection, participants were given instructions for the walking procedures and were able to perform practice walking trials. Participants then completed two barefoot walking conditions: 1) preferred walking velocity; and 2) fixed walking velocity at 1.0 m/s-1 (±5%). A successful trial was one in which the participant contacted the force platform at the required locomotor velocity. At least five complete strides of the left and right lower extremities were captured for each condition.

A Visual Analog Scale (VAS) based on a 10 mm range was used to evaluate participant pain during the study. If the participant complained of pain in excess of 8 mm on a 10 mm scale during study procedures, the visit was to be discontinued and a recommendation was to be made for the participant to visit his primary care physician as follow up.

5.2.4 Data Reduction

For all experimental groups, data were collected bilaterally and for both walking velocity conditions (preferred and fixed), but once the data collection stage was complete for the entire study, only the fixed walking velocity condition (1.0 m/s-1 ±5%) and the affected limb were analyzed for all experimental groups and for all variables of interest. For CTR participants and bilateral clubfoot participants, the right limb was selected as the affected limb. Marker positions were tracked using Vicon Nexus software (Vicon,
Kinematic data were filtered using a fourth order, zero-lag Butterworth digital low-pass filter with a cutoff frequency of 6 Hz. Visual 3D analysis software (C-Motion Inc., Germantown, MD) was used to calculate 3D segment angles for the thigh, leg, rearfoot and forefoot. Segment angles were calculated relative to the laboratory coordinate system (X-line of walking progression; Y-medio-lateral; Z-vertical) using a Cardan YXZ rotation sequence, a sequence representing flexion/extension (Y), (X) abduction/adduction and axial rotation (Z) (Cole et al., 1993). Segment angles were interpolated and normalized to 101 data points for each stance phase.

5.2.4.1 Coordination Analysis

A modified vector coding technique was performed using a custom MATLAB program to quantify the coordination and coordination variability throughout stance. Segmental angle-angle relative motion plots were created for: 1) forefoot-rear foot inversion/eversion (Ff-Rf); and 2) rear foot inversion/eversion-tibial internal/external rotation (Rf-Tib); and 3) femur-tibia internal/external rotation (Fem-Tib). Inter-segmental coordination was inferred from the segmental angle-angle plots by a vector joining two adjacent time points relative to the right horizontal to derive a phase angle ($\gamma$) (Chang et al., 2008; Heiderscheit, Hamill, & Van Emmerik, 2002; Sparrow, Donovan, van Emmerik, & Barry, 1987). The phase angles for each couple for the five stances were calculated for each participant. Circular statistics were used to calculate the circular mean and standard deviation of the phase angles over early (0-33%), mid-(34-67%) and late stance (68-100%) across the five trials for each participant (Batschelet, 1981).
circular standard deviation of the coupling angle across the five trials per participant was used to determine the between-trial coordination variability.

Coordination patterns were inferred by categorizing the mean coupling angle of each participant into $45^\circ$ bins of a $360^\circ$ unit circle (Table 5.1) (Chang et al., 2008). Frequency count values of each coordination pattern were derived by counting the number of occurrences AP, IP, DP and PP for each couple throughout early, mid- and late stance for each participant. The arithmetic mean of the frequency count values were calculated to obtain group coordination frequency counts values for early, mid- and late stance.

The arithmetic mean of the mean coupling angle for each participant was calculated to obtain the group mean phase angles for each speed. The arithmetic standard deviation of the group averaged mean coupling angle was calculated to obtain the group coordination variability.

Table 5.1: Coordination pattern categorization

<table>
<thead>
<tr>
<th>Coordination Pattern</th>
<th>Phase angle definitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anti-phase</td>
<td>$112.5^\circ \leq \gamma &lt; 157.5^\circ, 292.5^\circ \leq \gamma &lt; 337.5^\circ$</td>
</tr>
<tr>
<td>In-phase</td>
<td>$22.5^\circ \leq \gamma &lt; 67.5^\circ, 202.5^\circ \leq \gamma &lt; 247.5^\circ$</td>
</tr>
<tr>
<td>Proximal phase</td>
<td>$0^\circ \leq \gamma &lt; 22.5^\circ, 157.5^\circ \leq \gamma &lt; 202.5^\circ, 337.5^\circ \leq \gamma \leq 360^\circ$</td>
</tr>
<tr>
<td>Distal phase</td>
<td>$67.5^\circ \leq \gamma &lt; 112.5^\circ, 247.5^\circ \leq \gamma &lt; 292.5^\circ$</td>
</tr>
</tbody>
</table>
5.2.5 Statistical Analysis

A one-way analysis of variance was used to compare the coordination frequency count values and coordination variability values between groups. A criterion alpha level of 0.05 was used for all statistical tests. A post hoc Tukey test was employed where appropriate. Effect sizes were calculated between the groups for the dependent variables to supplement the interpretation of statistically significant results. Effect sizes greater than 0.5 represent clinically relevant differences between two means (Cohen, 1988).

5.3 Results

5.3.1 Participants

A summary of participant information revealed that there were no significant differences between groups for age and weight however, the CSR group had significantly greater body mass than CTR (adj. p=0.019) and PCT (adj. p= 0.01) groups (Table 5.2). No differences were observed between CTR, PCT and CSR groups for temporal and spatial parameters (Table 5.3).

Table 5.2: Group (mean ± SD) participant characteristics for age, height and weight for the three experimental groups (CTR: control; PCT: ponseti casting technique; CSR: comprehensive surgical release).

