MULTI-SEGMENT COORDINATION WITHIN THE FOOT IN CHILDREN WITH AND WITHOUT CLUBFOOT DURING WALKING, TOE RAISES AND SINGLE LIMB HOPPING

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To the Dean of the Graduate School:

I am submitting herewith a dissertation written by Kirsten Lynn Tulchin entitled "Multi-Segment Coordination Within the Foot in Children With and Without Clubfoot During Walking, Toe Raises and Single Limb Hopping." I have examined this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy with a major in Kinesiology.

Young-Hoo Kwon, Ph.D., Major Professor

We have read this dissertation and recommend its acceptance:

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ABSTRACT

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MULTI-SEGMENT COORDINATION WITHIN THE FOOT IN CHILDREN WITH AND WITHOUT CLUBFOOT DURING WALKING, TOE RAISES AND SINGLE LIMB HOPPING

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Children born with congenital idiopathic clubfoot have significant foot deformity that requires treatment at birth. Long term outcomes in patients who were treated for congenital clubfoot have reported gastrocnemius weakness, limited ankle motion and reduced ankle power during gait. There have been few studies, however, that have directly assessed how these changes in foot mechanics affect the ability to perform more challenging tasks. The purpose of this study was to assess kinematics, kinetics and joint coupling within the foot in children previously treated for clubfoot. Sixteen children with 23 affected clubfeet and 16 children without history of clubfoot underwent three-dimensional motion analysis using a multi-segment foot model, during three activities: walking, toe-raises and hopping. Children with clubfoot demonstrated a reduction of sagittal plane hindfoot range of motion during walking, with limited forefoot range of motion during toe raises and hopping. Decreased ankle power generation was seen during all three activities in children with clubfoot when compared to children without clubfoot. The addition of joint coordination assessment identified reductions in *in-phase* coupling during hopping and toe raise activities, which were not detected with kinematic evaluation alone. Overall children with clubfoot had reduced center of mass excursion during hopping and reduced heel height during toe raises. Although outcomes in clubfoot can vary greatly, the combination of multi-segment foot

kinematics, inter-joint and intra-segment foot coupling, and age-appropriate, challenging protocols which include tasks other than overground walking, can provide a means to define foot function and mobility in both children and adults. Understanding the biomechanics within the foot may help physicians with treatment-decision making, and lead to improved functional outcomes in patients with clubfoot and/or other foot pathologies.

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CHAPTER I

INTRODUCTION

Clubfoot, also known as congenital talipes equinovarus (TEV), affects 1 to 2 in every 1,000 live births (Faulks & Luther, 2005). Characterized by equinus and varus of the hindfoot, with adduction and inversion of the forefoot, this disease is initially treated at birth. Residual deformity later in childhood, however, has been reported in up to 95% of feet initially treated with surgical intervention (Herzenberg, Radler, & Bor, 2002). The implementation of nonoperative treatments has been shown to decrease the likelihood of recurrence, with successful outcomes approximating 60% in children treated with either the Ponseti Method (weekly serial long leg casts) and the French Physical Therapy Method (daily stretching, massage and taping; Faulks & Luther, 2005).

Quantitative outcomes in patients with clubfoot have been somewhat limited. Initial surgical treatment often results in limited successful correction rates and poor functional outcomes with weak triceps surae, leading to decreased plantarflexion at toe-off and associated decreases in ankle moment and ankle power generation (Davies, Kiefer, & Zernicke, 2001; Karol, Concha, & Johnston II, 1997). More recently, nonoperative treatments using the Ponseti and French Physical Therapy Methods have shown promising results at 2 years (El-Hawary, Karol, Jeans, & Richards, 2008) and 5 years (Karol, Jeans, & El-Hawary, 2009) of age, with close to 50% of patients demonstrating normal foot motion during gait at these early ages; long-term results, however, are not yet known.

The majority of gait outcomes studies have modeled the foot as a single rigid body at the end of the leg and the gross movement of the foot at the talocrural (ankle) joint has been assessed as the primary movement. Over the last 10 years, more advanced multi-segment foot models have enabled researchers to gain a better understanding of foot mechanics during walking. Multi-segment foot models require multiple markers to be placed on the foot, which was not feasible with motion capture system technology 20 years ago. Increased spatial resolution of the cameras, and advancements in motion capture software, now enable the foot to be modeled as three or more segments, which can potentially provide new insight into the biomechanics in the foot in patients with clubfoot.

To date, there are only two studies that have used multi-segment foot models to assess outcomes in patients with clubfoot. Theologis and colleagues reported on 20 children with clubfoot who were initially treated nonoperatively with a combination of casting and stretching; however all children went on to further surgical treatment (Theologis, Harrington, Thompson & Benson, 2003). Foot mechanics were assessed during the stance phase of barefoot walking using the Oxford Foot Model. They found significant increases in midfoot dorsiflexion, which they hypothesized was a compensation for the decreased range of motion seen at the hindfoot. Graf et al. (2010) studied 24 adult patients initially treated surgically for clubfoot and found residual hindfoot equinus and forefoot dorsiflexion and adductus at long term follow-up. Moreover, subjects had weakness and limited range of motion, and 96% reported foot pain.

One underlying similarity to all the studies examining gait/biomechanical functional outcomes in patients with clubfoot to date was the task performed during the analysis: barefoot walking at a self-selected speed. Bovi, Rabuffetti, Mazzoleni and Ferrarin (2011) recently recommended a multi-task gait analysis protocol to assess functional abilities in patients with pathologies. This is particularly useful in populations such as patients with clubfoot, in whom early results of nonoperative treatment at 2 to 5 years reveal only minor kinematic disturbances during gait in an otherwise functional child. Given the previous research that has shown significant plantarflexor weakness later in life (Graf et al., 2010; Karol et al., 1997; O'Brien, Karol, & Johnston II, 2004) it seems reasonable to assess activities, in addition to barefoot walking, that require plantarflexor activation and strength. Single limb toe raises and single limb hopping are two tasks that are often performed in the physician's office to assess strength and coordination. Maton and Wicart (2005) evaluated electromyography and ground reaction forces during a bilateral toe raise task in 8 to12 year old subjects with and without clubfoot. They found significant changes in the affected side gastrocsoleus electromyography and vertical acceleration in the clubfoot group, concluding that it is important to continue to follow a child with clubfoot in the medical clinics, even if they resume a 'normal' life following treatment.

Joint coordination within the foot has not been previously assessed in the clubfoot population. Methods of dynamic systems analysis, including vector coding, have been used primarily in the running literature to assess rearfoot coupling patterns to the tibia or forefoot (Ferber, Davis, & Williams, 2005; Heiderscheit, Hamill, & van Emmerik, 2002; Williams, McClay, Hamill, & Buchanan, 2001). Only one previous report was found that assessed dynamic coupling patterns using multi-segment foot kinematics, in a pathological foot (Dubbeldam, Buurke, Nene, Baan, & Hermens, 2011). In their study of patients with rheumatoid arthritis, Dubbeldam et al. (2011) found stronger coupling patterns in healthy adults compared to patients with arthritis. In addition, poor coupling between the first metatarsophalangeal joint and hindfoot eversion was found in patients who had plantar fascia degeneration as seen on magnetic resonance imaging. Pilot work in a case study looking at single limb hopping in a 10-year old child with clubfoot revealed a significant uncoupling of the hindfoot and forefoot on the affected side (Tulchin & Orendurff, 2009). Following only 12 single limb hops, fatigue-induced changes in this coupling pattern were also seen, as the hindfoot and forefoot began to uncouple and work against each other.

The novel application of these analysis techniques using multi-segment foot kinematics to the pediatric foot may lead researchers to discover new insights into the function *within* the foot in the idiopathic clubfoot. Gaining an understanding of the foot mechanics during overground walking and two tasks– single limb toe raises and single limb hopping, may allow clinicians to develop new treatment strategies and therapies for children with clubfeet.

Purpose

The purpose of this study was to assess foot mechanics and joint coupling in the pediatric foot, and specifically to compare the multi-segment foot biomechanics during (a) overground walking, (b) single limb hopping and (c) single limb toe raises between a group of children previously treated for congenital clubfoot and age-matched children without clubfoot. The use of a motion analysis protocol which incorporates multi-segment foot kinematics and more challenging activities such as single limb toe raises and single limb hopping may help identify biomechanical differences between children previously treated for clubfoot and children without clubfoot which may be missed by testing overground walking alone.

Research Questions

1. Do children previously treated for clubfoot demonstrate different ankle kinematics and kinetics, multi-segment foot kinematics, and coordination during overground walking at a self-selected speed compared to age-matched children without clubfoot?

2. Do children previously treated for clubfoot demonstrate different ankle kinematics and kinetics, multi-segment foot kinematics, and coordination during single limb hopping compared to age-matched children without clubfoot?
3. Do children previously treated for clubfoot demonstrate different ankle kinematics and kinetics, multi-segment foot kinematics, and coordination during single limb toe raises compared to age-matched children without clubfoot?

Null Hypotheses

$H_0 1$: There will be no differences in ankle kinematics and kinetics, multi-segment foot kinematics, and coordination during overground walking at a self-selected speed in children previously treated for clubfoot when compared to age-matched children without clubfoot.

$H_0 2$: There will be no differences in ankle kinematics and kinetics, multi-segment foot kinematics and coordination during single limb hopping in children previously treated for clubfoot when compared to age-matched children without clubfoot.

$H_0 3$: There will be no differences in ankle kinematics and kinetics, multi-segment foot kinematics and coordination during single limb toe raises in children previously treated for clubfoot when compared to age-matched children without clubfoot.

Definitions

Ankle Joint – the articulation of the talus in the ankle mortise (created by the tibia and fibula); also referred to as the talocrural joint.

Ankle Motion – the motion of the foot segment relative to the leg in the Conventional Gait Model.

Anti-Phase Coupling – a coordination pattern between two angular movements when one angular motion is occurring in the positive direction and the other angular motion is occurring in the negative direction.

Chopart Joint (Transverse Tarsal Joint) – articulations of the talonavicular and calcaneocuboid joints; connects the midfoot region of the foot to the hindfoot region.

Clubfoot (Congenital Talipes Equinovarus or TEV) – congenital deformity of the foot affecting 1 to 2 out of every 1,000 live births; it is characterized by equinus and varus of the hindfoot and adduction and inversion of the forefoot.

Conventional Gait Model – widely accepted, bilateral lower extremity biomechanical model first reported by Davis, Ounpuu, Tyburski and Gage (1991) and Kadaba, Ramakrishnan and Wootten (1990) for use in clinical gait analysis; in this model the foot is defined as a single rigid body at the end of the leg.

Forefoot – region of the foot that describes the metatarsals, and typically the phalanges; in the Texas Scottish Rite Hospital for Children (TSRHC) Foot and Ankle model, *FOREFOOT* motion refers to motion of the metatarsal/navicular segment with respect to the hindfoot.

Hindfoot – the talus and calcaneus; in the TSRHC Foot and Ankle model, *HINDFOOT* motion refers to motion of calcaneal segment with respect to the leg.

In-phase Coupling – a coordination pattern between two angular movements when either both angular motions occur in the positive direction or both angular motions occur in the negative direction.

Leg (Shank or Tibia) – the distal region of the lower limb between the ankle and knee joint centers, comprised of the tibia and fibula; in the TSRHC Foot and Ankle model, *TIBIA* motion refers to motion of the leg with respect to the global reference frame.

Lisfranc Joint – articulations of the tarsometatarsal joints; connects the midfoot region of the foot to the forefoot.

Midfoot – the region of the foot that consists of the tarsal bones; this region of the foot is between the Chopart and Lisfranc joints.

Multi-Segment Foot Model – biomechanical motion analysis models which represent the foot as a series of rigidly linked segments; these models provide more detailed analysis of the motion within the foot as compared to the Conventional Gait Model.

Out-of-Phase Coupling – a coordination pattern between two angular movements such that motion is predominately occurring through only one of the two angular motions.

Overground Walking – subjects walk comfortably across the room along an approximately ten meter level walkway.

Single Limb Hopping – subjects perform single footed hopping as high and as fast as possible, for as long as they can before they fatigue; the activity is then repeated on the opposite side.

Single Limb Toe Raises – subjects perform 20 consecutive single limb toe raises, lifting their heel and going up as high as possible on their toes; the activity is then repeated on the opposite side.

Subtalar Joint – articulation between the calcaneus and the talus.

Assumptions

1. Each defined segment was assumed to be a rigid body, and intra-segmental marker motion was negligible.
2. The body and feet were modeled as a system of rigidly linked segments, with friction-less pin joints connecting each segment.

Delimitations

1. All subjects with idiopathic congenital clubfoot were initially treated nonoperatively at Texas Scottish Rite Hospital for Children. Although these subjects potentially spanned across seven different treating orthopedic surgeons, institutional bias and physician-specific treatment techniques will not be considered.
2. All subjects were between the ages of 9.5 and 11.5 years old at the time of testing. While this is a limited age range, it is a sample of convenience. All subjects in the Clubfoot Group were already participating in an established research protocol and due for evaluation based on that protocol.
3. Individual variations in previous treatment for clubfoot were not specifically examined in this study, due to the limited sample size and the individual variations in both initial treatment and subsequent treatments. All subjects, however, were initially managed with a nonoperative approach.
4. Participants without clubfoot (Control Group) were age- and gender- matched to the children previously treated for clubfoot (Clubfoot Group), and all subjects in the Control Group were recruited primarily from the Dallas-Fort Worth community.

Limitations

1. All foot markers were placed directly on the skin, and therefore some skin motion artifact may exist between the marker and the underlying bony segments. Extensive research has been reported in the literature regarding the use of skin markers in comparison to measurement techniques using bone pins. Although bone pins may provide more direct measurements of foot bone motion, the inherent risks and invasive nature of these markers exclude them from use in the pediatric populations studied herein.

2. Intra-segment marker motion may occur as rigid body segments often spanned multiple foot joint articulations. Moreover, it is important to note that relative motion between segments may have represented more than one joint.
3. Adequate instructions were given to each participant prior to and during all phases of this protocol. Some intra-subject and/or inter-subject variability, however, may be expected.
4. Since the order of tasks was not randomized during the testing session, fatigue may have been a factor which was not considered. Adequate time for rest was given between tasks, and all subjects were allowed to take a seated break at their discretion.

Significance of Study

Children born with clubfoot have significant foot deformity that requires treatment at birth. Short term outcomes at 2 and 5 years of age in nonoperative patients have identified some mild to moderate variations in walking mechanics. Long term outcomes in patients who were treated with initial surgical intervention have been generally poor, with weakness and limited ankle motion and power during gait. New techniques using motion analysis with multi-segment foot models can provide additional insight into the biomechanics of the foot. Specifically the assessment of the coupling patterns seen between the hindfoot and forefoot during challenging tasks such as toe raises or hopping, which may require increased range of motion and /or increased ankle power generation, may better identify deficits of foot and ankle function. Through this study, it was hoped to gain a better understanding of the foot mechanics in both children previously treated with initial nonoperative treatment for congenital clubfoot, and children without clubfoot. This knowledge may help physicians with treatment-decision making, and lead to improved functional outcomes in patients with clubfoot.

CHAPTER II

REVIEW OF LITERATURE

Introduction

Research examining the kinematics within the foot using multi-segment foot modeling in children previously treated for clubfoot is limited. Those studies which have been reported primarily focused on kinematic and kinetic variables during overground walking. This review of the literature will explore five areas: an overview of the presentation and treatment of children with clubfoot, the biomechanical manifestations of residual clubfoot deformity, multi-segment kinematic foot modeling, biomechanical assessment of challenging activities other than walking, and dynamic systems theory. In order to fully understand these topics, a brief summary of the structure, arthrology and motion of the foot and ankle will first be presented.

Anatomical Review of the Foot and Ankle

The foot serves as the primary point of contact with the ground during ambulation, and therefore is the first in line to absorb impact forces to the body. With 28 bones, 23 muscles and numerous connective tissues, the foot must be pliable enough to conform to the terrain, yet rigid enough to withstand large propulsive forces (Neumann, 2002). It is the interaction and coordination of its bones and joints within that allow the foot to perform these two contradicting necessities.

Terminology of Movements

Terminology used to describe the motion of the foot can actually vary between specialties, and therefore it is important to define the terms that will be used throughout this manuscript (Table 1).

Table 1

Terminology for Regional Foot Motion

Plane of Motion	**Axis of Rotation**	**Angular Movement**	**Fixed Deformity or Abnormal Posture**
Sagittal	Medial-Lateral	Plantarflexion	Pes equinus
		Dorsiflexion	Pes calcaneus
Coronal	Anterior-Posterior	Inversion	Varus
		Eversion	Valgus
Transverse	Vertical	Adduction (Forefoot) Internal Rotation (Hindfoot)	Adductus (Forefoot)
		Abduction (Forefoot) External Rotation (Hindfoot)	Abductus (Forefoot)
Multi-planar	Oblique	Supination	Varying elements of plantarflexion, inversion and adduction
		Pronation	Varying elements of dorsiflexion, eversion and abduction

Bony Anatomy and Joint Arthrology

While there are many terms used to divide the foot into regions, specific language will be used throughout this document. The *leg*, or shank, is comprised of the tibia and fibula, while the *foot* refers to all bones and structures distal to the tibia and fibula. Figure 1 illustrates the bony anatomy of the foot. The 'true' ankle joint, or *talocrural* joint, is comprised of the tibia, fibula and talus, and is often referred to as the ankle mortise. The talocrural joint has only one primary degree of freedom, with the axis of rotation oriented superiorly, approximately 10°, and

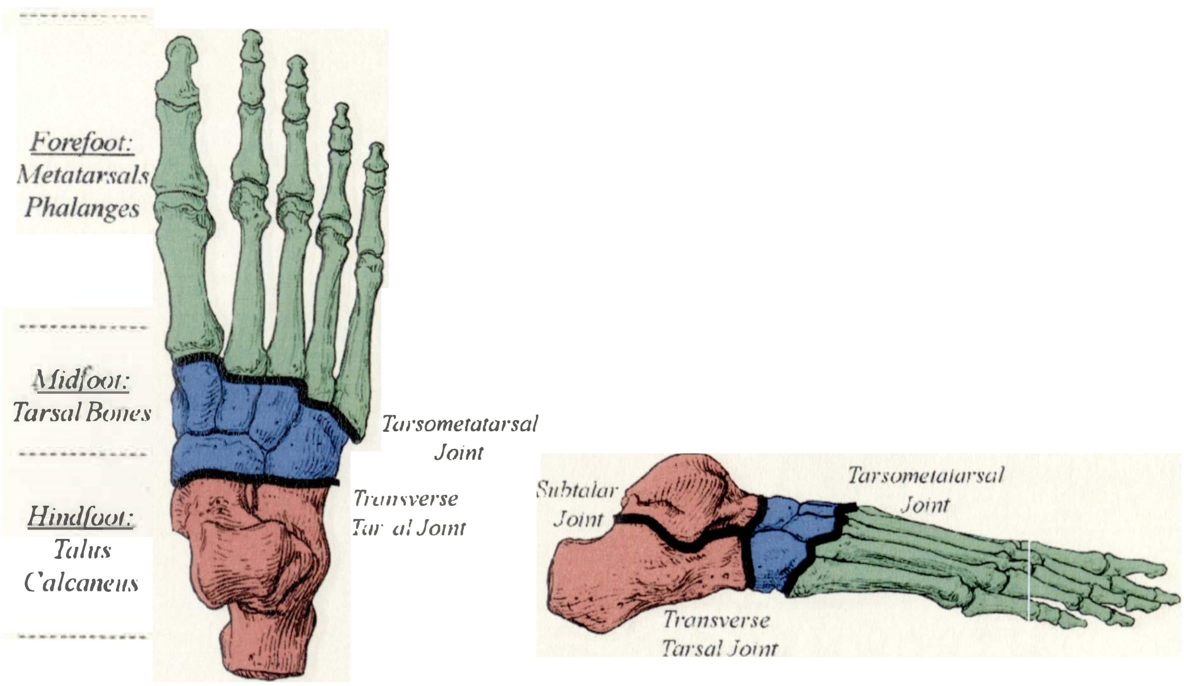


Figure 1: Bony anatomy of the foot. (S. Almond, Illus., Courtesy of Texas Scottish Rite Hospital for Children)

anteriorly, approximately 6°, as it passes from the lateral to the medial malleoli of the fibula and tibia, respectively (Figure 2, Neumann, 2002). Due to the orientation of the axis of rotation, there is slight abduction and eversion associated with dorsiflexion of the foot, and adduction and inversion with plantarflexion. However, while the movement at the talocrural joint is technically pronation and supination, it is predominately defined by 25° of dorsiflexion and almost 50° of plantarflexion. The neutral position, where plantarflexion and dorsiflexion are both zero, is the position where the plantar surface of the hindfoot is at 90° to the leg.

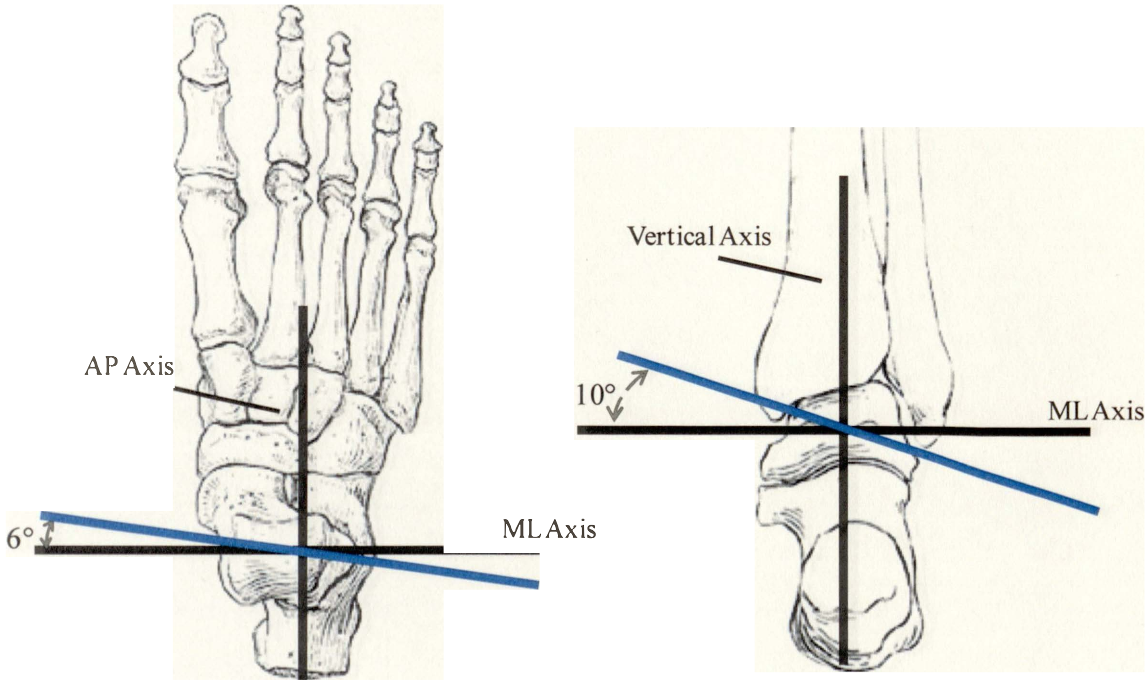


Figure 2: Talocrural joint axis of rotation. (S. Almond, Illus., Courtesy of Texas Scotti h Rite Hospital for Children)

Th *hindfoot,* or rearfoot is comprised of the talus and calcaneus and together with the talocrural joint it forms the ankle joint complex. The subtalar joint represents the articulation between the talus and calcaneus within the hindfoot. Motion of the subtalar joint follows a curvilinear arc of movement, and typically the axis of rotation runs superiorly, anteriorly and medially from the lateral-posterior heel. While significant variation can occur across subjects, the axis of rotation is typically oriented 42° from horizontal and 16° from the sagittal plane (Figure 3, Neumann, 2002). Due to this orientation, the main components of motion at the subtalar joint are inversion/eversion and abduction/adduction. Grimston, Nigg, Hanley, and Engsberg (1993) reported active range of motion at the ankle joint complex across a variety of age groups. In their study, the motion of the subtalar joint in 9 to 13 year olds was significantly increased in adduction

(42.2 vs. 33.6° average across all ages), slightly greater in inversion (26.7 vs. 22.6°) and abduction (41.6 vs. 38.3°) and slightly decreased in eversion (10.5 vs. 12.5°, Grimston et al., 1993). The mobility of the subtalar joint allows the foot to move independent of the leg/ankle, which is important in ambulation and function in the community, particularly during incline walking and maintaining balance on unstable surfaces (Neumann, 2002).

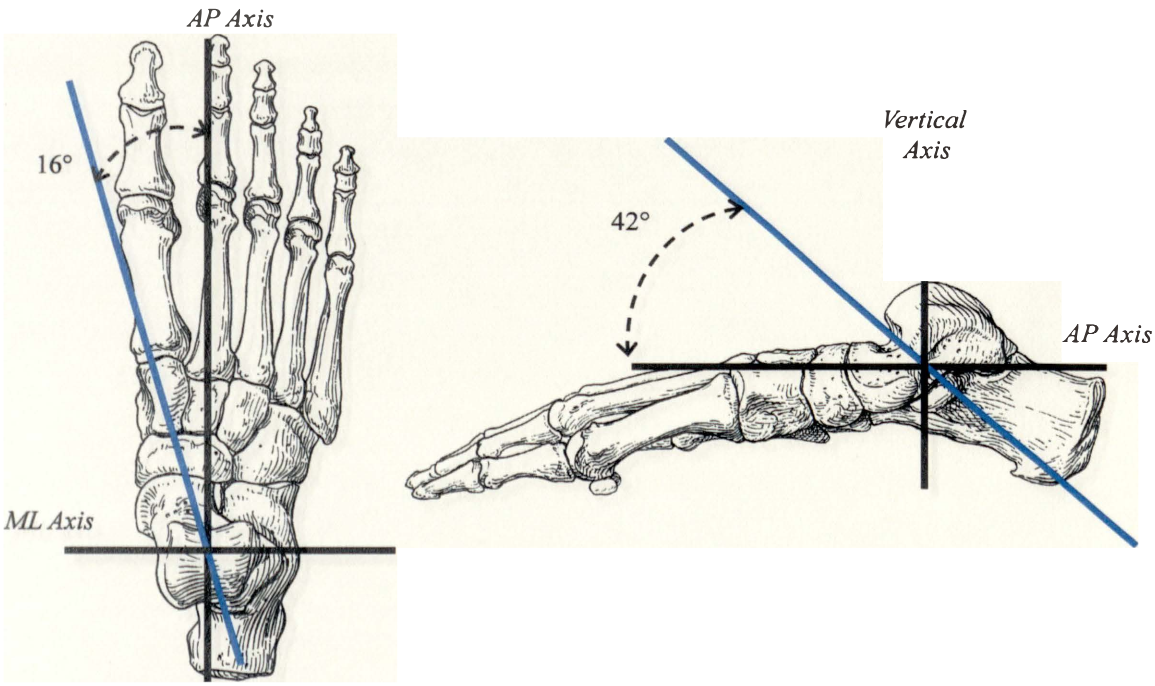


Figure 3: Subtalar joint axis of rotation. (S. Almond, Illus., Courtesy of Texas Scottish Rite Hospital for Children)

The *midfoot* is comprised of the navicular, cuboid and three cuneiforms. Connecting the midfoot to the hindfoot is the transverse tarsal joint, also known as the Chopart joint, comprised of the talonavicular and the calcaneocuboid joints (Neumann, 2002). As a set, the three cuneiform bones serve as a spacer between the navicular and the medial metatarsal bones (transverse tarsal joints), and help to form the transverse arch of the foot (Hamill & Knutzen, 1995). The transverse arch contributes to the dorsal convexity of the midfoot. The proximal surface of the navicular articulates with the head of the talus to form the talonavicular joint, while the proximal surface of the cuboid articulates with the calcaneus to form the calcaneocuboid joint (Neumann, 2002). These joints work closely with the subtalar joint in normal feet, and control most of the pronation and supination that occurs through the foot (Hamill & Knutzen, 1995). The plane of motion of the transverse tarsal joints is perpendicular to two different axes of rotation – the longitudinal and oblique axes (Figure 4). The longitudinal axis is closely aligned (approximately 15°) to the anterior-posterior axis and has a primary motion of inversion and eversion (Neumann, 2002). The oblique axis offers a combination of abduction/adduction and dorsiflexion/plantarflexion with its vertical (52°) and mediolateral (57°) orientation (Neumann, 2002).

The remaining joints within the midfoot include the cuneonavicular, cuboideonavicular, cuneocuboid and intercuneiform joints (Hamill & Knutzen, 1995). They also can produce additional, although small, degrees of pronation/ supination with the transverse tarsal joint. These joints primarily provide stability across the midfoot by forming the transverse arch mediolaterally across the foot. The transverse arch, specifically the intercuneiform and cuneocuboid joint complex, serves to assist in transverse stability of the foot and is supported by passive ligaments and connective tissues as well as both intrinsic and extrinsic muscles (Neumann, 2002). The keystone of the transverse arch is the intermediate cuneiform.

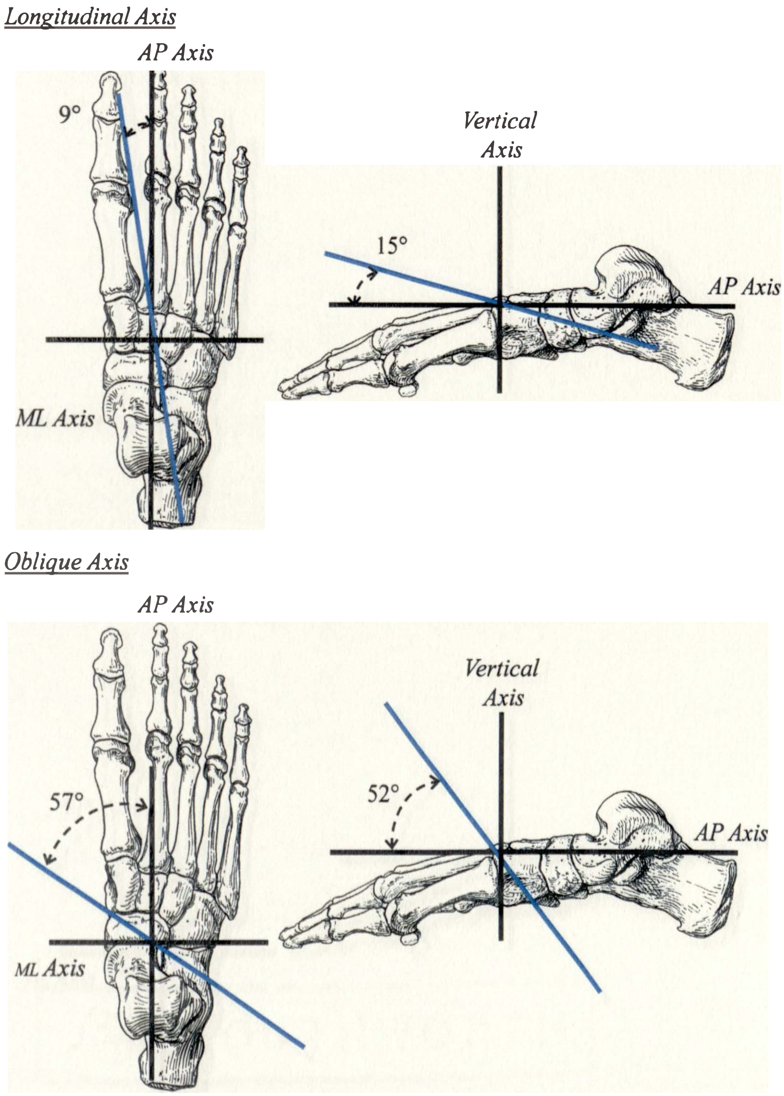


Figure 4: Longitudinal and oblique transverse tarsal joint axes of rotation. (S. Almond, Illus., Courtesy of Texas Scottish Rite Hospital for Children)

The *forefoot* consists of the rays of the foot, with each ray formed by a metatarsal and its associated phalanges. Of the five metatarsals, the first is the thickest and shortest, while the second metatarsal is typically most rigidly attached to the tarsal bones. Both of these features are due to the large forces placed on the medial forefoot during the later part of stance phase

(Neumann, 2002). There are 14 associated phalanges. The articulations between the bases of the five metatarsals and the tarsal bones (medial, intermediate and lateral cuneiforms and the cuboid) are called the tarsometatarsal joints, or collectively, the Lisfranc joint. Motion at the second metatarsal is the smallest, and it forms a central pillar of stability in the foot (Neumann, 2002). Motion of the first ray consists of a combination of dorsiflexion and inversion, or plantarflexion and eversion, and contributes greatly to the flexibility of the medial longitudinal arch.

The medial longitudinal arch (MLA) is formed by the entire foot – from the calcaneus and talus through the navicular and cuneiforms to the three medial metatarsals. The talonavicular joint is at the approximate location of the keystone of this arch (Figure 5). The MLA serves to provide shock-absorption and is a load-bearing structure that is supported by both passive structures including the plantar fascia, plantar calcaneonavicular ligament and short plantar ligaments and active forces from the intrinsic and extrinsic muscles of the foot (Neumann, 2002). Pe planus refers to a condition where the MLA has dropped leading to a flatfoot, while pes cavus r presents an abnormally high MLA.

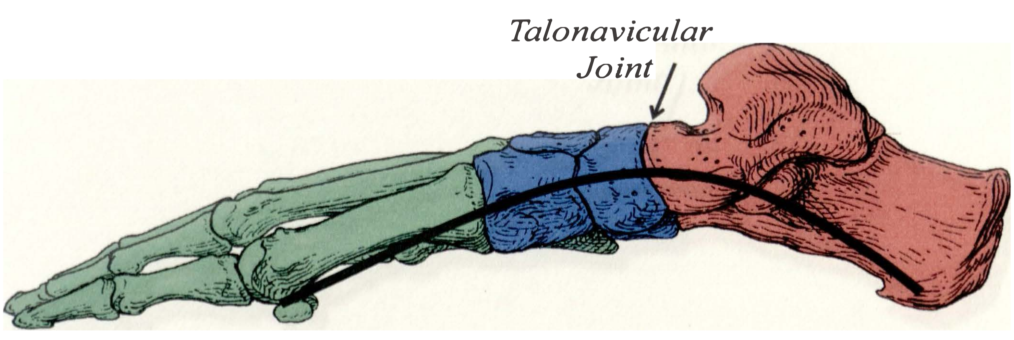


Figure 5: Medial longitudinal arch. (S. Almond, Illus., Courtesy of Texas Scottish Rite Hospital for Children)

Muscular Contributions

There are both extrinsic and intrinsic muscles for the foot and ankle which provide static stability, dynamic power, and shock absorption. Extrinsic muscles originate proximally above the ankle in the leg, while intrinsic muscles have both attachments within the foot (Hamill & Knutzen, 1995). Many of the extrinsic muscles cross multiple joints and therefore perform multiple actions. The following section of this text provides a brief overview of the muscular anatomy of the foot and ankle. Table 2 provides a brief overview of the muscular anatomy of the foot and ankle. Extrinsic muscles are divided into 3 compartments, with a separate nerve innervation for each compartment (Neumann, 2002).

The *anterior* compartment, which primarily dorsiflexes the ankle and is innervated by the deep branch of the peroneal nerve, is comprised of the anterior tibialis, extensor digitorum longus (EDL) and extensor hallucis longus (EHL). The peroneus tertius muscle is an extension of the EDL and attaches at the base of the fifth metatarsal (Neumann, 2002). Based on the insertion of the muscle, the anterior tibialis also inverts the foot through the subtalar joint, and inverts and adducts the forefoot through the transverse tarsal joint. The EDL can contribute to subtalar and forefoot eversion. The EHL provides minimal subtalar motion due to its close proximity to the axis of rotation.

The *lateral* compartment consists of the peroneus longus and peroneus brevis, which are the primary evertors of the foot, through the subtalar joint, and also contribute to ankle plantarflexion (Neumann, 2002). This eversion through the subtalar joint can occur regardless of whether the ankle is plantarflexed or dorsiflexed (Smith, Weiss, & Lehmkuhi, 1996). The distal attachment of the peroneus longus helps to plantarflex the first metatarsal as well as stabilize it against the strong medial pull of the anterior tibialis muscle (Neumann, 2002).

The *posterior* compartment is divided into the superficial and deep muscles. The superficial group, also known as the triceps surae, is comprised of the gastrocnemius, soleus and plantaris, and all three attach to the posterior calcaneus through the Achilles tendon (Neumann, 2002). These muscles provide powerful ankle plantarflexion. The deep posterior muscles include the tibialis posterior, flexor digitorum longus and flexor hallucis longus, which are located underneath the soleus muscle (Neumann, 2002). In addition to ankle plantar-flexion, these three muscles also provide strong inversion of the foot through the subtalar and/or transverse tarsal joints.

Intrinsically, there is only one dorsal muscle, the extensor digitorum brevis, which aids in extension of both the hallux and lesser toes. The remaining intrinsic muscles are all located in four layers on the plantar aspect of the foot. Superficial to these four layers is the plantar fascia, a thick strong band of connective tissue that supports the medial longitudinal arch (Neumann, 2002). The plantar fascia originates off the calcaneus and runs along the sole of the foot to connect to the metatarsophalangeal joints. The superficial surface of the planar fascia attaches to the dermis, while its deep surface covers and blends with the first layer of the intrinsic muscles. Specific details regarding the four layers of the intrinsic muscles of the foot are listed in Table 2, and will not be discussed here in detail. As a whole, the intrinsic muscle of the foot serves to provide stability and balance within the foot (Neumann, 2002). Activation of the intrinsic muscles can provide rigidity of the foot and support for the medial longitudinal arch, particularly during push-off phase (Neumann, 2002).

Table 2
Muscles of the Foot and Ankle

		Muscle	Origin	Insertion	Innervation	Action(s) in foot/ankle
Extrinsic	Anterior Compartment	Tibialis anterior	Lateral condyle and proximal $2/3^{rd}$s of lateral tibia	Medial plantar surface of medial cuneiform, base of 1^{st}MT	Deep branch, peroneal	Ankle dorsiflexion; subtalar inversion; forefoot inversion/ adduction; support MLA
		Extensor digitorum longus	Lateral condyle tibia; proximal $2/3^{rd}$s medial fibula; IM	(4 tendons) proximal, dorsal base of medial and distal phalanges	Deep branch, peroneal	Ankle dorsiflexion; toe extension (2 through 5); subtalar eversion
		Extensor hallucis longus	Middle section of medial fibula; IM	Dorsal base of distal phalanx of hallux	Deep branch, peroneal	Hallux extension; ankle dorsiflexion; minimal subtalar adduction
		Peroneus tertius	Distal $1/3^{rd}$ of medial fibula; IM	Dorsal base of 5^{th}MT	Deep branch, peroneal	Forefoot eversion; ankle dorsiflexion
	Lateral Compartment	Peroneus longus	Head and proximal $2/3^{rd}$s of lateral fibula; lateral condyle tibia	Medial cuneiform and lateral base of 1^{st}MT	Superficial branch, peroneal	Foot eversion; ankle plantarflexion; subtalar and transverse tarsal abduction
		Peroneus brevis	Distal $2/3^{rd}$s of the lateral fibula	Styloid process of 5^{th}MT	Superficial branch, peroneal	Foot eversion; ankle plantarflexion; subtalar and transverse tarsal abduction
	Posterior Compartment	Gastrocnemius	(2 heads) posterior aspect of medial/lateral femoral condyles	Calcaneus via the Achilles tendon	Tibial	Ankle plantarflexion (knee flexion)
		Soleus	Posterior fibular head, proximal $1/3^{rd}$ fibula, posterior tibia	Calcaneus via the Achilles tendon	Tibial	Ankle plantarflexion
		Plantaris	Inferior lateral condyles femur	Calcaneus via medial aspect of Achilles tendon	Tibial	Ankle plantarflexion
		Tibialis posterior	Proximal $2/3^{rd}$s posterior tibia/fibula; IM	Navicular and medial cuneiform (tendons: tarsal bones/bases 2^{nd} to 4^{th} MT)	Tibial	Foot inversion; ankle plantarflexion; MLA support
		Flexor digitorum longus	Middle $1/3^{rd}$ of posterior tibia (medial to tibialis posterior)	(4 tendons) base of distal phalanx of 4 lesser toes	Tibial	Toe flexion (2 through 5); foot plantarflexion
		Flexor hallucis longus	Distal $2/3^{rds}$ of posterior fibula; IM	Plantar base of distal phalanx of hallux	Tibial	Hallux flexion; forefoot adduction

Table 2, cont.