<table>
<thead>
<tr>
<th>Group (mean ± SD)</th>
<th>CTR (n=10)</th>
<th>PCT (n=10)</th>
<th>CSR (n=7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>11.92 ± 5.05</td>
<td>12.54 ± 3.99</td>
<td>16.08 ± 3.90</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.48 ± 0.19</td>
<td>1.48 ± 0.10</td>
<td>1.71 ± 0.19</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>46.46 ± 18.96</td>
<td>56.87 ± 31.05</td>
<td>76.79 ± 34.05</td>
</tr>
</tbody>
</table>
Table 5.3: Group (mean ± SD) temporal and spatial parameters for the three experimental groups (CTR: control; PCT: ponseti casting technique; CSR: comprehensive surgical release).

<table>
<thead>
<tr>
<th>Group (mean ± SD)</th>
<th>CTR</th>
<th>PCT</th>
<th>CSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Affected Stance Time (sec)</td>
<td>0.651 ± 0.113</td>
<td>0.630 ± 0.076</td>
<td>0.699 ± 0.112</td>
</tr>
<tr>
<td>Unaffected Stance Time (sec)</td>
<td>0.648 ± 0.107</td>
<td>0.647 ± 0.081</td>
<td>0.712 ± 0.106</td>
</tr>
<tr>
<td>Double Limb Support Time (sec)</td>
<td>0.107 ± 0.038</td>
<td>0.099 ± 0.022</td>
<td>0.131 ± 0.036</td>
</tr>
<tr>
<td>Affected Step Length (m)</td>
<td>0.542 ± 0.065</td>
<td>0.542 ± 0.059</td>
<td>0.563 ± 0.057</td>
</tr>
<tr>
<td>Unaffected Step Length (m)</td>
<td>0.539 ± 0.061</td>
<td>0.536 ± 0.043</td>
<td>0.572 ± 0.075</td>
</tr>
<tr>
<td>Stride Length (m)</td>
<td>1.081 ± 0.123</td>
<td>1.054 ± 0.101</td>
<td>1.136 ± 0.127</td>
</tr>
</tbody>
</table>

5.3.2 Coordination

No significant differences were found in Ff-Rf, Rf-Tib or Fem-Tib coordination patterns during early, mid and late stance between all groups. Although, differences did not reach statistical significance at p=0.05 there were some group effects on Ff-Rf, Rf-Tib and Fem-Tib coordination pattern frequency in early, mid and late stance.

Histograms summarize the group Ff-Rf kinematics into four distinct coordination patterns (Figure 5.3). No significant differences were found on Ff-Rf coordination pattern frequency between groups throughout stance (Table 5.4, Table 5.5). CSR participants demonstrated more Ff-Rf AP coordination than CTR and PCT in early stance (ES=0.97, ES=0.90) and during midstance, CSR and PCT participants exhibited more AP coordination than CTR participants (ES=1.03, ES=1.05). Similarly, CSR and PCT participants demonstrated more AP Ff-Rf coordination than CTR participants in late stance (ES=1.36, ES=1.64). Overall, there was no dominant coordination pattern for Ff-
Rf inversion/eversion during early and midstance for all three groups however, IP and DP coordination were the dominant coordination patterns in late stance for CTR, PCT and CSR participants. Figure 5.4 presents the ensemble group mean phase angle for Ff-Rf coordination throughout stance.

![Figure 5.3: Forefoot-rearfoot inversion/eversion coordination histograms (group mean + SD) for control (CTR), ponseti casting technique (PCT) and comprehensive surgical release (CSR) group for early (0-33%), mid (34-66%) and late stance (67-100%). The four coordination patterns were: anti-phase (AP), in-phase (IP), distal phase (DP) and proximal phase (PP).]
Table 5.4: Mean and standard deviation (SD) forefoot-rearfoot inversion/eversion coordination pattern frequency count for control (CTR), ponseti casting technique (PCT) and comprehensive surgical release (CSR) groups for early, mid and late stance. Coordination patterns: anti-phase (AP), in-phase (IP), distal phase (DP) and proximal phase (PP).

<table>
<thead>
<tr>
<th>Coordination Patterns</th>
<th>Early Stance</th>
<th>Midstance</th>
<th>Late Stance</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP</td>
<td>CTR 8.2 ± 6.7</td>
<td>PCT 8.1 ± 8.1</td>
<td>CSR 15.7 ± 8.8</td>
</tr>
<tr>
<td></td>
<td>7.0 ± 4.2</td>
<td>6.3 ± 5.9</td>
<td>5.9 ± 8.4</td>
</tr>
<tr>
<td></td>
<td>9.9 ± 7.1</td>
<td>6.8 ± 7.7</td>
<td>4.4 ± 5.3</td>
</tr>
<tr>
<td></td>
<td>7.9 ± 5.6</td>
<td>11.8 ± 7.8</td>
<td>7.0 ± 3.6</td>
</tr>
</tbody>
</table>