		Muscle	Origin	Insertion	Innervation	Action(s) in foot/ankle
Intrinsic	Dorsal	Extensor digitorum brevis	Lateral/distal calcaneus	3 tendons blend to extensor digitorum longus of 2nd to 5th toes, 4th tendon to proximal phalanx of hallux	Deep branch, peroneal	Toe extension (1 through 4)
	Layer 1	Flexor digitorum brevis	Medial calcaneus, central plantar fascia	4 tendons to plantar base of middle phalanx 2nd to 5th toes	Medial plantar	Toe flexion (2 through 5)
		Abductor hallucis	Flexor retinaculum, medial calcaneus, plantar fascia	Medial base proximal phalanx hallux	Medial plantar	Hallux abduction
		Abductor digiti minimi	Medial/lateral calcaneus, plantar aponerous, plantar base 5th MT	Lateral base phalanx 5th toe	Lateral plantar	5th toe abduction
	Layer 2	Quadratus plantae	2 heads, medial and lateral inferior calcaneus	Lateral flexor digitorum longus common tendon	Lateral plantar	Toe flexion (2 through 5)
		Lumbricals	Tendons of flexor digitorum longus	Base proximal phalanx 2nd to 5th toes; dorsal digital expansion of 2nd to 5th toes	Medial plantar (2nd toe), lateral plantar (3rd to 5th toes)	Proximal phalanx flexion (toes 2 through 5)
	Layer 3	Adductor hallucis	Plantar base 2nd to 4th MT and ligaments of 3rd to 5th MTP joints	Lateral base proximal phalanx hallux	Lateral plantar	Hallux adduction
		Flexor hallucis brevis	Plantar cuboid and lateral cuneiform	2 tendons to lateral and medial bases of proximal hallux	Medial plantar	Hallux flexion
		Flexor digiti minimi	Plantar base 5th MT	Lateral base proximal phalanx 5th toe	Lateral plantar	5thToe flexion
	Layer 4	Plantar interossei (3)	Medial side of 3rd through 5th MT	Medial proximal phalanx of 3rd to 5th toe	Lateral plantar	Toe abduction (3 through 5)
		Dorsal interossei (4)	Adjacent sides of 1st through 5th MT	Medial base proximal phalanx 2nd toe; lateral base proximal phalanx 2nd to 4th toe	Lateral plantar	Toe abduction (2 through 4); 2nd toe adduction; proximal phalanx flexion

Notes: IM=Interosseous membrane, MT= metatarsal

Congenital Clubfoot: History, Presentation and Treatment

Congenital idiopathic talipes equinovarus, also known as TEV or clubfoot, is believed to be the most common orthopedic condition affecting children that requires extensive treatment (Favre et al., 2007). There is an incidence of clubfoot in the US of 1 to 2 in every 1,000 live births (Delgado, Wilson, Johnston, Richards, & Karol, 2000). Idiopathic clubfoot is generally not considered to be a neurological disease, and often presents as the only musculoskeletal deformity in an otherwise healthy baby (Herring, 2002). In two-thirds of affected babies, the idiopathic condition is unilateral, and it is slightly more prevalent in males than females (Karol & Jeans, 2011). Nonidiopathic clubfoot can be associated with a variety of neuromuscular diseases and syndromes. It is very important to note that while idiopathic clubfoot is not considered neuromuscular in etiology, it does affect all structures within the foot, including both bone and soft tissues (muscles, ligaments and tendons).

The first known depictions of clubfoot were tomb paintings in ancient Egypt, with the first acknowledged written description occurring around 400 B.C. by Hippocrates (Dobbs, Morcuende, Gurnett, & Ponseti, 2000). One of the first known orthopedic reports of clubfoot was from Scarpa in 1803, and his basic description of this deformity has been relatively unchanged since that time (Herring, 2002). At birth, the clubfoot is held in an inverted, plantarflexed position, and may appear to be pointing almost upside down, with the plantar surface of the foot aiming in and up (Radler et al., 2007). The foot posture is a combination of intraosseous and interosseous deformities (Herring, 2002). Intraosseous deformities occur within the bone, mainly in the talus, although they may also be seen, less severely, in the calcaneus, navicular and cuboid. Interosseous deformities occur at the joint articulation between two bones. Affected joints can include, but are not limited to, the subtalar, calcaneocuboid and talonavicular joints. Soft tissues such as muscles, ligaments and tendons are also affected by clubfoot deformity. Contractions and/or neuromyogenic changes have been observed in the tibialis posterior, triceps surae, peroneals, flexor digitorum longus and flexor digitorum hallucis (Herring, 2002). Ligaments, such as the calcaneonavicular or tibionavicular, or tendons, such as the Achilles tendon, may often be thickened and tight. Tendon or capsular sheaths and other connective tissues, such as the plantar fascia, are often fibrous and require stretching or release (Herring, 2002).

The clinical presentation of a baby with congenital clubfoot may include ankle equinus hindfoot varu midfoot cavus and forefoot adduction and supination, based on the severity of the deformity which can vary greatly (Figure 6). A mildly affected foot can be passively corrected· however a very severe foot will be rigidly fixed in the abnormal position or posture, and will require treatment for correction. In patients with unilateral disease, the foot on the affected side also tends to be smaller than the normal foot.

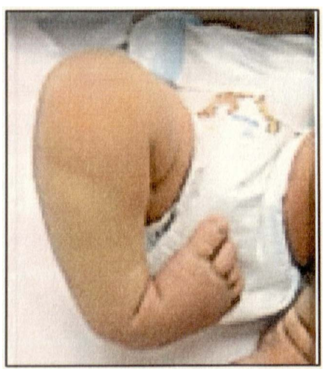
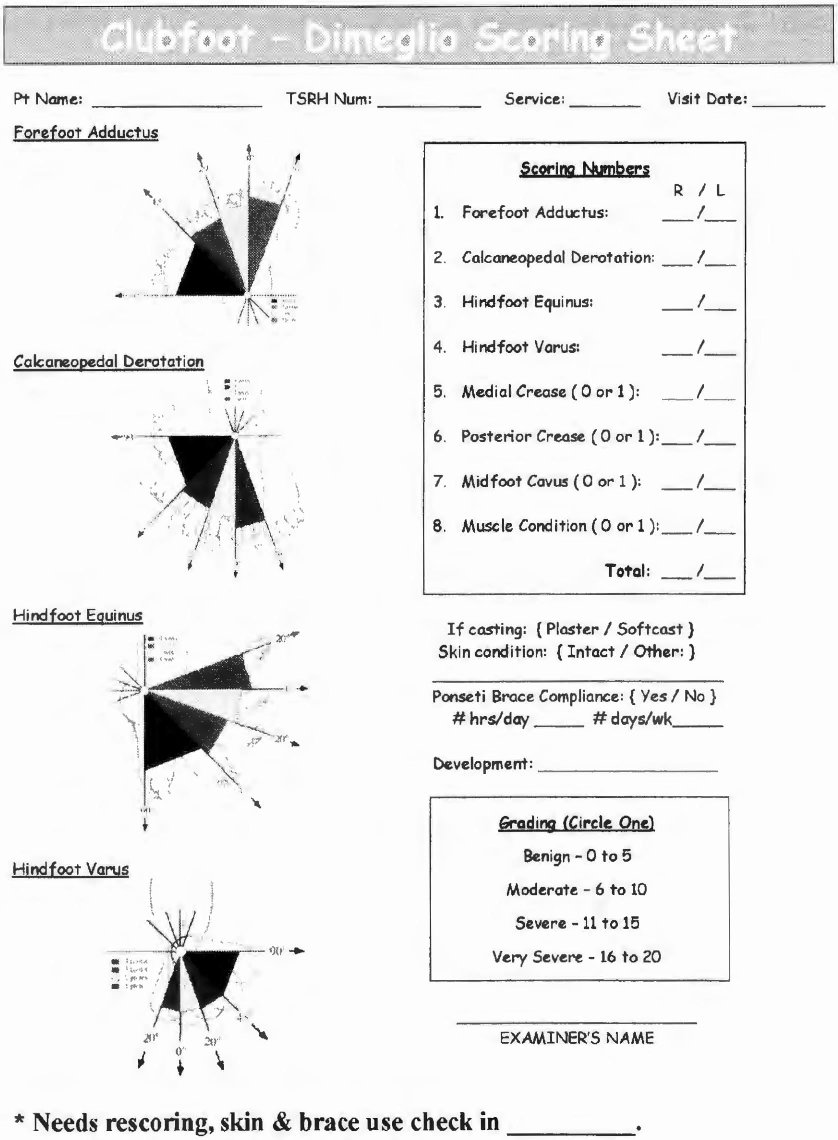


Figure 6: Typical clubfoot presentation at birth. (Courtesy of Texas Scottish Rite Hospital for Children)

Treatment for an idiopathic clubfoot is highly dependent on the severity of the deformity. Therefore, several scales have been proposed to assess the severity of deformity. One of the most common severity scales is the Dimeglio Scale. Each foot is scored based on ability to passively correct the foot in four measurements, with additional points given for pathological skin creases (Figure 7, Dimeglio, Bensahel, Souchet, Mazeau, & Bonnet, 1995).

The goal of clubfoot treatment is ultimately a pain-free foot for activities of daily living (Karol & Jeans, 2011). Furthermore, the child should have adequate foot motion to walk as normally as possible, run and play with their peers, and participate in typical activities of childhood. Originally, the main treatment of clubfoot was surgical intervention. However, as early was the 1920's, orthopedists began to recognize that nonoperative treatment could offer similar if not improved results for correction (Herring, 2002). Residual or recurrent deformity, specifically forefoot adductus and supination have been reported in as many as 95% of surgically treated clubfeet (Tarraf & Carroll, 1992). Today, almost all orthopedists choose to initiate treatment nonoperatively.

Nonoperative treatment for clubfoot includes short or long leg casts and/or physical therapy, stretching and massage. This more conservative approach is now undertaken as a primary method of treatment, with the hopes to eliminate or reduce the need for surgical correction. Early nonoperative casting techniques have had limited success, with correction rates ranging between 15 and 61% (Radler et al., 2007). One of the most common current methods of casting is the Ponseti method, which uses long leg serial casting. Each week, the foot is passively corrected and held in a more corrected position using a long-leg cast. The Ponseti casting method attempts to simultaneously correct all components of the deformity, unlike previous methods of casting techniques which focused on one aspect of the deformity at a time. Specifically, forefoot abduction and external rotation is achieved through rotation of the foot at the talus. Although this method is nonsurgical, the majority of patients, up to 75%, treated with the Ponseti method also receive a percutaneous Achilles tendon lengthening, which can be performed in the clinic to correct hindfoot equinus (Noonan & Richards, 2003). Ponseti has reported 78% of patients have excellent to good results using this methodology (Herring, 2002). Following several months of serial casting, patients who are treated with the Ponseti method typically are required to wear an abduction orthosis (bilateral shoes in external rotation attached to a bar) for 2 to 4 years to maintain the correction of the feet.



Clubfoot - Dimeglio Scoring Sheet

Pt Name: ________ TSRH Num: ________ Service: ________ Visit Date: ________

Forefoot Adductus

Calcaneopedal Derotation

Hindfoot Equinus

Hindfoot Varus

Scoring Numbers

		R / L
1.	Forefoot Adductus:	___/___
2.	Calcaneopedal Derotation:	___/___
3.	Hindfoot Equinus:	___/___
4.	Hindfoot Varus:	___/___
5.	Medial Crease (0 or 1):	___/___
6.	Posterior Crease (0 or 1):	___/___
7.	Midfoot Cavus (0 or 1):	___/___
8.	Muscle Condition (0 or 1):	___/___
	Total:	___/___

If casting: { Plaster / Softcast }
Skin condition: { Intact / Other: }

Ponseti Brace Compliance: { Yes / No }
hrs/day _____ # days/wk_____

Development: ________

Grading (Circle One)

Benign - 0 to 5
Moderate - 6 to 10
Severe - 11 to 15
Very Severe - 16 to 20

EXAMINER'S NAME

*** Needs rescoring, skin & brace use check in ________.**

Figure 7: Diméglio scoring system for clubfoot severity. Adapted from Diméglio et al. 1995. (Courtesy of Texas Scottish Rite Hospital for Children)

Stretching, massage and daily manipulations have been proposed by several groups in France. These French physical therapy programs use daily mobilization and massage of the foot with taping to hold correction between sessions (Faulks & Luther, 2005). Although percutaneous Achilles tenotomies were not originally part of the program, they have since been initiated at some institutions in patients in whom residual hindfoot equinus proves difficult. This method requires a trained physical therapist to work with the patient on a daily basis for up to 10 to 12 weeks, and therefore, is not logistically possible for some families.

Residual or recurrent deformity has been reported for between 4 and 41% of patients (Chu & Lehman, 2012). The details of surgical approach are beyond the scope of this paper, however, it should be noted that surgical interventions may involve soft tissue releases or transfers, bony realignments or some combination of both. Posteromedial releases, involving subtalar releases, ligament releases, posterior tibialis, Achilles tendon and long toe flexor lengthenings, and release of the talonavicular joint, is one of the more common, and more extensive, surgical treatments (Alexander, Ackman, & Kuo, 1999). Other surgical options include: plantar fascia release, calcaneocuboid joint capsulotomy, lateral column shortening, tibialis anterior lengthening or transfer, calcaneal or midfoot osteotomy, and triple arthrodesis (Alexander et al., 1999).

Despite the treatment applied, it is important to understand that the underlying anatomy of the foot is not, and will most likely not ever be, completely 'normal' in a patient with clubfoot. Roche et al., (2006) used magnetic resonance imaging to determine the shape, size and surface morphology of the hindfoot and proximal tarsal bones in seven adolescent patients with unilateral clubfoot who underwent surgical treatment. Results showed that the tarsal bones in the clubfeet were smaller in both volume and surface area than the patients' contralateral normal feet.

Ledoux, Rohr, Chang, and Sangeorzan (2006) used computerized topography (CT) scans to assess individuals without any known foot pathology with either high, neutral and low arched individuals. Even in 'normal' feet significant differences in bone shape was seen relating to the three-dimensional position of the feet (Ledoux et al., 2006). Based on findings from these two studies, differences in foot motion can be expected in patients with residual clubfoot deformity, even in those patients with the best clinical outcomes.

Biomechanical Manifestations of Residual Clubfoot Deformity

Outcomes in patients with clubfoot have traditionally focused on radiographic and clinical findings (Brand, Laaveg, Crowninshield, & Ponseti, 1981; Herzenberg et al., 2002; Ippolito, Farsetti, Caterini, & Tudisco, 2003; Laaveg & Ponseti, 1980; Roche et al., 2006; Simons, 1977; Thometz, Liu, Tassone, & Klein, 2005). However, there have been numerous studies that have assessed the biomechanical or functional outcomes in patients treated for congenital clubfoot (Table 3). The initial studies evaluated ground reaction forces, electromyography (EMG) and foot progression using inked walkways (Bill & Versfeld, 1982; Cooper & Dietz, 1995; Otis & Bohne, 1986; Yamamoto, Muneta, & Furuya, 1994; Yngve, 1990). Prolonged EMG activity of the gastrocnemius was found with no differences seen in EMG activity of the anterior tibialis, stride length or single limb support time (Otis & Bohne, 1986). Increased intoeing was noted (Yamamoto et al., 1994; Yngve, 1990) as well as peroneal weakness, leading to a muscle imbalance and residual forefoot adductus (Ezra, Hayek, Gilai, Khermosh, & Wientroub, 2000).

The first study to use instrumented gait analysis was the 1990 study by Aronson and Puskarich. They found a 42% decrease in ankle range of motion, 24% decrease in plantarflexion strength, and a 10% decrease in overall calf girth. Another early report demonstrated the ability of instrumented gait analysis to detect a variety of residual clubfoot deformities in symptomatic patients (Asperheim, Moore, Carroll, & Dias, 1995), and similar results have been reported more recently (Sankar, Rethlefsen, Weiss, & Kay, 2009). Many studies have reported poor results following surgical correction, fueling the current practice of nonoperative treatments, as these initial studies found decreased ankle plantarflexion and ankle power at push-off (Alkjaer, Pedersen, & Simonsen, 2000; Aronson & Puskarich, 1990; Asperheim et al., 1995; Beyaert, Haumont, Paysant, Lascombes, & Andre, 2003; Davies et al., 2001; Karol et al., 1997; Sawatzky, Sanderson, Beauchamp, & Outerbridge, 1994). Some researchers have correlated these results to a decrease in triceps surae strength and limited ankle range of motion both statically and/or dynamically. Specifically, Karol et al. (1997) found 87% of clubfeet that underwent surgical intervention had abnormal ankle range of motion, with a 23% decrease in ankle plantarflexion power in the surgical feet and an average of 27% decrease in the gastrocsoleus strength. Initial surgical treatment often resulted in an over-lengthened Achilles tendon and subsequent calcaneus gait pattern, demonstrating increased ankle dorsiflexion throughout stance phase. Attempts to correct this over-lengthening have been found to be ineffective (O'Brien et al., 2004). It has further been concluded that significant gait differences exist, even in clinically successful and asymptomatic clubfeet, indicating that future studies are needed to assess the possible long term musculoskeletal deficits of surgical treatment in children with clubfoot (Muratli, Dagli, Yavuzer, Celebi, & Bicimoglu, 2005). Graf et al. (2010) evaluated 24 adults with a mean age 21 years, who underwent initial surgical intervention. They found most patients experienced foot pain after a typical day of activities. Kinematically, these adult patients with clubfoot demonstrated increased hindfoot plantarflexion and increased forefoot dorsiflexion and adduction. Decreased ankle plantarflexion and inversion strength was noted in the clubfoot group compared to age matched individuals with clubfoot. Cooper and Dietz (1995) reported on 45 adult patients with clubfoot (mean age: 34 years) and found that a sedentary occupation and avoidance of excessive body mass may improve overall long-term results.

Given the relatively recent global implementation of nonoperative treatments over the last approximately 15 years, there has been little research on the long-term outcomes of these techniques in clubfeet. Early results at 2 years of age were reported in 127 clubfeet treated with either the Ponseti casting method or the French physical therapy (PT) method, and 51 feet went on to further surgical intervention (Karol, O'Brien, Wilson, Johnston, & Richards, 2005). Decreased ankle plantarflexion at toe off was more prevalent in the surgical feet compared to the PT and Ponseti groups. Moreover, 33% of the PT group had normal ankle motion compared to 14% of the Ponseti group. A further investigation into a larger cohort (273 clubfeet) including these same patients was published several years later (El-Hawary et al., 2008) and revealed that the PT group tended to have more ankle equinus and an increased rate of foot drop in swing phase. These results lead that institution to begin implementing Achilles tendon lengthening as part of the PT protocol in patients with residual equinus. The Ponseti group tended to have early signs of calcaneus gait, with increased dorsiflexion during stance phase. The most prevalent gait abnormality in both groups at 2 years of age was internal foot progression angle.

Children from this same cohort were again studied at 5 years of age with 51 requiring interim surgical intervention between the ages of 2 and 5 years of age (Karol et al., 2009). Overall the incidence of gait abnormalities in both the PT and the Ponseti casting groups was decreased at 5 years of age compared to 2 years of age. Kinetic evaluation showed decreased ankle power generation in all three groups (surgical, PT and Ponseti) compared to age-matched controls, with the largest decrease (30%) seen in the surgical feet. These results are similar to those seen in previous studies in older clubfeet that were initially treated surgically.

Theologis et al. (2003) evaluated 20 children, with a mean age of 10 years, who were treated with stretching and casting up to the age of 3 to 6 month and subsequent surgical treatment. Analysis of stance phase showed increased internal foot progression, as well as a mild foot drop and decreased ankle power generation. Midfoot dorsiflexion was increased to compensate for decreased range of motion at the hindfoot. These patients however were treated prior to the onset of the Ponseti casting technique at their institution (Theologis et al., 2003). These same researchers have also shown that there is only a moderate agreement between clinical examination measures and static foot posture using a multi-segment foot model, as well as static posture to dynamic foot motion during walking (MaCahill, Stebbins, & Theologis, 2008). They concluded that while some patients have residual deformity both in structure and function, up to 60% of residual deformity in clubfoot may have only a static or dynamic component.

All of the gait studies referred to thus far have involved walking, and most at the subjects' individual self-selected walking speeds. Maton and Wicart (2005) looked at EMG and ground reaction forces during bilateral toe raises in 10 children with unilateral idiopathic clubfoot. Significant differences were seen between the affected and unaffected sides, which they concluded were a result of triceps surae atrophy. This same group also examined the same biomechanical variables during a gait initiation task with similar findings (Wicart, Richardson, & Maton, 2006).

Table 3

Gait Studies Evaluating Patients with Clubfoot

Study	Patient Cohort	Average age and/or Follow-up	Details/Conclusions
Brand et al. (1981)	44 clubfeet	Average follow-up: 20.6 years	Pedobarograph and GRF Study: contact areas were wider and center of pressure paths were more variable in clubfeet, however results were not consistent
Bill & Versfled (1982)	25 clubfeet	Group 1: 1-19 days old Group 2: 3-22 months old	EMG and Motor Nerve Conduction Velocity Study: Unable to detect differences in EMG or nerve conduction in the anterior tibialis, peroneus, gastrocnemius, extensor digitorum brevis or abductor hallucis brevis.
Otis & Bohne (1986)	32 clubfeet 16 control group	Average age:7 years Comparison of patients with bilateral and unilateral clubfeet and patients without clubfeet	EMG Study: increased duration of medial gastrocnemius activity in those with bilateral clubfeet, with no change in anterior tibialis activity or temporal parameters
Aronson & Puskarich (1990)	29 clubfeet 23 control group	Average follow-up since last treatment: >10 years	No differences in maximum aerobic potential, no difference between unaffected side and control group. 42% decrease in ankle motion, 24% decreased in ankle plantarflexion strength, and 10% decrease in calf girth in clubfeet
Yngve (1990)	52 clubfeet 43 control group	Average age: between 6 and 10 years	43% of clubfeet had intoeing greater than 2 standard deviations from control mean. Causes of intoeing were adductus and internal tibial or femoral torsion.
Yamamoto et al. (1994)	24 clubfeet	Average age: 5.6 years Pre/post comparison following posteromedial surgical release	Average 12° decrease in foot progression post-operatively. 33% of clubfeet had residual intoeing following surgery.
Sawatzky et al. (1994)	7 clubfeet 16 control group	Average age: 7.7 years	GRF Study: more rigid, varus foot had greater internal torque, decreased plantarflexion resulted in decreased propulsion
Asperheim et al. (1995)	21 clubfeet	Average age: 5.1 years	Gait analysis and clinical assessment used for treatment decision making. 72% incidence of intoeing
Cooper & Dietz (1995)	71 clubfeet 97 control group	Average age: 34 years Comparison of clubfeet with excellent/good and fair/poor clinical outcomes	EMG and Pedobarograph Study: Significant difference in passive ankle range of motion, pressure-time integral, and number of toe raises performed before pain or fatigue

Table 3, cont.

Study	Patient Cohort	Average age and/or Follow-up	Details/Conclusions
Karol et al. (1997)	23 clubfeet	Average follow-up: 10 years	43% of patients with relative equinus, 17% with excessive DF, foot drop in 30%. Ankle power generation decreased 23%, gastrocnemius strength decreased 27%.
Huang et al. (1999)	159 clubfeet (42 underwent biomechanical assessment)	Average age: 20 years Average 11 years follow-up following surgical treatment	Pedobarograph Study: 35/42 feet had good or excellent results and pressure distribution was significantly different in those with poor or fair results.
Alkjaer et al. (2000)	9 clubfeet 15 control group	Average age: 19.7 years Comparison to adults without clubfeet	Lower ankle joint moments and higher hip and knee moments in the patients with clubfeet.
Ezra et al. (2000)	27 clubfeet 16 control group	Average age: 4.8 years Assessment following anterior tibialis tendon transfer for dynamic supination	EMG Study: peroneal weakness was noted, no patients had dynamic supination following surgery
Davies, et al. (2001)	35 clubfeet	Average age:12.1 years Compared patients with unilateral and bilateral clubfeet to children without clubfeet	Decreased ankle motion in clubfeet, decreased ankle plantarflexion strength in all clubfeet, as well as in the unaffected foot in patients with unilateral clubfeet.
Hee et al. (2001)	58 clubfeet	Average age: 6.1 years	Decreased ankle plantarflexion at push off, with increased internal foot rotation, and increased midfoot and forefoot plantar pressures
Tareco et al. (2002)	26 clubfeet 10 control group	Average age: 3.1 years Comparison of pinned and non-pinned fixation in clubfoot surgery	No difference in foot progression angle between groups, but decreased in clubfeet compared to patients without clubfeet.
Bayaert et al. (2003)	28 clubfeet 13 control group	Average age: 7.5 years Comparison to children without clubfeet	Intoeing in 46% of clubfeet had significant effects on the knee with increased knee flexion and knee extension moments.
Theologis et al. (2003)	20 clubfeet 15 control group	Average age: 9.8 years	Increased internal foot rotation and midfoot dorsiflexion, mild foot drop and decreased ankle power generation and hindfoot dorsiflexion in clubfeet

Table 3 cont.

Study	Patient Cohort	Average age and/or Follow-up	Details/Conclusions
O'Brien et al. (2004)	17 clubfeet	Average age: 11 years (Groups 1&2), 5 years (Group 3) Pre/Post comparison of 3 surgical attempts to correct over- lengthened Achilles tendon following previous clubfoot treatment	No increases in PF at toe-off. Decreased ankle power generation in older patients (Groups 1&2)
Muratli et al. (2005)	30 clubfeet 23 control group	Average age: 8.5 years Assessment following PMR in patients with bilateral clubfeet	Decreased ankle motion, dorsiflexion moment and power generation in clubfeet. Increased knee valgus and flexion moments, with 57% of clubfeet with knee hyperextension.
Karol et al. (2005)	127 clubfeet 15 control group	Average age: 2 years Comparison of French PT and surgical treatments	Limited stance phase DF in PT treated feet, lack of PF and increased rate of intoeing in surgical feet. 33% of PT feet had normal ankle motion compared to 14% of surgical feet.
Maton & Wicart (2005)	10 clubfeet 10 control group	Average age: 10 years Toe raise task comparison of unaffected and affected feet in patients with clubfeet and control group	EMG and GRF Study: decreased vertical acceleration in patients with clubfeet, with timing and magnitude differences in center of pressure and vertical GRF and evidence of triceps surae atrophy.
Thometz et al. (2005)	61 clubfeet	Average follow-up: 8 years Correlation of radiographs and plantar pressures	Higher correlations between plantar pressures and lateral radiographs as compared to AP radiographs.
Wicart et al. (2006)	10 clubfeet 10 control group	Average age: 10 years Gait initiation task	Center of gravity velocity not different at end of first step. Subtle differences in ankle muscular activation and duration of anticipation and execution phases.
Favre et al. (2007)	16 unilateral clubfeet 68 control group	Average age: 5.6 years Average follow-up: 5.5 years Comparison of contralateral (unaffected) side to children without clubfoot	Pedobarograph and GRF study: Significant differences in peak pressure and forces in the heel, midfoot and forefoot. **Conclusion**: use comparative group of children without clubfoot rather than the contralateral side in evaluating patients with unilateral clubfeet

Table 3 cont.

Study	Patient Cohort	Average age and/or Follow-up	Details/Conclusions
El-Hawary et al. (2008)	154 clubfeet 15 control group	Average age: 2 years Comparison of French PT and Ponseti techniques	65% of PT group and 47% of Ponseti group had normal kinematics. PT group had mild equines and/pr foot drop. Ponseti group had increased dorsiflexion
MaCahill et al. (2008)	37 clubfeet 15 control group	Age range: 6 to 24 years Comparison of clinical exam and foot kinematics	Strongest percent agreement (40-73%) between static foot postures and dynamic kinematics of hindfoot and forefoot in coronal and transverse planes
Sankar et al. (2008)	56 clubfeet 31 control group	Average age: 6.7 years	Incidence of gait deviations included: intoeing (80%), internal tibial torsion (71%), forefoot adductus (71%),stance supination (71%), overactive EMG activity of the anterior tibialis (50%)
Karol et al. (2009)	125 clubfeet 17 control group	Average age: 5 years Comparison of French PT, Ponseti and surgical treatments at 5years of age	Intoeing present in all groups, excessive dorsiflexion in 24% of Ponseti feet. Decreased ankle power generation in all groups.
Sinclair et al. (2009)	28 clubfeet 20 control group	Average age: 3 years	Pedobarograph study: decreased mean peak pressures, mean total maximum force, and force-time integral in clubfeet
Graf et al. (2010)	24 clubfeet 48 control group	Average age: 21 years	Increased hindfoot plantarflexion, forefoot dorsiflexion and adduction in clubfeet, with reduced ankle strength, increased hip power and foot pain after daily activities.
Jeans et al. (2010)	151 clubfeet 17 control group	Average age: 2 years Comparison of French PT and Ponseti treatments	Pedobarograph Study: PT group had lower peak pressures in the hindfoot compared to Ponseti group

Note: DF = dorsiflexion; EMG = electromyography; GRF=ground reaction force; PF = plantarflexion; PT = physical therapy;

In addition to traditional gait analysis, several studies have examined plantar pressures in patients with clubfeet. Thometz et al. (2005) found moderate correlations between radiographic measures of the foot and ankle and peak pressure and contact area under the midfoot. Favre et al. (2007) found that in children with unilateral clubfoot the unaffected foot demonstrated significantly different plantar pressures from individuals without clubfoot. They therefore concluded that a normative sample of children and/or adults without clubfoot should be used for comparison when assessing the plantar pressures in patients with unilateral clubfoot. Jeans and Karol (2010) studied the plantar pressures of the 2 year old patients whose kinematics were previously reported by El-Hawary et al. (2008). They found increased lateral midfoot pressure and contact time, increased forefoot angulation and lateralized center of pressure progression, indicating residual adductus in both groups. Furthermore, the decreased hindfoot pressure supported the kinematic findings of residual equinus in the PT group. Similar results have been seen in other studies as well (Hee, Lee, & Lee, 2001; Y. Huang, Lei, Zhao, & Wang, 1999; Sinclair, Bosch, Rosenbaum, & Bohm, 2009).

Recently, a comprehensive protocol was introduced to assess the long-term functional outcomes following clubfoot treatment. Graf et al. (2012) highlighted the need for initial classification of clubfoot severity at birth, as well as outlined a complete physical assessment of foot function. This included physical examination (range of motion, foot alignment observations), radiographic assessment, quality-of-life questionnaires, clinical strength and functional strength measures such as the standing heel rise test, and gait analysis, including lower extremity kinematics and kinetics, multi-segment foot kinematics and plantar pressures (Graf et al., 2012).

Kinematics of the Foot: Multi-Segment Foot Models

Three-dimensional gait analysis has been used across a variety of orthopedic conditions and diseases over the last 25 years in both children and adults. The conventional gait model represents the foot as a single rigid body at the end of the leg (Theologis & Stebbins, 2010). Foot motion is defined as the relative movement between this rigid block and the lower leg. Often times this foot segment is represented as a single vector connecting the heel and the toes, thus limiting the degrees of freedom that are measured at the ankle joint. Although several slight variations exist, this standard (Conventional Gait) model has been widely accepted since its inception over 20 years ago (Davis et al., 1991; Kadaba et al., 1990). At the time that these models were developed, the motion capture technology was limited in the resolution of the camera hardware and the power and versatility of the software.

However, as these single rigid body foot models first developed, a need for more detailed analysis of the foot was recognized (Kepple, Stanhope, Lohmann, & Roman, 1990). Due to the technology limitations however, researchers needed to make a choice: to investigate the motion patterns of the entire leg or focus the evaluation on the foot and lower leg alone, even with only a 2-segment three-dimensional model. These first models typically examined hindfoot, or rearfoot, motion relative to the lower leg, and several researchers proposed different models, (Johnason, Donatelli, Wooden, Andrew, & Cummings, 1994; Kidder, Abuzzahab, Harris, & Johnson, 1996; Liu, Siegler, Hillstrom, & Whitney, 1997; Moseley, Smith, Hunt, & Gant, 1996) however no single model was accepted as widely as the Conventional Gait lower extremity models of Kadaba et al. (1990) and Davis et al. (1991).

The first accepted, or at least widely adapted, model to consist of three or more segments at the distal limb was that of Kidder et al. (1996), now known as the Milwaukee Foot Model. This method uses a four segment model of the leg, hindfoot, forefoot and hallux, and is probably the most published model in the literature to date. It has been used to assess motion of healthy children and adults (Kidder et al., 1996; Long, Eastwood, Graf, Smith, & Harris, 2010; Myers, Wang, Marks, & Harris, 2004), as well as adults with posterior tibialis tendon dysfunction (Marks, Long, Ness, Khazzam, & Harris, 2009; Ness, Long, Marks, & Harris, 2008), ankle arthrosis (Khazzam, Long, Marks, & Harris, 2006), rheumatoid arthritis (Khazzam, Long, Marks, & Harris, 2007), clubfoot (Graf et al., 2010), hallux valgus (Canseco et al., 2010) and hallux rigidus (Canseco, Long, Marks, Khazzam, & Harris, 2008; Canseco, Long, Marks, Khazzam, & Harris, 2009). One significant limiting factor to the utility of the Milwaukee Foot Model however, is that it requires radiographic offsets to be used in conjunction with the kinematic data. The exposure of subjects to multiple radiographic images limits its applicability in many laboratories due to Institutional Review Board restrictions.

Although the Milwaukee Foot Model may have had the most applications in patients with pathologies affecting gait, most, if not all, of these studies originated from one of two specific institutions. Among all the models in the literature, the Oxford Foot Model (Carson, Harrington, Thompson, O'Connor, & Theologis, 2001) has been the most widely implemented across the largest number of laboratories around the world. The main reason for its acceptability is the Oxford Laboratory's collaboration with VICON, one of the forerunners in the motion capture industry. VICON offers the Oxford Foot Model processing code as an additional plug-in for its biomechanical/gait motion capture software. The developers of this model have reported extensively on the repeatability of foot kinematics (Carson et al., 2001; Curtis, Bencke, Stebbins, & Stansfield, 2009; Stebbins, Harrington, Thompson, Zavatsky, & Theologis, 2006), the use of the Oxford Foot Model in clinical practice to aid in the treatment of foot pathology in pediatric patients (MaCahill et al., 2008; Theologis et al., 2003; Theologis & Stebbins, 2010) and the use of foot markers to aid in the assessment of plantar pressure analysis (Stebbins et al., 2005).

Many other variations of multi-segment foot models have been proposed for various applications and patient populations. (Buczek, Walker, Rainbow, Cooney, & Sanders, 2006; Carson et al., 2001; Cobb et al., 2009; Y. C. Huang et al., 2006; Hunt, Smith, & Torode, 2001; Jenkyn & Nicol, 2007; Kitaoka et al., 2006; Leardini, Benedetti, Catani, Simoncini, & Giannini, 1999; MacWilliams, Cowley, & Nicholson, 2003; Neville, Flemister, Tome, & Houck, 2007; Rao, Saltzman, & Yack, 2007; Rao, Baumhauer, Tome, & Nawoczenski, 2009; Rattanaprasert, Smith, Sullivan, & Gilleard, 1999; Ringleb et al., 2007; Simon et al., 2006; Tome, Nawoczenski, Flemister, & Houck, 2006; Tulchin, Orendurff, & Karol, 2009b; Turner, Helliwell, Siegel, & Woodburn, 2008; Woodburn, Turner, Helliwell, & Barker, 1999; Woodburn, Nelson, Siegel, Kepple, & Gerber, 2004; Wu et al., 2000). Each of these studies utilized similar techniques of skin markers to track motion of the underlying bony segments, and determine three-dimensional joint angles using Euler angle rotations to determine joint movements of 3 to 4 segments. MacWilliams et al. (2003) proposed a 9-segment foot model, which was applied in adolescent patients. Simon et al. (2006) proposed a technique using two dimensional angular measurements rather than 3D joint angles. They have used this model to describe foot kinematics and/or differences in foot kinematics during walking between children and adults (Simon et al., 2006; Wolf, 2008), shod and barefoot conditions in children (Wolf et al., 2008) and between high and low arched individuals (Twomey, McIntosh, Simon, Lowe, & Wolf, 2010). Although kinetic multi-segment foot models have been proposed (Brueing, Cooney, & Buczek, 2011; Buczek et al., 2006; MacWilliams et al., 2003) forceplate technology has not evolved to the point of their feasibility at this time.

Table 4

Application of Multi-Segment Foot Models in Pediatric Populations

	Referenced studies	Subject Cohort	Num. of subjects	Average Age	Comments / Special Tasks
Healthy individuals	Kaufman et al. (1997)	Healthy child	1	8	
	MacWilliams et al. (2003)	Healthy children	18	13	
	Myers et al. (2004)	Healthy children	3	Between 6&11	
	Stebbins et al. (2006)	Healthy children	15	10	
	Tulchin, et al. (2006)	Healthy children and adults	45	4 age groups	
	Wolf et al. (2008)	Healthy children and adults	30	7	Barefoot vs. shod walking
	Curtis et al. (2009)	Healthy children	8	12	Repeatability study
Pediatric Foot Pathology	Theologis et al. (2003)	Children with clubfoot Children without clubfoot	20 15	10 11	Increased midfoot dorsiflexion, decreased hindfoot range of motion in Clubfoot group.
	Stebbins et al. (2008)	Children with cerebral palsy, hemiplegia Children without cerebral palsy	16 15	10 10	Repeatability of Oxford Foot Model similar in children with CP and children without CP. ROM variable less variable than maximum values.
	Alonso-Vázquez et al. (2009)	Children with forefoot varus Children with varus	10 11	10 10	Discriminant model variables to distinguish two groups included hindfoot sagittal (pre-swing) and coronal plane (loading response).
	Tulchin et al. (2010b)	Children with cavovarus feet Children with planovalgus feet	11 8	15 14	Significant differences between groups for hindfoot and forefoot motion.
	Twomey et al. (2010)	Children with low-arched feet Children with normal-arched feet	27 25	11 11	Increased forefoot supination and medial arch angle in low-arched children. No changes in hindfoot motion.

In addition to the varying definitions of segmental coordinate systems, many of these models use difference approaches to describe the neutral position between adjacent segments. Many researchers have used a static standing position to define the neutral alignment of the foot (Cornwall & McPoil, 1999; Curtis et al., 2009; Jenkyn & Nicol, 2007; Leardini et al., 1999; Stebbins et al., 2006), while others have used special jigs to align the tibia and foot (Carson et al., 2001; Simon et al., 2006; Woodburn et al., 2004) or require a seated position (Cobb et al., 2009) or plantigrade foot (MacWilliams et al., 2003). Still other studies have required placement of the foot in a subtalar neutral position – a position which some feet with severe foot deformity may not be able to achieve (Houck, Tome, & Nawoczenski, 2008; Tome et al., 2006). The stance phase mean posture has also been used an offset to define the neutral position (Rao et al., 2007; Wilken, Rao, Saltzman, & Yack, 2011). The main reason for the variations in neutral position is the placement of markers on the calcaneus. The lack of consistent, palpable bony landmarks on the hindfoot leaves the placement of those markers somewhat vague. The Milwaukee Foot Model (Kidder et al., 1996) uses radiographic measurements to define the anatomic orientation of the calcaneus relative to the skin markers during a static standing posture (although this is indirect as the markers are not in place during the x-ray.) There are also several models that have incorporated methods which used the nonweightbearing varus/valgus alignment of the hindfoot to define the orientation of the medial and lateral calcaneus markers, thus allowing quantification of static coronal hindfoot position (Moseley et al., 1996; Rattanaprasert et al., 1999; Tulchin et al., 2009b).

Few studies have been conducted using multi-segment foot kinematics in children (Carson et al., 2001; Leardini et al., 2007; MacWilliams et al., 2003; Myers et al., 2004; Tulchin & Karol, 2006; Twomey et al., 2010; Wolf et al., 2008). Kaufman, Kitaoka, Hansen and Shaughnessy

(1997) were first to report hindfoot and forefoot kinematics in an 8-year old child. Myers et al. (2004) first applied and validated the Milwaukee Foot Model in children. Several studies have examined kinematic differences between children and adults (MacWilliams et al., 2003; Tulchin & Karol, 2006; Wolf, 2008). Most studies in pediatric populations to date have been conducted using the Oxford Foot Model (Alonso-Vazquez, Villarroya, Franco, Asin, & Calvo, 2009; Curtis et al., 2009; MaCahill et al., 2008; Stebbins, Zavatsky, Thompson, & Theologis, 2008; Theologis et al., 2003), however many of these references have come from the Oxford laboratory, while the others are most likely due to the model's accessibility in the VICON motion capture software. A new model has also been proposed with intra-clinician, inter-clinician, and inter-laboratory variability reported to be less than 6° in the ankle and forefoot in pediatric feet (Saraswat, MacWilliams, & Davis, 2011).

Two of the major oppositions regarding multi-segment foot models are lack of repeatability and skin motion, both related to marker placement. The effects of skin motion on error propagation using surface markers has been well examined in cadaver studies (Kitaoka, Lundberg, Luo, & An, 1995; Reinschmidt et al., 1997) and in vivo using either bone pins (Arndt et al., 2007; Lundgren et al., 2008; Nester et al., 2007; Westbald, Hashimoto, Winson, Lundberg, & Arndt, 2002) or imaging (Shultz, Kedgley, & Jenkyn, 2008; Tranberg & Karlsson, 1998). Reported differences between bone pins and surface markers are around 3 to 5°. Nester et al., (2007) reported that only 35% of all mean differences were greater than 3° and only 3.5% were greater than 5°. Some maximal differences, however, were found to be greater than 8°. Currently there are no methods, numerical or otherwise, to correct for skin motion artifact and researchers applying surface-marker based models do so with the assumption that skin motion is negligible.

Marker placement errors are also an important factor to consider. In an effort to overcome this obstacle, researchers have reported repeatability assessments of their surface marker based models in vivo. The linear and angular accuracy and resolution of the Milwaukee Foot Model was tested in both children (Myers et al., 2004) and adults (Kidder et al., 1996) with excellent results (greater than 98% accuracy). Long et al. (2010) also reported on the multi-site application of the Milwaukee Foot Model in 6 healthy adult subjects. They found subject variability to be highest, while session variability and site variability were within 3.5° for most measures (Long et al., 2010). Repeatability of the Milwaukee Foot Model is similar to that which has been reported for the Leardini model (Caravaggi, Benedetti, Berti, & Leardini, 2011; Deschamps et al., 2011).

The original Oxford Foot Model (Carson et al., 2001) was adapted for clinical application in patient populations, and over the last 10 years, they have found a improvement in the initial repeatability which was initially assessed in adults (Theologis & Stebbins, 2010). The Oxford Foot Model has also been assessed for repeatability in both healthy children (Stebbins et al., 2006) and children with hemiplegic cerebral palsy (Stebbins et al., 2008). They found that the repeatability of the Oxford Model was similar between the neuromuscular patients with cerebral palsy (CP) and healthy adults without CP, with the largest variations in the transverse plane. A more detailed analysis of the repeatability of the Oxford Foot Model in healthy children was recently published by Curtis et al. (2009). They found no variations in repeatability across different phases of the gait cycle, however their maximum measurement error reached 8.6° in the hindfoot transverse plane during first rocker. Similar to previous studies, the sagittal plane measures were found to have the least error. The repeatability of a modified version of the Oxford Foot Model has also been reported to be slightly higher in adults compared to the previous study in children (Wright, Arnold, Coffey, & Pidcoe, 2011).