Table 5.5: Summary of Tukey statistical post-hoc analysis (Adj p) and effect sizes (ES) for group forefoot-rearfoot inversion/eversion coordination patterns over early, mid and late stance. Coordination patterns: anti-phase (AP), in-phase (IP), distal phase (DP) and proximal phase (PP). Large difference between group means (ES>0.8): bold text.

```
<table>
<thead>
<tr>
<th>Group Comparison</th>
<th>Early Stance</th>
<th>Midstance</th>
<th>Late Stance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>p value</td>
<td>Effect Size</td>
<td>p value</td>
</tr>
<tr>
<td>AP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTR, PCT</td>
<td>1.00</td>
<td>0.01</td>
<td>0.18</td>
</tr>
<tr>
<td>CTR, CSR</td>
<td>0.15</td>
<td>0.97</td>
<td>0.16</td>
</tr>
<tr>
<td>PCT, CSR</td>
<td>0.15</td>
<td>0.90</td>
<td>0.98</td>
</tr>
<tr>
<td>IP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTR, CSR</td>
<td>0.07</td>
<td>0.11</td>
<td>0.34</td>
</tr>
<tr>
<td>PCT, CSR</td>
<td>0.93</td>
<td>0.17</td>
<td>0.40</td>
</tr>
<tr>
<td>DP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTR, PCT</td>
<td>0.60</td>
<td>0.37</td>
<td>0.96</td>
</tr>
<tr>
<td>CTR, CSR</td>
<td>0.26</td>
<td>0.89</td>
<td>0.83</td>
</tr>
<tr>
<td>PCT, CSR</td>
<td>0.78</td>
<td>0.37</td>
<td>0.95</td>
</tr>
<tr>
<td>PP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTR, PCT</td>
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<td>0.40</td>
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<tr>
<td>CTR, CSR</td>
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<td>0.89</td>
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<td>PCT, CSR</td>
<td>0.28</td>
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Figure 5.4: Forefoot-rearfoot inversion/eversion coordination ensemble group mean phase angle plot for control (CTR), ponseti casting technique (PCT) and comprehensive surgical release (CSR) group during stance (0-100%).

Histograms summarize the group Rf-Tib kinematics into four distinct coordination patterns (Figure 5.5). No significant differences were found on Rf-Tib coordination pattern frequency between groups throughout stance however, there were large group effects in mid and late stance (Table 5.6, Table 5.7). CSR participants demonstrated more Rf-Tib AP coordination than CTR participants in midstance (ES=1.38) and during late stance, PCT participants exhibited more AP coordination than CTR and CSR participants (ES=1.11, ES=1.15). Overall, PP was the dominant Rf-Tib coordination pattern for CTR, PCT and CSR participants for early, mid and late stance.
Figure 5.5: Rearfoot inversion/eversion-tibial internal/external rotation coordination histograms (group mean ± SD) for control (CTR), ponseti casting technique (PCT) and comprehensive surgical release (CSR) group for early (0-33%), mid (34-66%) and late stance (67-100%). The four coordination patterns were: anti-phase (AP), in-phase (IP), distal phase (DP) and proximal phase (PP).

Table 5.6: Mean and standard deviation (SD) rearfoot inversion/eversion-tibial internal/external rotation coordination pattern frequency count for control (CTR), ponseti casting technique (PCT) and comprehensive surgical release (CSR) groups for early, mid and late stance. Coordination patterns: anti-phase (AP), in-phase (IP), distal phase (DP) and proximal phase (PP).
Table 5.7: Summary of Tukey statistical post-hoc analysis (Adj p) and effect sizes (ES) for group rearfoot inversion/eversion-tibial internal/external rotation coordination patterns over early, mid and late stance. Coordination patterns: anti-phase (AP), in-phase (IP), distal phase (DP) and proximal phase (PP). Large difference between group means (ES>0.8): bold text.

<table>
<thead>
<tr>
<th>Rearfoot Inversion/eversion- Tibial Internal/external Rotation</th>
<th>Early Stance</th>
<th>Midstance</th>
<th>Late Stance</th>
</tr>
</thead>
<tbody>
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<td>Group Comparison</td>
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<td>Effect Size</td>
<td>p value</td>
</tr>
<tr>
<td>AP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTR, PCT</td>
<td>0.69</td>
<td>0.30</td>
<td>0.74</td>
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<tr>
<td>CTR, CSR</td>
<td>0.88</td>
<td>0.49</td>
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<td>PCT, CSR</td>
<td>0.45</td>
<td>0.63</td>
<td>0.33</td>
</tr>
<tr>
<td>IP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTR, PCT</td>
<td>0.91</td>
<td>0.00</td>
<td>0.69</td>
</tr>
<tr>
<td>CTR, CSR</td>
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<td>PCT, CSR</td>
<td>0.86</td>
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<td>0.48</td>
</tr>
<tr>
<td>DP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>1.00</td>
<td>0.00</td>
<td>0.52</td>
</tr>
<tr>
<td>CTR, CSR</td>
<td>1.00</td>
<td>0.00</td>
<td>0.57</td>
</tr>
<tr>
<td>PCT, CSR</td>
<td>1.00</td>
<td>0.00</td>
<td>1.00</td>
</tr>
<tr>
<td>PP</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>CTR, PCT</td>
<td>0.72</td>
<td>0.36</td>
<td>0.68</td>
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<tr>
<td>CTR, CSR</td>
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<td>0.14</td>
<td>0.75</td>
</tr>
<tr>
<td>PCT, CSR</td>
<td>0.91</td>
<td>0.16</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Histograms summarize the group Fem-Tib kinematics into four distinct coordination patterns (Figure 5.6). No significant differences were found on Fem-Tib coordination pattern frequency between groups throughout stance however, there were large group effects in midstance and late stance. PCT participants demonstrated more IP Fem-Tib coordination than CSR participants in midstance (ES=0.99). Also during mid stance, CSR participants demonstrated more DP and PP coordination than PCT and CTR participants (Table 5.8 and Table 5.9). During late stance, CSR participants demonstrated more AP Fem-Tib coordination than PCT participants (ES=0.94). Overall, in early stance the dominant coordination patterns were IP and DP for CTR, PCT and CSR participants. During mid stance, all groups