The Texas Scottish Rite Hospital for Children Foot and Ankle Model (TSRHC-FAM) has be used to quantify the effects of walking speed (Tulchin et al., 2009b) and incline (Tulchin, Orendurff, & Karol, 2010a) on foot kinematics, as well as comparing overground and treadmill walking (Tulchin, Orendurff, & Karol, 2009a) in healthy adults. Data has also been presented on the comparison of foot kinematics in children and adults (Tulchin & Karol, 2006), the functional outcomes following triple arthrodesis in adolescent patients (Tulchin, Karol, & St Remy, 2003), and other pediatric foot deformities (Tulchin, Orendurff, & Karol, 2010b). Repeatability of the TSRHC foot model has been reported to be between 2 and 5° in adults without foot deformity (Tulchin & Haideri, 2004), and is consistent with that of other models previously discussed.

Biomechanical Assessment of Activities Other Than Walking

To date, the majority of studies evaluating outcomes using multi-segment foot models have assessed the kinematics of the foot during walking, typically at a self-selected speed. Bovi et al. (2011) recommended a multi-task gait analysis protocol to assess the functional abilities in patients beyond walking. They presented normative data in both children and adults during slow, self-selected and fast walking, heel and toe walking and stair ascent and descent, and concluded that a multi-task protocol will elicit more deficits in the patient with mild pathology. However, they used a conventional lower extremity model to assess kinematics and kinetics of the hip, knee and ankle joints, and did not implement a detailed multi-segment foot model.

There are few studies evaluating multi-segment foot kinematics during activities other than walking. (Running kinematics/injury mechanics have been studied in detail, however, these studies will not be discussed in this literature review.) Kitaoka, Wikenheiser, Shaughnessy and An (1997) evaluated ankle and hindfoot motion during level overground walking and side slope walking in adult patients following resection of talocalcaneal coalition. They found decreased sagittal and coronal range of motion in both joints during level and side slope walking, and concluded that while clinical outcomes based on pain and self-reported function were satisfactory, significant residual biomechanical deficits remained. Forefoot and hallux motion is also significantly affected during side slope running, with increased joint excursions during sloped conditions compared to level running (Dixon, Tisseyre, Damavandi, & Pearsall, 2011). It is unclear how these required changes in foot flexibility necessary on unlevel ground are affected in the patient with foot pathology, as uneven terrain can often be encountered in the community. More importantly, a study evaluating plantar pressures during side slope walking found significant increases in peak pressures with slopes as small as 2° (Urry, 2002), indicating that even small changes in slope can have a great impact on foot mechanics. Ambulation on inclined ramps has also been reported to require increased and early peak dorsiflexion at the hindfoot, with delayed peak hindfoot varus and no associated changes in the forefoot (Tulchin et al., 2010b).

The effect of variations in speed on multi-segment foot kinematics have also been assessed in both healthy individuals (Dubbeldam et al., 2010; Tulchin et al., 2009b) and adult patients with rheumatoid arthritis (Dubbeldam et al., 2011). Faster walking speeds result in a shift towards plantarflexion of the hindfoot and forefoot, with early peak dorsiflexion and no changes in 1st rocker (Tulchin et al., 2009b). Decreased walking speed lead to decreased hallux dorsiflexion and increased minimum medial arch and minimum midfoot supination (Dubbeldam et al., 2010). Pilot work in healthy individuals has also shown increased hindfoot dorsiflexion and valgus during a heel walking task and decreased hindfoot sagittal and forefoot sagittal and coronal ranges of motion (Tulchin & Kwon, 2011). Toe walking required increased hindfoot and forefoot plantarflexion, hindfoot varus and forefoot eversion with no changes in overall range of motion.

Foot motions in adult patients with pathology have also been evaluated during step descent and heel rise tests. Rao et al. (2009) evaluated 30 patients with midfoot arthritis and found they exhibited greater hindfoot eversion range of motion compared to adults without arthritis. They concluded that excessive motion within the foot may contribute to articular stress and symptomatic arthritis. During a bilateral heel rise test, patients with posterior tibialis tendon dysfunction (PTTD) displayed greater ankle plantarflexion, first metatarsal dorsiflexion and less hallux dorsiflexion compared to subjects without PTTD, however hindfoot inversion at peak heel rise was similar between groups (Houck, Neville, Tome, & Flemister, 2009).

Graf et al. (2012) recently outlined a new comprehensive protocol to evaluate long term outcomes in patients with clubfoot. They recommended ankle plantarflexion strength evaluation, clinical assessment of ability to perform toe raises, and multi-segment foot kinematics during overground walking. The idea of utilizing a task such as hopping to assess gastrocnemius strength is not new (Ghanem & Seringe, 1995). However, research evaluating activities other than walking specifically in the clubfoot population is limited. Although kinematic assessment was not included, Maton and Wicart (2005) evaluated electromyography and ground reaction forces during a bilateral toe raise test in 8 to12 year old subjects with and without clubfoot. Electromyography of the gastrocsoleus found to significant differences in the affected side in patients with clubfoot, which led to differences in vertical acceleration of the center of mass in the clubfoot group.

Given that previous research in patients with clubfoot has identified deficits in ankle plantarflexion strength and ankle/foot range of motion, it seems logical to assess activities which challenge the posterior calf musculature in these patients, for example toe raises and hopping. Clinical guidelines during a toe raise test aim to evaluate hindfoot eversion, however stability of the tarsal joints is necessary to provide a rigid level during the movement (Houck et al., 2009). It is unclear how limited plantarflexion strength and/or limited motion through the hindfoot or forefoot would affect the mechanics of the foot during this test. There are no other studies that have evaluated the biomechanics of the toe raise in any population.

There have been several studies that have examined the mechanics of both unilateral (Augustsson et al., 2006; Ferris, Bohra, Lukos, & Kinnaird, 2006; Holm, Tveter, Fredriksen, & Vollestad, 2009; Orishimo & Kremenic, 2006; Tulchin & Orendurff, 2009) and bilateral hopping (Demirbuken, Yurdalan, Savelberg, & Meijer, 2009; Farley & Morgenroth, 1999), however these studies have mainly evaluated leg stiffness and the effects of fatigue on conventional lower extremity kinematics. Demirbuken et al. (2009) assessed a two legged hop in 22 young men and women and found women were able to modify their leg stiffness (defined as peak vertical force divided by center of mass vertical excursion during the contact phase) more than males. They suggested that these results indicated there was no gender limiting capacity to produce faster hopping. Other researchers compared a preferred vs. maximal hopping height in five adults (Farley & Morgenroth, 1999). Using computer simulation Farley and Morgenroth (1999) found that modification of ankle stiffness was the primary mechanism used to increase hopping height. These findings may have significant implications in the patient with limited ankle motion. Based on spring-mass models, any increase in ankle (or total leg) stiffness will lead to smaller vertical excursion of the COM during contact phase (Farley & Morgenroth, 1999). With limited studies done previously, it is unclear if there is an age effect to leg stiffness and ability to hop.

Augustsson et al. (2006) investigated the effects of single limb hopping and found decreased hip and knee angles, ankle power generation and ground reaction forces during the take-off phase following induced fatigue. In addition they found increased power absorption at the knee during the landing phase representative of the large eccentric demand on the quadriceps muscle, and speculated that this may have an impact on one's ability to perform successive hops. Increased ankle dorsiflexion following fatigue, coincidence with increased knee flexion, has also been reported, with a subsequent increase in peak ankle moment (Orishimo & Kremenic, 2006). This increase in demand for ankle performance to compensate for weakness of the knee musculature may lead to poor hopping endurance in patients with foot pathology. As the proximal leg muscles begin to tire, the patient with foot pathology will be unable to compensate at the ankle, leading to a more sudden decline in performance. Tulchin and Orendurff (2009) compared walking and single limb hopping in 10 adults without history of leg or ankle pathology. They found that sagittal hindfoot and forefoot motion was more highly correlated during hopping compared to walking ($r = .89$ vs. $r = .57$, respectively).

Hopping performance has been evaluated previously in children; however only two studies assessed the movement from a biomechanics perspective. The development of hopping skills has been reported to continue up to and beyond 5 to 7 years of age, with the most advanced level of hopping achieved by 10 years of age. Parker, Larkin & Ackland (1993) compared the ground reaction forces during a single limb hopping activity in children ages 3 through 9 years and adults, and found that a decreased standard deviation and coefficient of variation of vertical and mediolateral force, along with shorter flight time, was more indicative of efficient hopping. They concluded that using measures of variability as opposed to mean scores was more sensitive in determining a child's performance (Parker et al., 1993).

Table 5

Biomechanical/Kinematic Assessment of Activities

Study	Subject Cohort	Activity
Parker et al. (1993)	25 children 10 adults	GRF Study: Single limb hopping
Holm et al. (2008)	360 children	Temporal-spatial parameters only: Single Limb Hopping
Tulchin et al. (2009b)	24 healthy adults	MSFM: Increased and decreased walking speed
Tulchin & Orendurff (2009)	10 healthy adults	MSFM: Pilot study– single limb hopping
Dubbelham et al. (2010)	14 healthy adults	MSFM: Self-selected speed walking (SSW), 75% SSW and 50% SSW
Tulchin et al. (2010b)	24 healthy adults	MSFM: Gait-level overground, incline to 12%, & decline to 7.5%
Dixon et al. (2011)	9 adults	MSFM: Cross-slope running
Dubbelham et al. (2011)	23 adults with rheumatoid arthritis 14 control group	MSFM: Self-selected walking (SSW) in patients with RA, 75% SSW and 50% SSW

Note: Excludes self-selected walking and running studies

Dynamic Systems Theory

During gait analysis, the movement of the body is described as a combination of joint motions. In order to quantitatively assess these patterns, time-series data (i.e. joint angles, moments, powers) are interpreted and typically further reduced to individual discrete kinematic or kinetic measures (i.e. peak motion or power, joint excursion). An alternative to this traditional approach is to examine the relationship, coordination or coupling between two adjacent body segments or joints with one of many dynamic systems theory analysis techniques (Glazier, Davids, & Barlett, 2003). These methods are based on the idea that one segment or joint influences the motion of another segment or joint, and allow the researcher to describe a movement using a system-based approach.

The simplest method to assess the coordination between two joint movements is to use discrete point analysis. Using time-series data, discrete point analysis and spatio-temporal measures are used to describe angles or motions during an activity by determining the value at a specific point in time or the minimum, maximum and/or overall range of motion over a portion of (i.e. stance phase for walking, countermovement phase for hopping, etc.) or the entire movement cycle (i.e. gait cycle or hopping cycle.) In addition to the magnitude of the angle, the timing of the peak movements within the cycle can also be evaluated. The time to peak difference can then be calculated as the difference between, for example, peak dorsiflexion of the hindfoot and peak dorsiflexion of the forefoot. This method has been used in the running literature to assess injury mechanics by determining coupling patterns of the rearfoot and the tibia, and coordination of the subtalar and knee joints (Dierks, 2010; McClay & Manal, 1997; Stergiou, Bates, & James, 1999; Stergiou, Bates, & Kurz, 2003).

Excursion ratios, or coupling coefficients, are another common method to assess the coordination between two joint movements. First described by Nigg, Cole and Nachbauer (1993) as the transfer coefficient, the *excursion ratio* is simply calculated as the ratio of the total excursion of one segment or joint to the total excursion of another segment or joint. Excursion of a movement differs slightly from total range of motion over a defined interval. For example, dorsiflexion excursion of the ankle would typically be defined as the difference between the maximal dorsiflexion and the position at initial contact, whereas ankle total angular range of motion during stance phase would be defined as the difference between the maximal dorsiflexion and maximal plantarflexion throughout stance phase. Coupling coefficients can be determined by using either excursion (Nigg et al., 1993) or total angular motion over an interval (Nawoczenski, 1998; Wilken et al., 2011) and has been applied in the analysis of foot motion the assessment of barefoot and/or shod running mechanics (Stacoff, Nigg, Reinschmidt, van den Bogart, & Lundberg, 2000) and the effects of arch height, excessive pronation or foot structure on walking or running patterns (McClay & Manal, 1997; Nawoczenski, 1998; Nigg et al., 1993; Wilken et al., 2011). In addition, similar linear correlations between the two angles over an interval have been evaluated to assess the coupling between two joint motions (Dubbeldam et al., 2011; Tulchin & Orendurff, 2009; Wilken et al., 2011). Pearson correlation coefficients however are only applicable in situations where the coupling pattern is assumed to be linear.

There are several more advanced methods to evaluate the coordination between two segments or joints, including discrete and continuous relative phase and vector coding. Relative phase plots are created by graphing the angular velocity of the joint as a function of its angular position. Data points on the relative phase plot are then converted from Cartesian to polar coordinates and the phase angle is defined as the inverse tangent of angular velocity and angular movement. Relative phase angle can then be determined as the difference between two segment or joint phase angles, typically expressed as the proximal segment minus the distal segment (Hamill, van Emmerik, Heiderscheit, & Li, 1999). The main advantage to using relative phase is that both angular and temporal data is maintained (Wheat & Glazier, 2006). Disadvantages to the relative phase include the potential need for time normalization of the data prior to analysis and the inclusion the higher order derivative angular velocity which may propagate errors such as marker placement or skin motion (Wheat & Glazier, 2006). Most importantly, Field-Fote and Tepavac (2002) have recognized that most clinicians think of movement in terms of joint or segment angles, not phase values, which make relative phase very difficult to interpret. For this reason, relative phase analysis was not considered for this study.

Vector coding is an alternative method for analysis based on the angle-angle, or relative angle plot, where two angles are graphed against each other (Figure 8a, Hamill, Haddad, & McDermott, 2000). Based on methods first described by Sparrow, Donovan, van Emmerick & Barry (1987), the orientation of the vector connecting two consecutive data points relative to the right horizontal is termed the *coupling angle*, which can therefore range from 0 to 360°. Values on or near the axes, i.e. 0, 90, 180 and 270° therefore indicate that movement is primarily occurring in one segment or joint, and this motion is consider *out-of-phase* (Figure 8b). When both segments or joints are moving at nearly equal magnitudes, with a 1:1 ratio, the coupling angle will approximate 45, 135, 225 or 315° depending which direction each segment is moving. When the two segments are moving together towards positive or negative motion, it is termed *in-phase* motion. The coupling angle for in-phase motion will be either 45 or 225° based on if they are both increasing or decreasing, respectively. If the two segments are moving in opposite directions, in terms of their negative and positive directions, it is considered to be *anti-phase* motion, and the coupling angle will be either 135 or 315° based upon which segment is moving in each direction. The coupling angle is determined for each point-pair across the gait (or activity) cycle, a plot of the coupling angle over time can be determined (Figure 8c). The coupling angle is circular (360° is equivalent to 0°) and it is necessary to calculate mean and standard deviations across trials using circular statistics (Hamill et al., 2000). The point-by-point, between-trial coupling angle is then determined for each point in the activity cycle, for each person in the analysis.

Chang, van Emmerik & Hamill (2008) defined a classification scheme to describe the type of coordination pattern, based on in-phase, anti-phase, proximal segment or distal segment motion. In Figure 8c, the color coded bar through the coupling angle plot indicates the associated classification bin for each data point-pair. Chang et al. (2008) presented these classification bins in histogram form to visualize the pattern of motion within specific intervals of stance phase. They used this method to describe the coupling patterns between the rearfoot and the forefoot during walking in adults without foot pathology. Coupling angles were divided into equally spaced 45° bins and were assigned to in-phase, out-of-phase, rearfoot phase, and forefoot phase, accordingly. They concluded that this expanded version of vector coding allows researchers to better quantify the coordination patterns using typical kinematic variables.

Vector coding techniques have been used to describe foot coupling angles, with many studies examining running mechanics and rearfoot motion (Chang et al., 2008; Ferber et al., 2005; Ferber & Pohl, 2011; Hamill et al., 2000; Heiderscheit et al., 2002). Heiderscheit et al., (2002) expanded the vector coding technique to emphasis the importance of the coupling variability. Coupling variability is determined by the point-by-point standard deviation of the coupling angle across multiple trials, and has also been used to describe coupling patterns in the foot (Ferber et al., 2005; Ferber & Pohl, 2011; MacLean, van Emmerick, & Hamill, 2010). Unfortunately there is conflicting reports of whether decreased variability is desired for proper mechanics, detrimental and may cause injury, or indicates pathology. For example, Heiderscheit et al., (2002) reported that patients with patellofemoral pain exhibited less variability and concluded that this represented a less flexible system, causing subjects to be more prone to injury. However, Ferber, Kendall and Farr (2011) reported that following a strengthening program, a reduction in coupling variability was seen in a similar population, suggesting a more consistent, predictable pattern of movement. Therefore it is unclear whether or not increased or decreased coupling variability is ideal, and most likely this would depend on the joints and movements under investigation. Only one study was found that examined foot coupling in a group of patients with foot pathology.

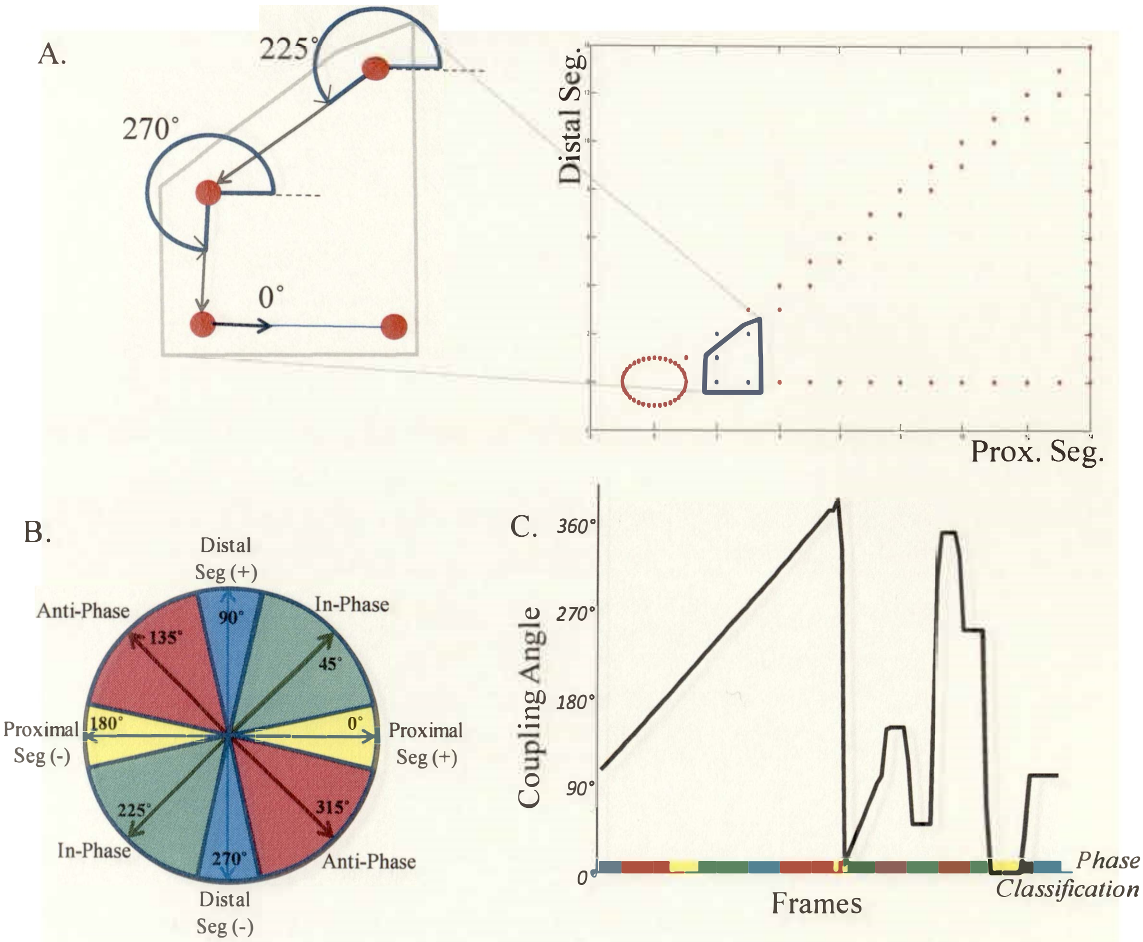


Figure 8: Vector coding technique. A) An angle-angle plot is created between the distal and proximal segment motions. The angle between each data point pair from the right horizontal is used to define the coupling angle. B) Polar coordinate plot indicates which classification bin each value of the coupling angle falls into. C) Resulting coupling angle graph with highlighted color bar indicating phase classification for each data point.

Dubbelham et al. (2011) evaluated foot coupling using a multi-segment foot model in patients with rheumatoid arthritis using a variety of methods, including linear correlation, vector coding and continuous relative phase. Using simple linear correlations, stronger coupling patterns were seen in the healthy adults compared to patients with arthritis. In addition, poor coupling between the first metatarsophalangeal joint and hindfoot eversion was seen in patients who had plantar fascia degeneration as seen on magnetic resonance imaging. To date there are no studies that have quantitatively evaluated coupling patterns within the foot in children with or without clubfoot.

Summary

The long-term outcomes of nonoperative clubfoot treatment remain unknown. Preliminary work following surgical treatment indicates significant decreases in ankle range of motion and ankle plantarflexion strength with or without the presence of residual hindfoot and forefoot deformity. It has recently been recommended that more challenging activities be included in the assessment of gait in patients with mild pathology, and specifically in patients with clubfoot, this has included tasks focused on plantarflexion strength. Although the utilization of multi-segment foot modeling has increased in adults with foot pathology, limited work exists in the evaluation of the pediatric foot, and in particular the child with clubfoot. Therefore, the assessment of the kinematics and coupling patterns within the foot during both walking and more challenging tasks focused on plantarflexion strength, i.e. toe raises and hopping, may provide an important insight into the pathomechanics of clubfoot.