demonstrated predominantly IP Fem-Tib coordination and during push-off all groups exhibited DP, IP and AP Fem-Tib coordination.

Figure 5.6: Femur-tibia internal/external rotation histograms (group mean + SD) for control (CTR), ponseti casting technique (PCT) and comprehensive surgical release (CSR) group for early (0-33%), mid (34-66%) and late stance (67-100%). The four coordination patterns were: anti-phase (AP), in-phase (IP), distal phase (DP) and proximal phase (PP).
Table 5.8: Mean and standard deviation (SD) femur-tibia internal/external rotation coordination pattern frequency count for control (CTR), ponseti casting technique (PCT) and comprehensive surgical release (CSR) groups for early, mid and late stance. Coordination patterns: anti-phase (AP), in-phase (IP), distal phase (DP) and proximal phase (PP).

<table>
<thead>
<tr>
<th>Femur-Tibia Internal/external Rotation</th>
<th>Frequency Count (Mean ± SD)</th>
<th>AP</th>
<th>IP</th>
<th>DP</th>
<th>PP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Early stance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTR</td>
<td>0.0 ± 0.0</td>
<td>19.1 ± 6.3</td>
<td>13.0 ± 5.2</td>
<td>0.9 ± 2.2</td>
<td></td>
</tr>
<tr>
<td>PCT</td>
<td>0.0 ± 0.0</td>
<td>17.6 ± 5.6</td>
<td>13.7 ± 4.2</td>
<td>1.8 ± 3.1</td>
<td></td>
</tr>
<tr>
<td>CSR</td>
<td>0.0 ± 0.0</td>
<td>21.3 ± 8.5</td>
<td>10.4 ± 7.3</td>
<td>1.3 ± 3.0</td>
<td></td>
</tr>
<tr>
<td>Midstance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTR</td>
<td>0.0 ± 0.0</td>
<td>30.1 ± 5.9</td>
<td>0.5 ± 1.1</td>
<td>2.4 ± 6.0</td>
<td></td>
</tr>
<tr>
<td>PCT</td>
<td>0.0 ± 0.0</td>
<td>30.9 ± 3.2</td>
<td>0.0 ± 0.0</td>
<td>2.1 ± 3.2</td>
<td></td>
</tr>
<tr>
<td>CSR</td>
<td>0.0 ± 0.0</td>
<td>22.6 ± 13.5</td>
<td>0.0 ± 0.0</td>
<td>10.4 ± 13.5</td>
<td></td>
</tr>
<tr>
<td>Late stance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTR</td>
<td>5.6 ± 2.9</td>
<td>9.7 ± 7.1</td>
<td>18.7 ± 5.1</td>
<td>0.0 ± 0.0</td>
<td></td>
</tr>
<tr>
<td>PCT</td>
<td>4.1 ± 2.3</td>
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<td>17.9 ± 2.4</td>
<td>0.0 ± 0.0</td>
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<td>CSR</td>
<td>5.7 ± 1.1</td>
<td>11.3 ± 4.8</td>
<td>17.0 ± 5.5</td>
<td>0.0 ± 0.0</td>
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</tr>
</tbody>
</table>

Table 5.9: Summary of Tukey statistical post-hoc analysis (Adj p) and effect sizes (ES) for group femur-tibia internal/external rotation coordination patterns over early, mid and late stance. Coordination patterns: anti-phase (AP), in-phase (IP), distal phase (DP) and proximal phase (PP). Large difference between group means (ES>0.8): bold text.

<table>
<thead>
<tr>
<th>Femur-Tibia Internal/external Rotation</th>
<th>Early Stance</th>
<th>Midstance</th>
<th>Late Stance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>p value</td>
<td>Effect Size</td>
<td>p value</td>
</tr>
<tr>
<td>CTR, PCT</td>
<td>1.00</td>
<td>0.00</td>
<td>1.00</td>
</tr>
<tr>
<td>CTR, CSR</td>
<td>1.00</td>
<td>0.00</td>
<td>1.00</td>
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<tr>
<td>PCT, CSR</td>
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<td>0.00</td>
<td>1.00</td>
</tr>
<tr>
<td>CTR, PCT</td>
<td>0.87</td>
<td>0.25</td>
<td>0.98</td>
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<tr>
<td>CTR, CSR</td>
<td>0.79</td>
<td>0.30</td>
<td>0.16</td>
</tr>
<tr>
<td>PCT, CSR</td>
<td>0.52</td>
<td>0.52</td>
<td>0.12</td>
</tr>
<tr>
<td>CTR, PCT</td>
<td>0.96</td>
<td>0.15</td>
<td>0.26</td>
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<td>CTR, CSR</td>
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<td>CTR, PCT</td>
<td>0.77</td>
<td>0.34</td>
<td>1.00</td>
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<tr>
<td>CTR, CSR</td>
<td>0.96</td>
<td>0.15</td>
<td>0.13</td>
</tr>
<tr>
<td>PCT, CSR</td>
<td>0.93</td>
<td>0.16</td>
<td>0.12</td>
</tr>
</tbody>
</table>
5.3.3 Coordination Variability

No statistically significant differences were found between groups for Ff-Rf, Rf-Tib, Fem-Tib coordination variability throughout stance (Figure 5.7, Table 5.10). It is however, worth mentioning that CSR individuals demonstrated greater Ff-Rf coordination variability than PCT individuals during late stance. Although this difference did not reach statistical significance at \( p=0.05 \), it did reach a \( p \)-level of 0.07 and a correspondingly large effect size (ES=1.09). In addition, there was a large group effect on Ff-Rf coordination variability during late stance where CSR individuals demonstrated greater amounts of Ff-Rf variability than CTR individuals (ES=0.99).

![Figure 5.7: Coordination Variability](image-url)

**Figure 5.7: Coordination Variability.** Forefoot-rearfoot inversion/eversion (FF-RF), rearfoot inversion/eversion-tibial internal/external rotation (RF-Tib) and femur-tibia internal/external rotation (Fem-Tib) coordination variability (mean + SD) for control, ponseti casting technique and comprehensive surgical release groups throughout early, mid and late stance.
Table 5.10: Group coordination variability mean ± standard deviation (SD) and summary of Tukey statistical post-hoc analysis (Adj p) and effect sizes (ES) for group comparisons. Forefoot-rearfoot inversion/eversion, rearfoot inversion/eversion-tibial internal/external rotation and femur-tibia internal/external rotation coordination variability for early, mid and late stance. Bold text indicates a large difference between group means (ES>0.8).

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<th>Forefoot-Rearfoot Inversion/eversion</th>
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<th>Effect Size</th>
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<td><strong>Early Stance</strong></td>
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<td>39.86 ± 9.46</td>
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<tr>
<td>PCT</td>
<td>40.35 ± 14.13</td>
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<td>0.59</td>
</tr>
<tr>
<td>CSR</td>
<td>45.96 ±14.13</td>
<td>PCT, CSR</td>
<td>0.65</td>
</tr>
<tr>
<td><strong>Midstance</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTR</td>
<td>41.89 ± 14.95</td>
<td>CTR, PCT</td>
<td>0.97</td>
</tr>
<tr>
<td>PCT</td>
<td>40.18 ±15.39</td>
<td>CTR, CSR</td>
<td>0.90</td>
</tr>
<tr>
<td>CSR</td>
<td>45.41 ± 17.84</td>
<td>PCT, CSR</td>
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<td><strong>Late Stance</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>CTR</td>
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<td>CTR, PCT</td>
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</tr>
<tr>
<td>PCT</td>
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<td>CTR, CSR</td>
<td>0.15</td>
</tr>
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<td>CSR</td>
<td>32.80 ± 15.95</td>
<td>PCT, CSR</td>
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<td><strong>Early Stance</strong></td>
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<td>CTR</td>
</tr>
<tr>
<td>PCT</td>
</tr>
<tr>
<td>CSR</td>
</tr>
<tr>
<td><strong>Midstance</strong></td>
</tr>
<tr>
<td>CTR</td>
</tr>
<tr>
<td>PCT</td>
</tr>
<tr>
<td>CSR</td>
</tr>
<tr>
<td><strong>Late Stance</strong></td>
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<tr>
<td>CTR</td>
</tr>
<tr>
<td>PCT</td>
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<td>9.89 ± 8.34</td>
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<td>9.30 ± 3.34</td>
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<td>PCT, CSR</td>
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<td>0.94</td>
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<tr>
<td>CSR</td>
<td>10.85 ± 13.42</td>
<td>PCT, CSR</td>
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5.4 Discussion

The purpose of this study was to determine the multi-segment foot and lower extremity coordination and coordination variability during walking in individuals treated with either PCT or CSR 5-7 years after treatment compared to a healthy non-involved control group in an effort to differentiate how individuals treated with PCT or CSR have adapted in response to the outcomes of the different interventions. Contrary to the hypothesis that the CTR group would exhibit greater AP coordination than the two treatment groups and the PCT group would exhibit more AP coordination than the CSR group, it was found that the Ff-Rf, Rf-Tib and Fem-Tib coupling relationships during walking in PCT and CSR treated clubfeet demonstrate similar organization of the forefoot, rearfoot, tibia and femur as an individual with no history of a clubfoot. In addition, it was hypothesized that the CTR group would demonstrate greater coordination variability than the two treatment groups and the PCT group would exhibit greater coordination variability than the CSR group. Although prior research reported that PCT, CSR and CTR individuals exhibit foot and lower extremity functional differences, no differences were observed in Ff-Rf, Rf-Tib and Fem-Tib coordination variability between the groups. The findings of the present study indicate that PCT and CSR-treated clubfeet demonstrate similar multi-segment foot and lower extremity coordination patterns and coordination variability during the functional task of walking as healthy, non-involved feet 5-7 years post-treatment.
AP Ff-Rf inversion/eversion coordination was not predominantly observed in any group during early, mid and late stance. Previous literature has suggested the articulating forefoot-rearfoot relationship is characterized by AP motion throughout stance. Particularly during pushoff, where it has been thought concomitant forefoot pronation and rearfoot supination occurs (Bojsen-Moller, 1979; ELFTMAN, 1960). Our findings demonstrate that the frontal plane forefoot-rearfoot relationship in the pediatric and adolescent foot is not characterized by predominantly AP motion and is more complex than what has been previously described in the literature. In addition, there were no significant differences between groups in Ff-Rf IP, DP and PP coordination pattern frequency counts during early, mid and late stance. This suggests that PCT and CSR-treated clubfeet demonstrate similar organization of the forefoot and rearfoot throughout stance as a foot with no history of clubfoot. Although no studies have investigated the coordinative patterns of the forefoot-rearfoot relationship during walking in either children or in individuals with a treated clubfoot, the frequency of observations for all frontal plane Ff-Rf coordinative motions in the present study during early, mid and late stance are in good agreement with previously reported data on healthy adults (Chang et al., 2008; James et al., 2013) where no particular dominant Ff-Rf frontal plane motion was observed throughout stance. While the mean values were similar, it is also worth mentioning that the Ff-Rf coupling was observed to have high intra-subject variability in all three groups throughout stance. This is supported by other studies on adults during walking and running, where this motion was subject dependent and highly variable from day to day (Hunt, Smith, Torode, & Keenan, 2001; Pohl, Messenger, & Buckley, 2006;
These results suggest that the frontal plane angular displacements of the forefoot and rearfoot may be independent of each other.

While the mean coordination frequency count values for the Ff-Rf couple did not differ between groups, a closer look at the group ensemble mean phase angle plot revealed qualitative group differences in the order and timing of coordinative patterns throughout early and midstance. Overall, the Ff-Rf group mean phase angle differed not only between the experimental groups and the CTR group but also between the PCT and CSR groups suggesting that CTR, PCT and CSR individuals exhibited different frontal plane Ff-Rf movement strategies throughout early, mid and late stance. Since the treatment methods aim to correct the deformity in fundamentally different ways it is not surprising to observe different frontal plane Ff-Rf movement strategies throughout stance between CTR, PCT and CSR groups.