CHAPTER III

QUANTIFYING JOINT COUPLING PATTERNS: EFFECTS OF BIN SIZE AND ORIENTATION ON COUPLING CATERGORIZATION

A paper to be submitted for publication

in the *Journal of Biomechanics*

Introduction

The interpretation of inter-joint or inter-segmental coupling can be difficult, and many previous methods, such as continuous relative phase or cross-correlation, do not provide an intuitive clinical interpretation for health practitioners. Angle-angle plots provide a technique to quantify the relationship between two simultaneous motions, and have been proposed as being easier to understand (Field-Fote & Tepavac, 2002). Vector coding is a method used to determine the orientation of the slope between two consecutive data points on the angle-angle plot. When both segments or time-series angles move in a 1:1 ratio, the slope of the angle-angle plot would approximate 45° (both moving in positive direction) or 225° (both moving in negative direction). Slopes of 0° and 90° would represent purely abscissa and ordinate motion on the angle-angle plot, respectively, and a slope of 135° would indicate opposite 1:1 motion of the two time-series angles, as one increases and the other decreases. The vector coding technique results in a new time series plot known as the coupling angle, and has been used, for example, to assess rearfoot mechanics during walking and running (Chang et al., 2008; Ferber et al., 2005; Ferber & Pohl, 2011; Hamill et al., 2000; Heiderscheit et al., 2002).

In practice, it is uncommon for coupling angles to align with these distinct patterns. For that reason, Chang et al. (2008) introduced the terms *in-phase, anti-phase, proximal-phase and distal-*

phase, and proposed the use of contiguous "bins" having an interior angle of 45° to categorize the movement patterns. In their study, *in-phase* movement was centered about the 45° diagonal with the bin boundaries being at ± 22.5° from that line.

Joint anatomy and pathology, however, can often dictate movement patterns in which one segment moves through a smaller available range of motion than another. The sagittal plane range of motion of the knee during walking, for example, in an individual without pathology is approximately 60°, while the range of motion at the ankle may be 35°. Given that the available excursions of these joints are very different, using a 45° coupling angle (1:1 excursion ratio of the two angles) between these two joints may not be the most effective way to define *in-phase* motion.

Although not specifically presented, Chang et al. (2008) reported that during walking, the coordination pattern of rearfoot and forefoot motion in the coronal plane did not significantly change when using smaller bins of 30°. In their study, however, the overall range of motion of these two segments was approximately equal. Variations in the definition of category bin widths and locations may result in significant changes in coupling patterns when the excursion ratio between the two angles is not equal. This may be particularly important in the foot where available excursions may be small, and changes in the range of motion between patient groups or testing conditions may only be a few degrees. During walking the ability to coordinate movement between two joints within the foot allows for modulations in foot stiffness, with rigidity of the foot to aid in push off and a more flaccid foot to allow accommodations to uneven terrain. In pathology, contractures and/or lack of strength may limit movement in one joint, causing compensatory motion in another. It is crucial therefore that coupling categorization methods are sensitive enough to detect small changes in the coordination patterns in these patients pathology. In addition, activities, such as jumping or running may require more (or less) range of motion in some joints, which may require activity-specific definitions for category bins.

In this study, a new modified version of the method originally proposed by Chang et al, (2008) is introduced which uses the excursion ratio of the movements to define the bins for each coordination category. The purpose of this paper was to examine the effects of bin size and bin location definition on the identification of coordination patterns, and in particular, evaluate the application of this method to a task other than walking.

Methods

Fifteen children (10 males/ 5 females; average age: 10.4 ± 0.6 years; weight: 36.3 ± 6.9 kg; height: 141.5 ± 5.2 cm), with no history of foot or lower extremity pathology/injury, underwent three-dimensional motion analysis with Institutional Review Board approval. Kinematic and kinetic data were obtained simultaneously using a 12-camera VICON motion analysis system at 120Hz (VICON, Oxford Metrics Group, Denver Colorado, USA) and 5 AMTI force plates (Advanced Mechanical Technology, Inc., Watertown MA, USA). A full-body marker set (VICON-Plug-in-Gait) and the TSRHC Foot and Ankle Model (TSRHC-FAM) marker set were applied to each subject (Tulchin et al., 2009a).

Data for both sides were collected with one side randomly selected for analysis. Each subject was asked to perform 20 consecutive single-limb toe-raises with each foot. Relative motion was determined for the hindfoot relative to the tibia (termed *HINDFOOT* motion, Tulchin et al., 2009). The start and end of each toe raise was determined using the vertical position, velocity and acceleration of the posterior heel marker. The maximum vertical position of the heel marker was used to determine the transition between UP and DOWN phases, and was set to 50% of the toe raise cycle. UP and DOWN phases were time normalized independently. Due to differences toe raise cycle. UP and DOWN phases were time normalized independently. Due to differences in toe raise execution, it was decided to exclude the middle of the cycle (40-60%) from analysis, resulting in 0-40% of the cycle for the UP phase and 61-100% for the DOWN phase. For this investigation, the first three toe raises were selected for analysis to avoid the influence of fatigue. Coupling angles between the sagittal and coronal planes for relative hindfoot motion were determined using the vector coding method previously described by Heiderscheit et al. (2002). Three-dimensional kinematic time-series data of the hindfoot were used to determine the overall range of motion in each plane during the toe raise test. Based on previous work by Chang et al. (2008), the coupling angles were categorized into 1 of 4 bins, *in-phase, anti-phase, sagittal-phase* and *coronal-phase*, using three different categorization schemes (Table 6). The first method used 45° bins, with a 1:1 ratio (45°) centered at the middle of *in-phase* coupling.

Table 6

Criteria Used for Coupling Classification Bins: Effects of Bin Size

Category Scheme	***Sagittal-phase* (°)**	***In-phase* (°)**	***Coronal-phase* (°)**	***Anti-phase* (°)**
30° bins	0 : 30 150 : 210 330 : 360	30 : 60 210 : 240	60 : 120 240 : 300	120 : 150 300 : 330
45° bins	0 : 22.5 157.5 : 202.5 337.5 : 360	22.5 : 67.5 202.5 : 247.5	67.5 : 112.5 247.5 : 292.5	112.5 : 157.5 292.5 : 337.5
Excursion Ratio Centered at 1:2 Range 1:1 to 1:3	0 : 18 162 : 198 342 : 360	18 : 45 198 : 225	45 : 135 225 : 315	135: 162 315 : 342

Bin sizes and orientations differed using 3 different categorization schemes to assess the coupling patterns between sagittal and coronal plane hindfoot motion, 45° bins, 30° bins and using an excursion ratio of 1:2 which corresponds to approximately 26°.

The second method assigned the *in-phase* and *anti-phase* bins to 30° intervals, also centered about a 1:1 ratio (45°, 135° for *in-phase* and *anti-phase* coupling, respectively). The third method, which was proposed in this paper, utilized the excursion ratio of the two angles to determine the center of *in-phase* and *anti-phase* coupling bins.

For this example, using the minimum and maximum of each kinematic time-series, the average ratio of coronal to sagittal plane motion was 0.5. This equates to an approximate 26° coupling angle (slope) on the angle-angle plot. With the excursion ratio at 1:2, the *in-phase* boundaries were defined at ratios of 1:3 to 1:1, (approximately 18° and 45°, respectively). This method allowed for a magnitude normalization of phasic movements based on the overall, mean range of motion of the hindfoot in each of the two planes during a single-limb toe-raise test across all subjects. Similar to the 30° method, this approach resulted in having category bins of unequal widths (Figure 9, Table 6).

The coupling category distribution was determined using each method (45°, 30° and excursion ratio) on a point by point basis during the cycle for the UP phase and DOWN phase. The median of three toe raises was selected for analysis for each subject, as the median would ignore extreme values that would bias the mean. The number of points in each category was summed for UP and DOWN phases using each method, and the average percent in each category was determined. Since each movement phase (UP and DOWN) was computed using 40 points, a percentage-stacked histogram was created to better illustrate the differences in coupling patterns categorizations between methods. A Kruskal-Wallis test, with alpha set to .05, was used to evaluate differences between the three methods with respect to the number of points in a given category.

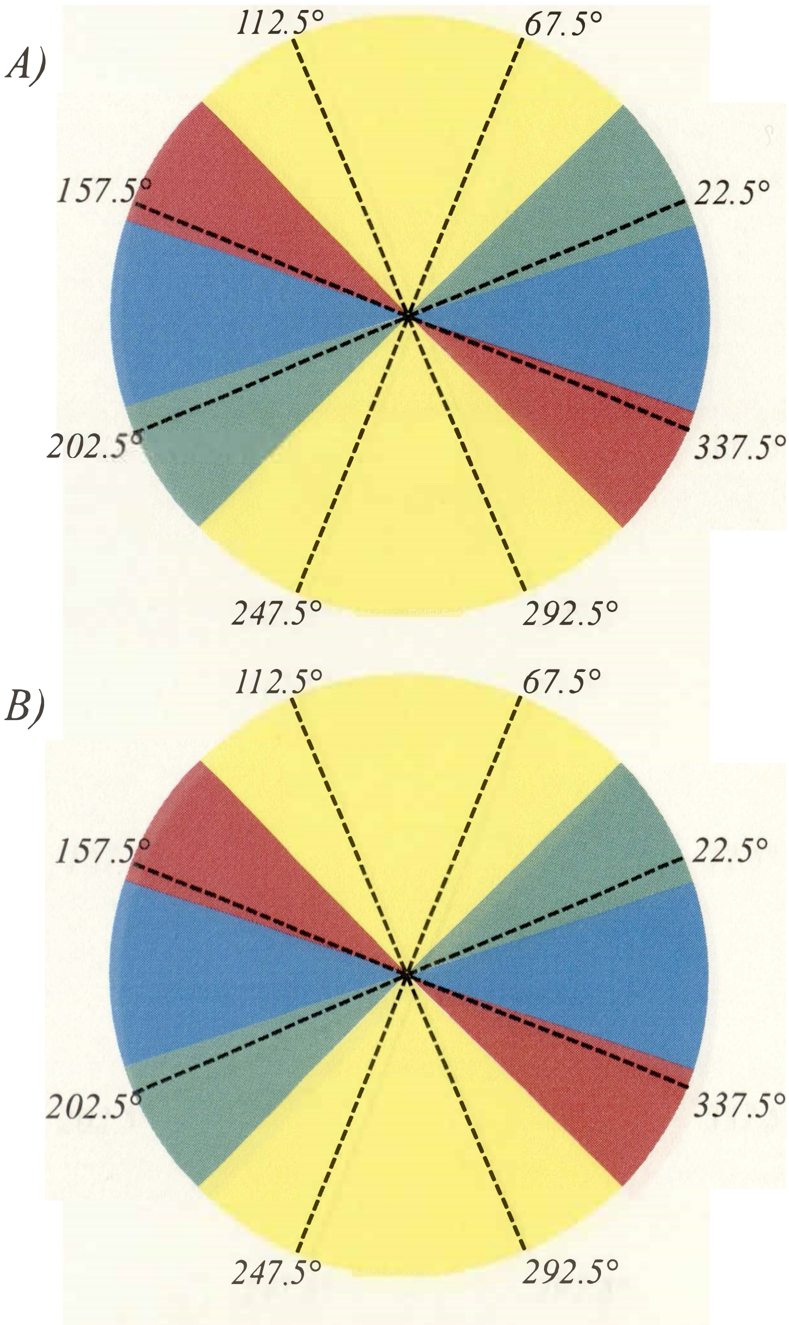


Figure 9: Category bins for coupling angles. In this example the ratio of coronal to sagittal motion is 1:2 and categorization of coupling angles does not result in equal bins when using the excursion ratio method, The color-coded regions represent each of the four categories using the excursion ration method: Green: *in-phase,* Red: *anti-phase,* Blue: *sagittal-phase* and Yellow: *coronal-phase* . A) Comparison of excursion ratio method to 45° bins (dashed lines); B) Comparison of excursion ratio method to 30° bins (dashed lines)

Results

The average coupling distribution between sagittal and coronal plane hindfoot motion for UP and DOWN phases across the group is shown in Figure 10. The reduction in *sagittal-phase* coupling approached significance for the UP movement (p = .082), and was significantly reduced during the DOWN movement (p = .049). In addition, there was a significant change in the *coronal-phase* coupling during the DOWN movement (p = .001).

As a case example, a single subject was selected whose excursion ratio (0.44) was similar to that used to define the bins. The time-series data during the UP movement, shown in Figure 11a, illustrate a possible anti-phase relationship between hindfoot plantarflexion and hindfoot varus. With the range of motion of the sagittal plane movement greater than twice that of the coronal

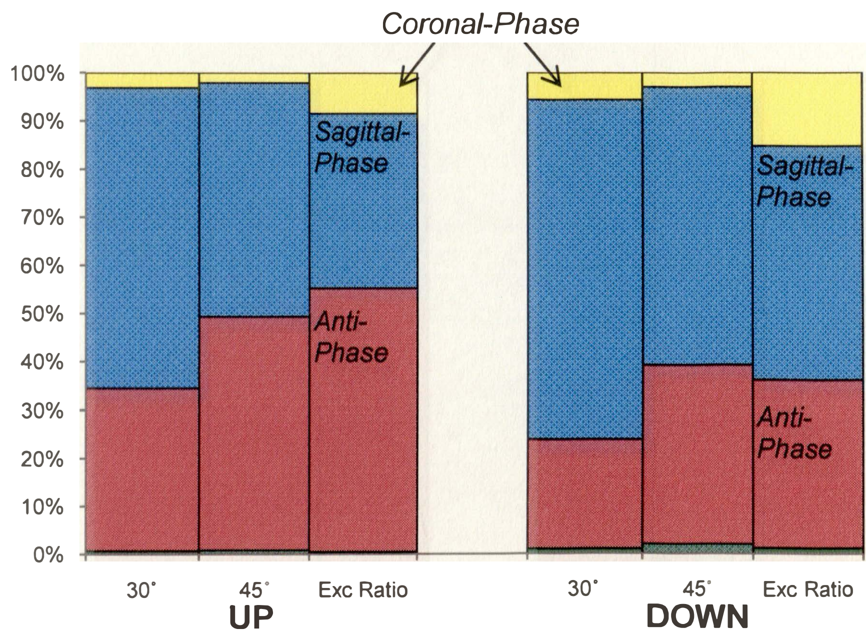


Figure 10: Comparison of coupling categorization methods for UP and DOWN phases of a toe raise test. A significant reduction in the amount of *sagittal-phase* coupling was found when the excursion ratio bin was realigned to more accurately represent the range of motion seen across these planes (p = .049). Green: *in-phase,* Red: *anti-phase,* Blue: *sagittal-phase* and Yellow: *coronal-phase.*

plane, the angle-angle plot has a slope of approximately 155°. Using the 45° bin method, the coupling pattern is split, with the majority of the movement (80%) occurring with a *sagittal-phase* coupling, and it was categorized as 100% *sagittal-phase* movement using the smaller, 30° bins. Using the excursion ratio method, this coupling pattern was categorized entirely as *anti-phase* movement.

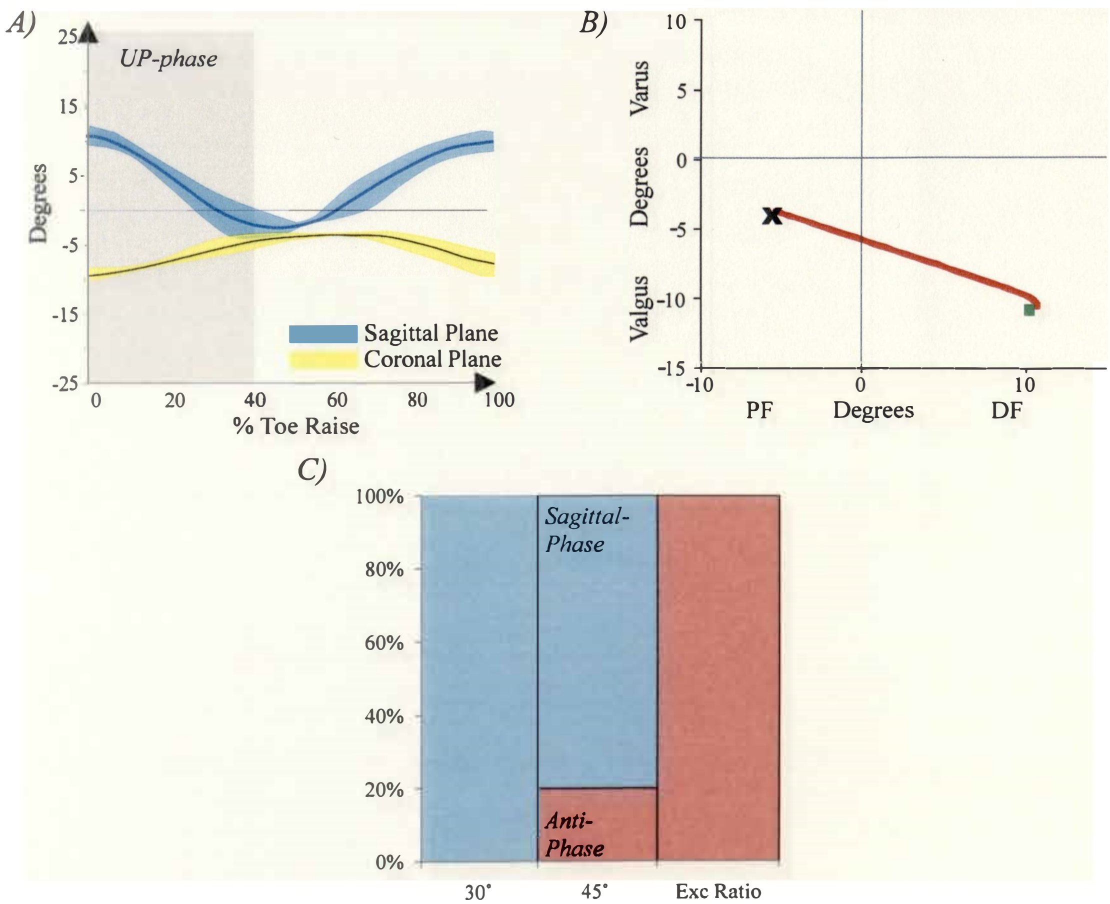


Figure 11: Coupling categorization bin definition comparison - case example. This subject had an overall excursion ratio of 0.44 between hindfoot varus/valgus and hindfoot DF/PF. A) Average time-series data for each angle. Blue and yellow bands are the standard deviations of 3 toe raises for DF/PF (sagittal plane) and varus/valgus (coronal plane) respectively. The UP phase is shown in gray region. B) Angle-angle plot for the UP phase. C) Comparison of coupling categorization using the three methods. Green: *in-phase,* Red: *anti-phase,* Blue: *sagittal-phase* and Yellow: *coronal-phase*.

Discussion

A new categorization technique has been proposed to provide a coupling analysis method to describe the relationship between two joint motions, which are normalized to the overall excursion of the angles during the activity of interest. Field-Fote and Tepavac (2002) have previously identified the difficulty in the clinical interpretation of previous methods which assessed coupling. Physicians and allied health professionals typically examine angular range of motion on a joint by joint basis, and describe the motion of joints over time. Angle-angle plots may not be intuitive to these clinical researchers. The use of a simple categorization scheme to define coupling patterns can aid clinicians in quantifying joint coordination. Using the coordination of hindfoot varus/valgus and hindfoot dorsiflexion/plantarflexion, the current study illustrated the importance that category definitions had on the coupling patterns.

The introduction of a categorization scheme to describe the coupling patterns between two angles first utilized 45° bins equally distributed about a 360° circle (Chang et al., 2008). With a 1:1 ratio, the coupling between the two angles would equate to 45° if they are moving in the same direction (*in-phase* motion). In some situations, however, the range of motion of one joint movement may be significantly more (two to four-fold increase) than another joint movement based on the joint arthrology, joint degrees of freedom and overall excursion during the activity. Despite the differences in the magnitude of the angular motion, there is still clinical importance to understanding if the two angular movements are coupled. Using properly defined coordination categories based on the excursion ratio of two angular movements, investigators can quantitatively describe small changes in the overall stiffness or rigidity of a combination of joint movements, rather than evaluating each angle independently using time-series data.