No significant differences in Rf-Tib AP coordination frequency counts between PCT, CSR and CTR groups were observed throughout stance. Previous literature has suggested that there is a strong mechanical link between rearfoot eversion/tibial internal rotation during early stance and reversely, rearfoot inversion/tibial external rotation during late stance (Hamill, Bates, & Holt, 1992). In the present study, the tibia exhibited greater relative internal rotation throughout stance than rearfoot eversion for all groups. This is in contrast to previous reports in the literature on rearfoot inversion/eversion-tibial internal/external rotation couple in adult uninjured runners where adults exhibited greater relative rearfoot frontal plane motion (DP) throughout stance (Dierks & Davis,
The coordinative patterns of the Rf-Tib during stance have not been characterized in a pediatric population and it is therefore, difficult to make comparisons. However, it has been suggested that the Rf-Tib coupling proportion is dependent on the sagittal plane subtalar joint axis angle which is highly subject dependent (Spasovski, Stevanovic, Vukasinovic, & Slavkovic, 2011). As there were no significant differences observed between groups it may be suggested that pediatric Rf-Tib coordination differs from adult runners.

Fem-Tib coordination was characterized by IP coordination in early and midstance by all three groups. In late stance, exclusive tibial rotation and secondly, IP coordination was observed by all three groups. At heel-strike, maximal shock absorption is achieved by coupled tibial internal rotation and femoral external rotation (AP) which allows the knee to flex. It has been reported that PCT and CSR groups exhibit limited knee flex/extension compared to CTR. The results of the current study are in slight disagreement because the treatment groups demonstrated consistent Fem-Tib coordination as the CTR group throughout stance indicating that Fem-Tib coordination in the pediatric population does not exhibit primarily AP motion to produce knee flexion and extension.

As can be observed in Figure 5.7, the results indicate that multi-segment and lower extremity coordination variability was not significantly different between groups throughout stance. Prior research on coordination variability and pathology suggests greater variability indicates an approach towards a healthy state (Hamill et al., 1999). As there were no statistically significant differences in coordination variability
between groups, the results indicate that the PCT and CSR individuals are able to use similar amounts of movement possibilities of the Ff-Rf, Rf-Tib and Fem-Tib interaction during walking as CTR individuals. In terms of function, it may be suggested that the dynamic foot and lower extremity function in PCT and CSR individuals 5-7 years post-treatment is comparable to healthy, non-involved control feet.

It has been suggested that coordinative variability may be used to discriminate levels of pathology within a cross-sectional population (Hamill et al., 1999; Seay et al., 2011). An important implication of the work of Seay et al. (Seay et al., 2011) is that “recovered” runners, although pain-free, demonstrated less coordination variability than those with no history of an injury. In slight contrast, the treated clubfoot individuals in the present study were pain-free but demonstrated amounts of coordination variability that were not significantly different from individuals with no history of a clubfoot. Therefore, it is suggested that the PCT and CSR are both, successful clinical interventions for clubfoot correction as function was restored or alternate movement strategies were available for pain-free gait for individuals in our clubfoot treatment groups.

The findings of the present study indicate that PCT and CSR-treated clubfeet demonstrate similar multi-segment foot and lower extremity coordination patterns and coordination variability, indicating that at 5-7 years post-treatment function has been restored and PCT and CSR-treated clubfeet are able to utilize alternate movement strategies for pain-free gait.
5.4.3 Limitations

The findings of this study are influenced by a few limitations. No differences were detected between our treatment groups and the control group 5-7 years post-treatment. These results may not be indicative of the long-term functional outcomes of PCT and CSR. While there is support in the literature for the notion that too little or too much coordination variability may be indicative of a pathological or dysfunctional state, an optimal window or threshold of coordination variability has not been determined in adult or pediatric populations. The assumption in the current study is that healthy children with no history of major orthopedic deformities characterize healthy levels of coordination variability and thus, any deviation from this would indicate a pathological or less optimal state in the PCT or CSR-treated clubfoot.

The clubfoot children recruited in this study were pain-free, able to walk at least fifty feet without assistance, not currently using braces/orthoses and not anticipating further clubfoot treatment. It is possible that the lack of pain and use of braces/orthotics in the clubfoot individuals included in the current study characterizes a subgroup of PCT and CSR individuals that are functionally similar to healthy, non-involved controls. Thus, the similarities in coordination and coordination variability quantified in the current study may not be indicative of all PCT and CSR-treated clubfeet 5-7 years post-treatment. Also, the high intra-subject variability in multi-segment foot and lower extremity coordination and coordination variability measures between PCT, CSR and CTR groups can potentially be attributed to high variability in participant characteristics. While all individuals within the PCT and CSR groups where treated by the same orthopedic
surgeon, each child did not necessarily undergo the same PCT or CSR treatment protocol. Number of casting episodes, length of time in casts and foot abduction orthosis, minor follow-up surgeries and/or re-casting episodes are variable and are difficult to control for. Further, a limitation of clinical samples is difficulty with sample size. The large group effects on coordination and coordination variability in the current study suggest that there may be true differences between the PCT, CSR and CTR groups. Our understanding of the after-effects and functional adaptations in PCT and CSR-treated feet and further characterization of multi-segment foot and lower extremity coordination and coordination variability in pediatric populations could be enhanced by future work in these areas.

5.4.4 Conclusion

To our knowledge, this is the first study to identify the coordination patterns and quantify the coordination variability of the multi-segment foot and lower extremity segments during walking in typically-developing children and in children with a treated clubfoot. The coordination and coordination variability results indicate that the PCT and CSR groups are not functionally limited and demonstrate similar multi-segment foot and lower extremity movement patterns and function as healthy, non-involved controls. In the current study, the treatment outcomes of PCT and CSR indicate successful clinical intervention as PCT and CSR individuals demonstrated restored function and exhibited alternate movement strategies for pain-free gait.
CHAPTER 6

SUMMARY AND FUTURE DIRECTIONS

6.1 Summary

Clubfoot is a common 3D deformity of the foot in newborn children, occurring in three in every 1,000 live births (Wynne-Davies, 1972). The deformity consists of equinus, hindfoot varus, forefoot adductus and forefoot cavus and if left untreated, the deformity may lead to severe discomfort and disability later in life. The Ponseti casting technique (PCT) and comprehensive surgical release (CSR) are the two primary treatment methods for the clubfoot correction. The PCT is currently the standard of care for clubfoot correction (Ponseti, 1992; Zionts et al., 2010). However, there is a lack of reliable, reproducible, and accurate objective measures of dynamic foot function after clubfoot treatment. Therefore, despite previous reports in the literature, there is very little understanding of the dynamic function of the PCT and CSR-treated clubfoot 5-7 years after treatment. Since the clubfoot deformity exists in the foot, further understanding of the position and orientation of the foot segments during walking is integral in order to investigate the biomechanical and functional differences that exist between typically-developing, PCT and CSR-treated feet. Further, the coordinative function of the treated clubfoot in children has yet to be characterized and may offer insight into how individuals treated with PCT or CSR have adapted in terms of dynamic function, in response to the different interventions.

Therefore, the purpose of this study was to examine group differences in lower extremity segmental/joint kinematics, kinetics and to determine the
lower extremity coordination and coordination variability, specifically of the rearfoot and forefoot, during walking in individuals treated with either the PCT or CSR 5-7 years after treatment compared to typically-developing controls. This study utilized a dynamical systems analysis approach and a multi-segment foot model to characterize the coordinative function of the foot and lower extremity segments to understand the impact of two radically different clubfoot treatment interventions on dynamic function.

6.2 Study Results

The current study found few multi-segment foot and lower extremity ROM values that were significantly different compared with typically-developing feet; despite having good overall function, restricted midfoot and MTP joint motion and abnormal lower extremity joint moments were the main characteristics of the gait observed for both PCT and CSR groups.

Ankle dorsi/plantar flexion ROM values were similar between all groups which is in opposition to results reported in the literature. A more detailed analysis using the multi-segment foot model revealed reduced midfoot and MTP joint ROM in CSR-treated feet while the PCT-treated feet demonstrated values comparable to typically-developing feet. It has been suggested that abnormal forefoot and rearfoot kinematics are compensatory movement strategies and are responsible for the appearance of normal sagittal plane ankle kinematics (Smith et al., 2013).

Perhaps the most consistent abnormal finding of this study was the reduced ankle plantar flexion moment in the last 50% of stance in the clubfoot groups. Reduced ankle
plantar flexion moment, midfoot ROM and MTP dorsiflexion at pushoff may be suggestive of reduced muscular strength in PCT and CSR treated clubfeet.

The current study found few deviations from normal in the ROM of the proximal joints which is in disagreement with some previous studies (Alkjaer et al., 2000; C. T. Davies et al., 2001). The results of this study did find abnormal joint moments at the ankle, knee and hip. The CSR group demonstrated greater knee and hip moments compared to CTR and PCT which is in agreement with previous gait analysis studies. However, compared to PCT, CSR participants demonstrated significantly reduced frontal plane ankle ROM. Compared to typically-developing participants, the PCT individuals demonstrated diminished peak ankle eversion, knee external rotation and knee valgus moments.

In the current study, PCT and CSR treated clubfeet 5-7 years post-treatment, without pain and not anticipating further interventions demonstrate nearly normal movement in the lower extremity. Despite having good overall function, restricted midfoot and MTP joint motion as well as abnormal lower extremity joint moments were the main characteristics of the gait of children with a clubfoot treated by PCT or CSR. The current study has shown that not all PCT-treated clubfeet are free from recurrent deformity.

Although the kinematic and kinetic results of this study indicated abnormal movement patterns suggestive of residual deformity, no significant differences were observed in Ff-Rf, Rf-Tib and Fem-Tib coordination and coordination variability between the groups. Contrary to the hypothesis, AP Ff-Rf inversion/eversion