Chang et al. (2008) previously reported that for the assessment of rearfoot to forefoot motion in the coronal plane during walking in healthy adults, there were no differences between coupling patterns when using 45° bins compared to 30° bins. In the current study there was a significant difference in the distribution of coupling patterns between sagittal and coronal plane hindfoot motion during a single-limb toe-raise test. Based on the visual inspection of the time-series data, as well as the angle-angle plots, there does seem to be an *anti-phase* coupling pattern between these two planes, with hindfoot plantarflexion associated with hindfoot varus as the subjects went up onto their toes. The excursion ratio of coronal to sagittal hindfoot motion across the group of healthy children approximated 1:2, which equates to a 26° coupling angle and lies very close to the bin boundaries using the 45° bin method. In the case example, this resulted in a split between *anti-phase* and *sagittal-phase* motion using the 45° bin method. When 30° bins were used, the cut-off for *in-phase* motion was 30°, well above the average coupling angle, resulting in all *sagittal-phase* coupling. The relationship between hindfoot plantarflexion and hindfoot varus can be very important in the assessment of patients with foot pathology (Houck et al., 2009). For example, a reduction in hindfoot varus, often seen in patients with posterior tibialis tendon dysfunction (PTTD) would lead to a shift towards more *sagittal-phase* coupling. Using 45° or 30° bins, as seen in this study, coupling angles would tend to align at or above the *in-phase* to *sagittal-phase* bin boundary, and may not be sensitive to detect the shift towards *sagittal-phase* coupling seen in patients with PTTD. Using the excursion ratio method, the results of coupling analysis become more clinically meaningful, as an alteration in coordination patterns can be identified.

This study proposed the use of the overall range of motion of each angular movement for a reference group, such as a group of individuals without pathology, so that all study subjects utilized the same bins for comparison. Coupling analysis using the excursion ratio categorization method can require more organization and analysis, as the bin assignments for multiple angle-angle comparisons can and will vary, particularly when assessing multiple activities or tasks. For example the relationship between hindfoot to forefoot motion in the sagittal and coronal planes may have different excursion ratios, and therefore would require different bin definitions. In addition, different bin assignments may be necessary for different activity evaluations such as walking patterns versus those for a toe raise test. Researchers should clearly define their bins, as well as the rationale behind them, prior to analysis. Furthermore, it is important that bin assignments be clearly outlined when reporting results. For the hindfoot sagittal and coronal plane assessment presented here, boundaries were defined by varying the relationship by one-fold change in each direction, i.e., 1:3 to 1:1 for a 1:2 excursion ratio.

In conclusion, these preliminary results support the use of a new coupling angle categorization method to provide insight into the association between various inter-joint/inter-phase relationships. However, care must be taken to properly define *in-phase*, *anti-phase*, and *abscissa-/ordinate-phase* couplings for each angle-angle relationship. The excursion ratio categorization method can provide a more clinically-driven assessment of coupling patterns by normalizing the categories to the anticipated range of motion of the joints of interest. This method allows realignment of category bins such that the excursion ratio for the two angles falls within *in-phase* coupling pattern. The excursion ratio method will allow clinicians to quantify small changes in joint mechanics, by better assessing a patient's ability to modulate joint stiffness and joint coupling.

CHAPTER IV

FOOT KINEMATICS AND JOINT COORDINATION: APPLICATION OF A COUPLING METHOD IN THE ASSESSMENT OF FOOT MECHANICS IN CHILDREN WITH AND WITHOUT CLUBFOOT

A paper to be submitted for publication

in *Clinical Biomechanics*

Introduction

Children born with clubfoot have significant foot deformity that requires treatment at birth. Long term outcomes in patients who were initially treated with surgical intervention have shown poor outcomes, with gastrocnemius weakness, limited ankle motion and reduced push-off ankle power during gait (Graf et al., 2010; Karol et al., 1997). Muratli et al. (2005) reported that significant gait differences exist even in successful and asymptomatic clubfeet. These results led many institutions to adopt nonoperative treatment methods over the last 15 years. Short term outcomes at 2 and 5 years of age in patients treated with nonoperative methods have identified mild to moderate variations in gait mechanics (El-Hawary et al., 2008; Karol et al., 2005; Karol et al., 2009) and plantar pressures (Hee et al., 2001; Jeans & Karol, 2010; Sinclair et al., 2009; Thometz et al., 2005) when compared to age-matched children without clubfoot.

New techniques using motion analysis and multi-segment foot models can provide additional insight into the biomechanics of the foot. Using a multi-segment foot model, children previously treated surgically for clubfoot were found to have decreased hindfoot range of motion and compensatory midfoot dorsiflexion (Theologis et al., 2003). In young adults with clubfeet, Graf et al. (2010) found increased hindfoot plantarflexion, increased forefoot dorsiflexion and forefoot adduction, suggesting residual deformity. These studies support the application of multi-segment foot models in assessing the mechanics within the foot in patients with clubfeet.

The majority of outcome studies evaluating children with clubfeet were reported during walking at a self-selected velocity. Ghanem and Seringe (1995) first suggested that an activity such as hopping should be used to assess gastrocsoleus strength in children with clubfeet. Maton and Wicart (1995) assessed electromyography (EMG) and ground reaction forces during a bilateral toe raise test in 8 to 12 year old children with and without clubfoot. They found significant differences in the EMG activity of the gastrocsoleus, which lead to decreased vertical acceleration of the center of mass. Graf et al. (2012) recently outlined a comprehensive protocol to evaluate the long term outcomes in patients with clubfoot, recommending ankle plantarflexion strength evaluation, clinical evaluation of ability to perform toe raises, and multi-segment foot kinematics during overground walking.

Expanding on the protocol set forth by Graf et al. (2012), this study proposes the inclusion of multi-segment foot kinematic assessment during activities that focus on plantarflexion strength in the evaluation of individuals with clubfoot; specifically two tests that have previously been identified for this population: hopping and toe raises. This would suggest that the increased range of motion and/or ankle power generation required for these tasks may better identify deficits in foot and ankle function, for example in children with mild residual clubfoot deformity. Functionally assessing posterior calf musculature, these activities, and specifically hopping, may be important in a child's ability to play with other children in the community and on the playground. Youth activities such as hopscotch and sporting activities such as basketball, require adequate ankle motion and strength for jumping, cutting and overall agility. Furthermore, to better evaluate foot mechanics, the assessment of coupling patterns between the hindfoot and forefoot may lead to a better understanding of foot function by assessing one's ability to modulate the rigidity or stiffness of the foot during different movements.

Therefore the purpose of this exploratory study was to assess the foot mechanics, using ankle kinematics and kinetics, multi-segment foot kinematics and joint coupling patterns, in children with and without clubfoot, during three activities: 1) overground walking, 2) single limb hopping and 3) single limb toe raises. More specifically, it was hypothesized that limited hindfoot motion and weakness in children with clubfoot would result in significant changes in the coupling patterns between the hindfoot and forefoot, with decreased in-phase/anti-phase motion, particularly during the hopping and toe raises tests.

Methods

Participants

Sixteen children (Control Group; 10 males/6 females; age: 10.4 ± 0.5 yrs; height: 142 ± 6 cm; and weight: 36.5 ± 6.7 kg) with no history of foot pathology or lower extremity injury, and sixteen children with 23 clubfeet (Clubfoot Group; 10 males/6 females; age: 10.2 ± 0.3 yrs; height: 141 ± 6; and weight: 36.7 ± 8.0 kg) underwent three-dimensional motion analysis with Institutional Review Board approval. All subjects in the Clubfoot Group were initially treated nonoperatively for idiopathic clubfoot with either the Ponseti serial casting and/or French physical therapy treatments at Texas Scottish Rite Hospital for Children. Patients with underlying neuromuscular diagnoses or syndromes were not included. Eight clubfeet failed initial nonoperative treatment and underwent subsequent surgical intervention beyond a tendo-Achilles lengthening; however no subject had undergone any procedure within the last 24 months.

Data Acquisition and Testing Protocol

Three-dimensional motion analysis was performed using an 12-camera VICON motion analysis system at 120Hz (VICON, Oxford Metrics Group, Denver Colorado, USA) and 5 AMTI force plates (Advanced Mechanical Technology, Inc., Watertown MA, USA). The full-body Conventional Gait Model marker set used within the VICON software called Plug-in-Gait (PIG) and the TSRHC Foot and Ankle Model (TSRHC-FAM) marker set was applied to each subject. The Conventional Gait Model marker set was used to determine lower extremity kinematics and kinetics as well as total body center of mass. Multi-segment foot kinematics were determined using the TSRHC-FAM previously described by Tulchin et al. (2009). Briefly, the TSRHC-FAM consisted of four segments: the tibia, hindfoot, forefoot and hallux. Markers placed on the posterior calcaneus, lateral malleolus and the dorsum of the foot as part of the Conventional Gait Model are also incorporated within the TSRHC-FAM. The hindfoot segment definition used the posterior calcaneus marker and two markers placed on the medial and lateral aspect of the calcaneus aligned using a cross-haired laser device. In order to place the hindfoot markers, a vertical bisection of the hindfoot during nonweightbearing was marked, representing the midline of the calcaneus (Rattanaprasert et al., 1999). During weightbearing, the posterior calcaneus marker was placed at the center of the cross-hair, and the medial and lateral calcaneus markers were then placed perpendicular to the vertical bisection line using the cross-hair laser.

Each subject performed three activities, in the barefoot condition, during a single testing session: overground walking, single limb hopping and single limb toe raises. Data for both sides were collected; however only the affected limbs are reported for the Clubfoot Group, and a single side was randomly selected for analysis for each subject in the Control Group. Overground walking was conducted along a 10 m walkway at each subjects' self-selected speed. A minimum of 7 trials with forceplate strikes were collected for each side. Following the walking trials, subjects were asked to perform single limb hopping on one of the forceplates. Explicit instructions were given for the subject to hop as high and as fast as possible, while trying to keep their foot contacts within the forceplate. If their foot landed outside the box, the subject continued to hop as verbal cues were given instructing the subject to correct their landing position. Subjects were asked to hop as long as possible. Each subject was allowed to self-randomize which foot they hopped on first, and a single trial was collected for each side. Following a rest period given to the subject as needed, all subjects were asked to perform 20 single limb toe raises with each foot. Instructions were given to keep their stance-knee straight and to go up onto their toes as high as possible. Subjects were allowed to place one hand on the back of a chair, placed to the side, to help with balance. They were given strict instructions not to use the chair for support; however, this was not explicitly quantified. The order of testing conditions was not randomized. Due to marker dropout, data during toe raises was available for 22 of the 23 affected clubfeet and 15 of the 16 children without clubfoot.

Data Analysis

Tri-planar, relative motions of the following segments were examined in this analysis: hindfoot relative to the tibia (termed *HINDFOOT* motion) and forefoot relative to the hindfoot (*FOREFOOT* motion, Tulchin et al., 2009). Hindfoot motion represented motion at the talocural and subtalar joints. Forefoot motion included the Chopart and Lisfranc joints. These orientation angles were described using Euler rotations about the moving segment axes using an X-Y'-Z" (sagittal-coronal-transverse) rotation order.

Event Definitions and Kinematic Assessment

For overground walking, all trials were time-normalized to the gait cycle. Data from three representative trials were selected and averaged for each subject. The vertical position, velocity and acceleration of the toe marker were used to determine the start/end of each hopping cycle, as well as the division between the stance and flight phases. Peak knee flexion was used to further subdivide stance into countermovement and propulsive phase. The vertical position, velocity and acceleration of the posterior heel marker were used to determine the start and end of each toe raise cycle. The maximum vertical position of the heel marker was also used to determine the transition between UP and DOWN phases. In an attempt to avoid the effects of fatigue, the first 3 hops and first 3 toe raises were selected for analysis of each subject.

Coupling Mechanics

Coupling between two angles was determined using the vector coding method previously described by Heiderscheit et al. (2002) for each angle-angle plot. A coordination categorization, based on work by Chang et al., (2008) was used to determine if the point by point relationships between angles were: 1) *in-phase*, 2) *anti-phase*, or 3&4) motion primarily occurring within one of the two segments (Figure 12). The criteria used to define the *in-phase* category for each angle-angle relationship was based on the average excursion ratio of the two angular motions in the Control Group, and varied based upon the angles analyzed and the movement. Table 7 lists the various categorization schemes used for this analysis. This method allows for a normalization of phasic movements based on the overall range of motion of each segmental/planar angle examined during each task.

Joint coordination for the walking trials was limited to stance phase only, and all data was time normalized to 100% stance phase for coupling analysis. During the walking trial analysis coupling patterns were categorized for early stance (0-33%), midstance (34-66%) and late stance (67-100%). Flight phase was excluded from analysis for the hopping cycles, and due to slight differences in the timing of peak knee flexion, all coupling analysis data during stance phase were independently time normalized within the countermovement (CM, 0-50%) and propulsive phases (PROP, 51-100%). Similarly, data were time normalized to the UP (0-50%) and DOWN phases (51-100%) during the toe raise trials. Due to variations in technique, for example holding or not holding the toe raise at the maximal position or the speed of the hopping movement, the middle of stance phase (40-60%) was excluded from coupling analysis for both toe raise and hopping trials. The distribution of the coupling patterns categorizations were summed over the time intervals of 0-40% (CM and UP phases for hopping and toe raises, respectively) and 60-100% (PROP and DOWN phases).

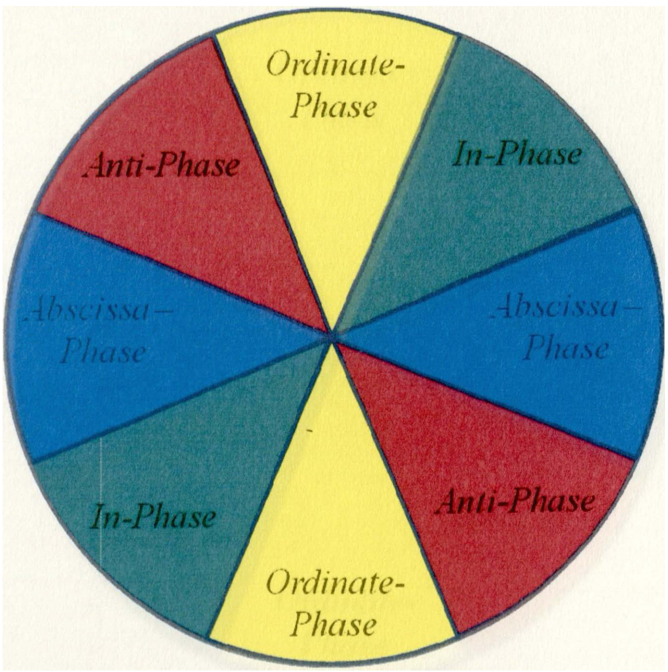


Figure 12: Example: Coupling category scheme for 2:1 (ordinate to abscissa) excursion ratio.

Table 7

Criteria Used for Coupling Classification Bins: Application in the Pediatric Foot

Excursion Ratio (Ordinate : Abscissa)	Bin Boundaries /Range	*Abscissa Angle-phase (°)*	*In-phase (°)*	*Ordinate Angle-phase (°)*	*Anti-phase (°)*
1:1	45° bins	0 : 22.5 157.5 : 202.5 337.5 : 360	22.5 : 67.5 202.5 : 247.5	67.5 : 112.5 247.5 : 292.5	112.5 : 157.5 292.5 : 337.5
1:2	1:1 to 1:3	0 : 18 162 : 198 342 : 360	18 : 45 198 : 225	45 : 135 225 : 315	135: 162 315 : 342
1:3	1:2 to 1:4	0 : 14 166 : 194 346 : 360	14 : 26 194 : 206	26 : 154 206 : 334	154 : 166 334 : 346
1:4	1: 3 to 1: 5	0 : 11 169 : 191 349 : 360	11 : 18 191 : 198	18 : 162 198 : 342	162 : 169 342: 349
2:1	1:1 to 3:1	0 : 45 135 : 225 315 : 360	45 : 72 225 : 252	72 : 108 252 : 288	108 : 135 288 : 315
3:4	~ 1:2 to 1:1	0 : 30 150 : 210 330 : 360	30 : 45 210 : 225	45 : 135 225 : 315	135 : 150 315 : 330
4:3	1:1 to ~2:1	0 : 45 135 : 225 315 : 360	45 : 60 225 : 240	60 : 120 240 : 300	120 : 135 300 : 315

Outcome Measures

For each subject, kinematic outcome variables were determined for each cycle and averaged across three cycles for each activity. Group ensembles were then determined. For all testing conditions, analysis of kinematic and kinetic variables using the Conventional Gait Model focused on ankle motion, dorsiflexion moment and power generation, as well as tibial rotation. TSRHC-FAM kinematic variables included peak values and overall range of motions of inter-segmental joint angles, as well as the timing of peak motion. For walking trials, tempo-spatial analysis including cadence, walking speed and step length were also assessed. Center of mass excursion (peak vertical position during flight phase relative to the vertical position at foot off) was evaluated for all hopping trials. Heel excursion and time to peak heel excursion were also assessed during the toe raise test.

For both groups the distribution of coupling defined by the categorization scheme previously mentioned was determined for several different angle-angle relationships, both intra-segment (inter-planar) and inter-segment. Specifically, intra-segment analysis included hindfoot sagittal to coronal plane motion and hindfoot sagittal to transverse plane motion, as well as forefoot sagittal to transverse plane, and forefoot coronal to transverse plane motions. Inter-segment motions examined the relationship between the hindfoot and forefoot in the sagittal, coronal and transverse planes, as well as hindfoot coronal to forefoot transverse and hindfoot transverse to forefoot coronal. All coupling categorizations were expressed as a percentage of the movement phase (i.e. early/mid/late stance, CM/PROP, and UP/DOWN).

Statistical Analysis

Kinematic and kinetic variables were assessed using two-tailed Student t-tests, with alpha was set to .05. For coupling analysis, χ^2-tests (2x4) were used to assess differences in the distribution of coordination patterns across the 4 coupling categories between the Clubfoot and Control Groups. Post-hoc χ^2-tests were conducted by collapsing data into 2x2 contingency tables – e.g., *in-phase* and *non-in-phase* for each phase category. Alpha was set to 0.001 for post-hoc χ^2-tests.

Results

Walking Kinematics and Coupling

There were few significant differences in walking kinematics and kinetics between the Clubfoot and Control Groups. Using the Conventional Gait Model, children with clubfoot demonstrated decreased sagittal ankle range of motion ($p = .027$) and with slightly decreased external tibial rotation ($p = .039$) and foot progression angle ($p = .035$, Figure 13). Although walking speed was not significantly different ($p = .568$), the Clubfoot Group had decreased peak ankle dorsiflexion moment ($p = .011$) and ankle plantarflexion power ($p = .002$). Multi-segment foot analysis revealed that this overall stiffness of ankle motion was primarily due to decreases in hindfoot range of motion ($p = .012$), specifically with decreased peak hindfoot plantarflexion ($p = .014$). In addition, the Clubfoot Group demonstrated delayed peak hindfoot dorsiflexion ($p = .014$) in second rocker. The Clubfoot Group had slightly increased forefoot adduction compared to the Control Group, although this also was not statistically significant ($p = .153$). There were no differences in hindfoot varus/valgus alignment during gait.

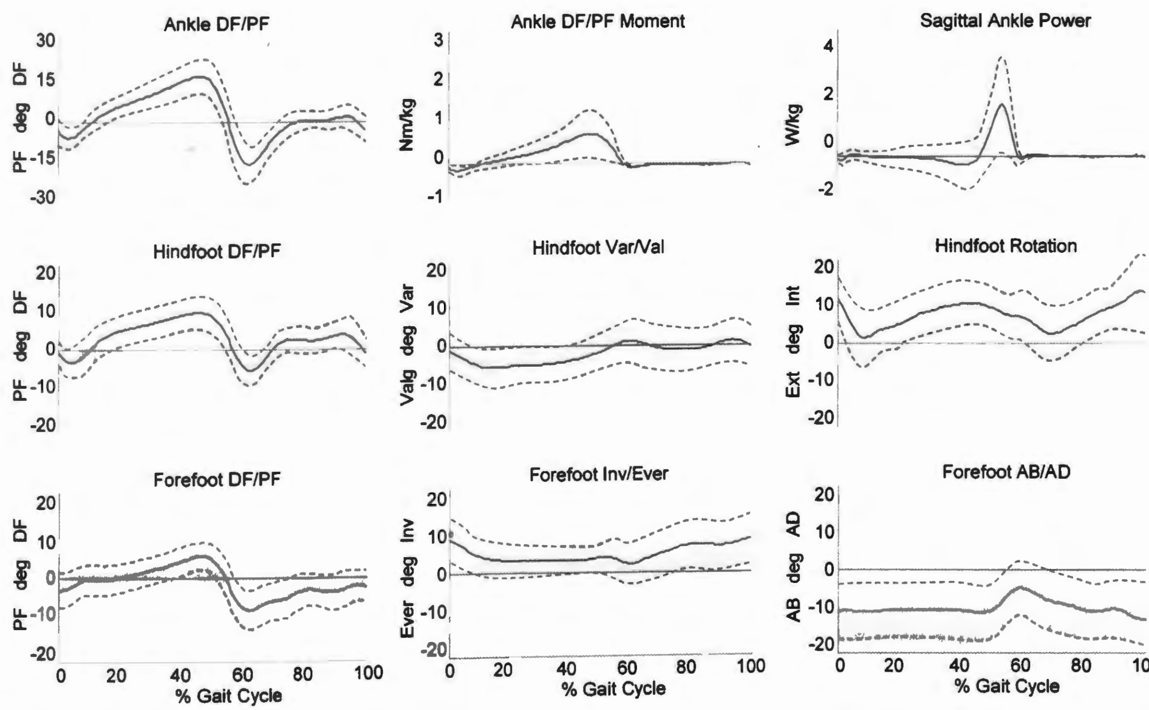


Figure 13: Kinematic time-series data for overground walking. Solid gray band – ensemble average ± 1 standard deviation for Control Group. Solid line – ensemble average for Clubfoot Group, dashed lines - ± 1 standard deviation for Clubfoot Group. DF/PF = Dorsiflexion/ Plantarflexion, Var/Val = Varus/Valgus, Inv/Ever = Inversion/Eversion, AB/AD = Abduction/ Adduction.