coordination was not predominantly observed in any group during early, mid and late stance. Our findings demonstrate that the frontal plane Ff-Rf relationship in the pediatric and adolescent foot is not characterized by predominantly AP motion and is more complex than what has been previously described in the literature. In addition, there were no significant differences between groups in Ff-Rf IP, DP and PP coordination pattern frequency counts during early, mid and late stance. This suggests that PCT and CSR-treated clubfeet demonstrate similar organization of the forefoot and rearfoot throughout stance as a foot with no history of clubfoot. While the mean values were similar, it is also worth mentioning that the Ff-Rf coupling was observed to have high intra-subject variability in all three groups throughout stance, which suggests that the frontal plane angular displacements of the forefoot and reafoot may be independent of each other.

While the mean coordination frequency count values for the Ff-Rf couple did not differ between groups, the Ff-Rf group mean phase angle differed between the CTR, PCT and CSR groups. This suggests that CTR, PCT and CSR individuals exhibited different frontal plane Ff-Rf movement strategies throughout early, mid and late stance. Since the treatment methods aim to correct the deformity in fundamentally different ways, it is not surprising to observe different frontal plane Ff-Rf movement strategies throughout stance between CTR, PCT and CSR groups.

No significant differences in Rf-Tib AP coordination frequency counts were observed between PCT, CSR and CTR groups throughout stance. In the present study, the tibia exhibited greater relative internal rotation throughout stance than rearfoot eversion for all groups. The coordinative patterns of the Rf-Tib during stance have not been
characterized in a pediatric population and it is therefore, difficult to make comparisons. However, it has been suggested that the rearfoot inversion/eversion and tibial internal/external rotation coupling proportion is dependent on the sagittal plane subtalar joint axis angle which is highly subject dependent (Spasovski et al., 2011).

Fem-Tib coordination was characterized by IP coordination in early and midstance by all three groups. Exclusive tibial rotation and secondly, IP coordination was observed by all three groups in late stance. At heel-strike, maximal shock absorption is achieved by coupled tibial internal rotation and femoral external rotation (AP), which allows the knee to flex. The results of this study indicate that Fem-Tib coordination in the pediatric population does not exhibit primarily AP motion to produce knee flex/ext.

Multi-segment foot and lower extremity coordination variability was not significantly different between groups throughout stance indicating that PCT and CSR individuals are able to use similar amounts of movement possibilities of the Ff-Rf, Rf-Tib and Fem-Tib interaction during walking as CTR individuals. In terms of function, it may be suggested that the dynamic foot and lower extremity function in PCT and CSR individuals 5-7 years post-treatment is comparable to healthy, non-involved control feet. It has been suggested that coordinative variability may be used to discriminate levels of pathology within a cross-sectional population (Hamill et al., 1999; Seay et al., 2011). The treated clubfoot individuals in the present study were pain-free but demonstrated amounts of coordination variability that were not significantly different from individuals with no history of a clubfoot.
The findings of the present study indicate that PCT and CSR-treated clubfeet demonstrate similar multi-segment foot and lower extremity coordination patterns and coordination variability, indicating that at 5-7 years post-treatment function has been restored and PCT and CSR-treated clubfeet are able to utilize alternate movement strategies for pain-free gait.

6.3 Future Directions

No significant differences in multi-segment foot and lower extremity coordination variability were detected between CTR, PCT and CSR groups 5-7 years post-treatment. While there is support in the literature for the notion that too little or too much coordination variability may be indicative of a pathological or dysfunctional state, an optimal window or threshold of coordination variability has not been determined in adult or pediatric populations. The assumption in the current study is that healthy children with no history of major orthopedic deformities characterize healthy levels of coordination variability and thus, any deviation from this would indicate a pathological or less optimal state in the PCT or CSR-treated clubfoot. Also, the clubfoot children recruited in this study were pain-free, able to walk at least fifty feet without assistance, not currently using braces/orthoses and not anticipating further clubfoot treatment. It is possible that the lack of pain and use of braces/orthotics in the clubfoot individuals included in the current study characterizes a subgroup of PCT and CSR individuals that are functionally similar to healthy, non-involved controls. Thus, the similarities in coordination and coordination variability quantified in the current study may not be indicative of all PCT and CSR-
treated clubfeet 5-7 years post-treatment. Also, the high intra-subject variability in multi-segment foot and lower extremity coordination and coordination variability measures between PCT, CSR and CTR groups can potentially be attributed to high variability in participant characteristics. While all individuals within the PCT and CSR groups where treated by the same orthopedic surgeon, each child did not necessarily undergo the same PCT or CSR treatment protocol. Number of casting episodes, length of time in casts and foot abduction orthosis, minor follow-up surgeries and/or re-casting episodes are variable and are difficult to control for. In addition, a limitation of clinical samples is difficulty with sample size. The large group effects on coordination and coordination variability in the current study suggest that there may be true differences between the PCT, CSR and CTR groups. Our understanding of the after-effects and functional adaptations in PCT and CSR-treated feet and further characterization of multi-segment foot and lower extremity coordination and coordination variability in pediatric populations could be enhanced by future work in these areas.
BIBLIOGRAPHY