Table 8

Kinematic and Kinetic Outcomes During Walking

Variable	Control Group M ± SD	Clubfoot Group M ± SD	p-value
Lower Extremity Kinematics/Kinetics			
Mean Tibial Rotation (Stance, °)	-18.4 ± 3.6	-13.6 ± 8.6	.039
Maximum Ankle PF (Stance, °)	-15.7 ± 6.1	-10.4 ± 4.9	.005
Sagittal Ankle ROM (°)	29.8 ± 4.5	26.5 ± 4.2	.027
Mean Foot Progression Angle (°)	-6.6 ± 6.3	-2.0 ± 6.6	.035
Maximum Sagittal Ankle Moment (Nm/kg)	1.23 ± 0.18	1.01 ± 0.29	.011
Maximum Ankle Power Generation (W/kg)	4.1 ± 0.7	3.2 ± 1.0	.002
Multi-Segment Foot Kinematics			
Maximum Hindfoot PF (°)	-11.9 ± 6.3	-7.7 ± 4.0	.014
Timing Maximum Hindfoot DF (% GC)	36.9 ± 8.2	45.8 ± 11.9	.014
Sagittal Hindfoot ROM (°)	22.6 ± 4.7	18.9 ± 3.9	.012

Notes: DF = Dorsiflexion, PF = Plantarflexion, ROM = Range of Motion, GC = Gait Cycle

Coupling distribution patterns were assessed between groups during early, mid and late stance phase. The most prominent changes were seen during early stance. Sagittal-coronal intra-hindfoot coordination patterns revealed less *sagittal-phase* coupling (19 vs. 41% of early stance, $\chi^2 = 73.1, p = < .001$) and more *in-phase* coupling (39 vs. 18%, $\chi^2 = 67.7, p = < .001$) in the Clubfoot Group compared to the Control Group (Figure 14). In addition, the Clubfoot Group demonstrated less *sagittal-phase* coupling (22 vs. 46%, $\chi^2 = 82.8, p < .001$) and increased *transverse-phase* coupling (48 vs. 22%, $\chi^2 = 89.4, p = < .001$) in intra-forefoot, sagittal to transverse coordination during early stance. Examining hindfoot and forefoot coronal plane coordination, the Clubfoot Group demonstrated less *hindfoot-phase* coupling compared to the Control Group (12 vs. 33%, $\chi^2 = 79.9, p = < .001$). Hindfoot coronal to forefoot transverse coordination analysis revealed less *hindfoot-phase* coupling in the Clubfoot Group (47 vs. 67%, $\chi^2 = 48.5, p = < .001$).

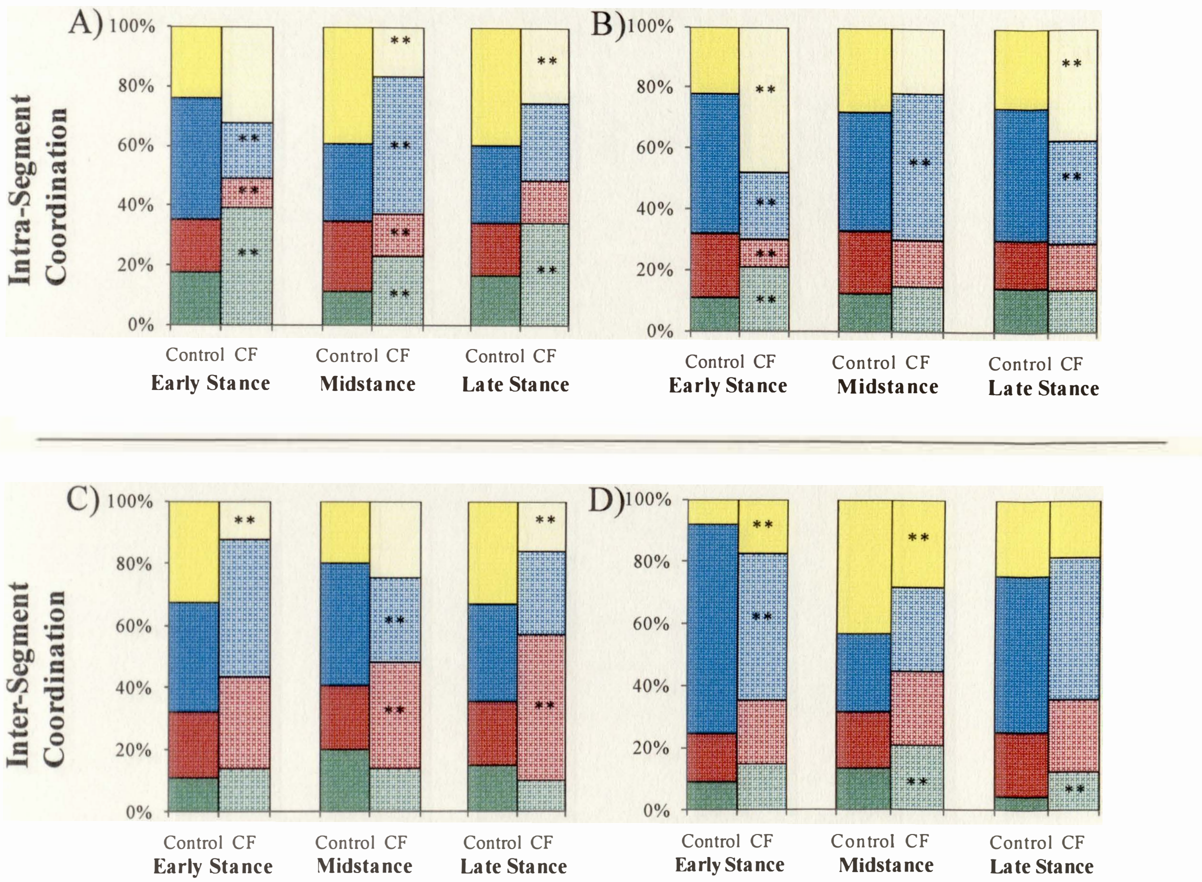


Figure 14: Coupling categorization results for overground walking. A) Coupling patterns between sagittal and coronal hindfoot motion. B) Coupling patterns between sagittal and transverse forefoot motion. C) Inter-segmental coupling between the hindfoot and forefoot in the coronal plane. D) Inter-segmental coupling between coronal hindfoot and transverse forefoot motion. ** Indicates statistically significant difference between Control and Clubfoot (CF) Groups. Green: *in-phase,* Red: *anti-phase,* Blue: *abscissa-phase* and Yellow: *ordinate-phase.*

There was also a significant redistribution of coupling patterns in the Clubfoot Group for intra-hindfoot sagittal to coronal coordination during midstance and late stance when compared to the Control Group. In midstance, an increase in *anti-phase* coupling for inter-segment coronal plane coordination was seen in the Clubfoot Group (34 vs. 21%, $\chi^2 = 28.2$, $p = < .001$), with an associated decrease in *hindfoot-phase* coupling (27 vs. 39%, $\chi^2 = 20.5$, $p = < .001$). During late stance, the Clubfoot Group continued to show an increase in *anti-phase* coupling for inter-segment coronal plane coordination (47 vs. 21%, $\chi^2 = 95.6$, $p = < .001$), with a decrease in *forefoot-phase* coupling (16% vs. 33%, $\chi^2 = 52.1$, $p = < .001$).

Hopping Kinematics and Coupling

Similar to the walking condition, there were few statistically significant kinematic or kinetic differences between subject groups during single limb hopping. Specifically, there were no significant differences in ankle kinematics between the Clubfoot and Control Groups using the Conventional Gait Model. The Clubfoot Group did show significantly decreased eccentric power absorption ($p = .046$) and concentric power generation ($p = .007$) during hopping (Figure 15). Overall, the Clubfoot Group also exhibited a lower excursion of the center of mass (56.3 vs. 71.9 mm, $p = .019$) than the Control Group (Table 9). Using the TSRHC-FAM, reductions in the sagittal plane forefoot range of motion ($p = .015$) and specifically, forefoot plantarflexion ($p = .041$) were seen in the Clubfoot Group compared to the Control Group. Peak forefoot dorsiflexion was delayed, occurring approximately 10% later in the hopping cycle in the Clubfoot Group ($p = .003$).

During the concentric PROP phase, the Clubfoot Group demonstrated less *in-phase* coupling for inter-segment sagittal plane coordination (52 vs. 87%, $\chi^2 = 208.3$, $p < .001$), and more dominant hindfoot plantarflexion (*hindfoot-phase* coupling, 41 vs. 10%, $\chi^2 = 186.9$, $p < .001$) due to the reduced plantarflexion seen at the forefoot. Changes in sagittal forefoot plantarflexion also resulted in significant differences in the coupling for intra-forefoot sagittal to coronal motion, and intra-forefoot sagittal to transverse motion (Figure 16).

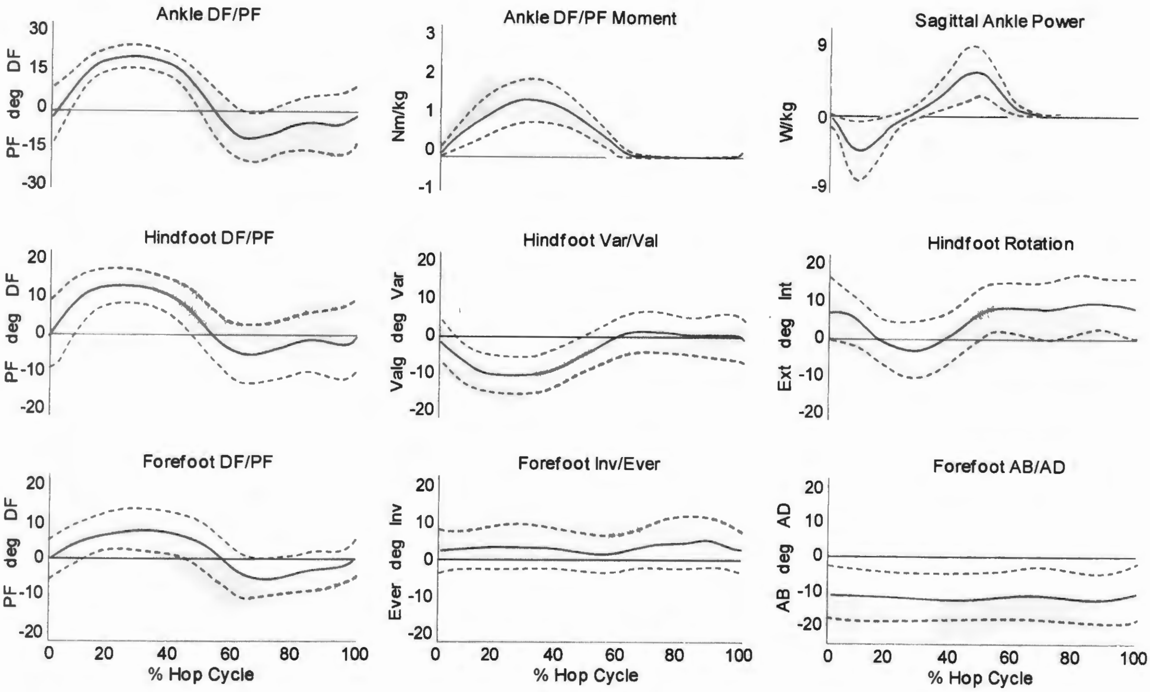


Figure 15: Kinematic time-series data for single limb hopping. Solid gray band – ensemble average ± 1 standard deviation for Control Group. Solid line – ensemble average for Clubfoot Group, dashed lines - ± 1 standard deviation for Clubfoot Group. DF/PF = Dorsiflexion/ Plantarflexion, Var/Val = Varus/Valgus, Inv/Ever = Inversion/Eversion, AB/AD = Abduction/ Adduction.

Table 9

Kinematic and Kinetic Outcomes During Single Limb Hopping

Variable	Control Group M ± SD	Clubfoot Group M ± SD	p-value
Lower Extremity Kinematics/Kinetics			
Maximum Ankle Power Absorption (W/kg)	-6.6 ± 3.1	-4.5 ± 3.3	.046
Maximum Ankle Power Generation (W/kg)	7.7 ± 2.4	5.2 ± 2.8	.007
COM Excursion –Flight Phase (mm)	71.9 ± 21.2	56.3 ± 18.4	.019
Multi-Segment Foot Kinematics			
Maximum Forefoot PF (°)	-11 ± 4.5	-7.2 ± 6	.041
Timing Maximum Forefoot DF (% HC)	26.5 ± 6.7	35 ± 9.2	.003
Sagittal Forefoot ROM (°)	20 ± 6.3	14.4 ± 6.9	.015
Timing Maximum Forefoot ABD (°)	41.5 ± 22	60.8 ± 19.5	.006

Notes: COM = Center of Mass, DF = Dorsiflexion, PF = Plantarflexion, ROM = Range of Motion, ABD = Abduction, HC = Hop Cycle

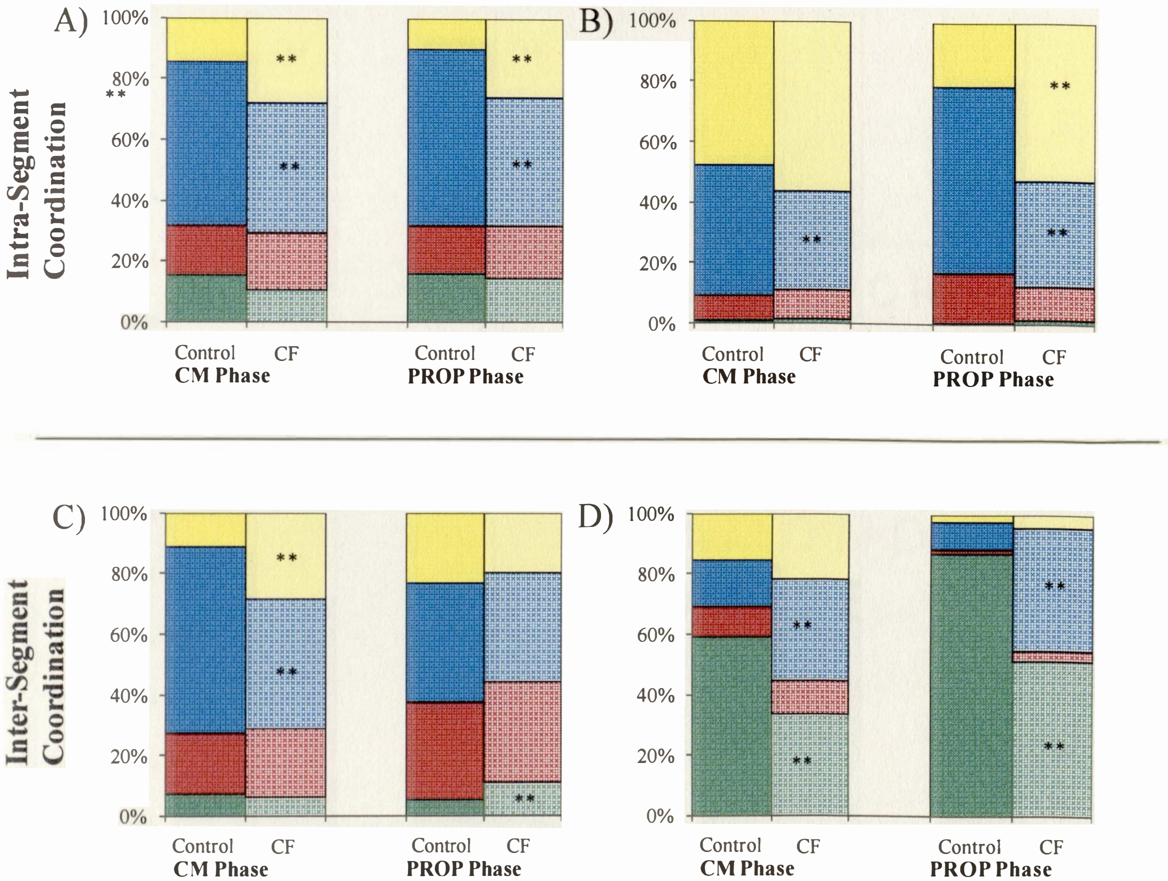


Figure 16: Coupling categorization results for single limb hopping. A) Coupling patterns between sagittal and coronal forefoot motion. B) Coupling patterns between sagittal and transverse forefoot motion. C) Inter-segmental coupling between the hindfoot and forefoot in the coronal plane. D) Inter-segmental coupling seen between the hindfoot and forefoot in the sagittal plane. ** Indicates statistically significant difference between Control and Clubfoot (CF) Groups. Green: *in-phase,* Red: *anti-phase,* Blue: *abscissa-phase* and Yellow: *ordinate-phase.*

During the CM phase of the hop, inter-segmental sagittal plane coordination revealed decreased *in-phase* coupling (34 vs. 59%, $\chi^2 = 100.3$, $p < .001$) and increased *hindfoot-phase* coupling (33 vs. 16%, $\chi^2 = 61.6$, $p < .001$) due to the decreased sagittal forefoot range of motion in the Clubfoot Group. In the coronal plane, however, the Clubfoot Group demonstrated increased *forefoot-phase* coupling (25 vs. 11%, $\chi^2 = 65.2$, $p < .001$), and a trend for decreased *hindfoot-phase* coupling (43 vs. 61%, $\chi^2 = 51.9$, $p < .001$).

Toe Raise Kinematics and Coupling

During the toe raise test, the Clubfoot Group demonstrated decreases in sagittal plane ankle range of motion (p = .018) and maximum ankle plantarflexion (p = .025, Table 10). During the UP (concentric) phase, the Clubfoot Group had decreased ankle power generation (p = .013, Figure 17), however there was no difference in the eccentric ankle power absorption during the DOWN phase. Maximal heel excursion was significantly lower in the Clubfoot Group (p = .003). Heel excursion and peak ankle power generation were more highly correlated in the Clubfoot Group (r = .69) than the Control Group (r = .34, Figure 18). The Clubfoot Group also demonstrated significantly increased maximum forefoot plantarflexion (p = .002) and overall sagittal plane forefoot range of motion (p = .002).

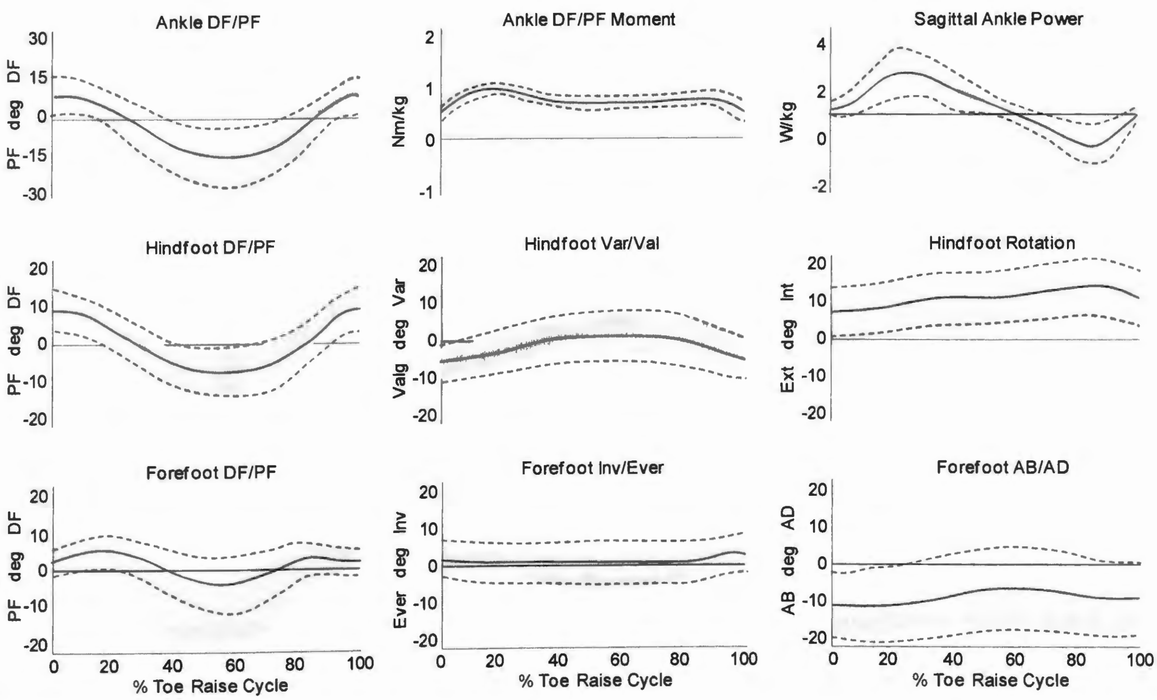


Figure 17: Kinematic time-series data for single limb toe raises. Solid gray band – ensemble average ± 1 standard deviation for Control Group. Solid line – ensemble average for Clubfoot Group, dashed lines - ± 1 standard deviation for Clubfoot Group.

Table 10

Kinematic and Kinetic Outcomes During Single Limb Toe Raises

Variable	Control Group M ± SD	Clubfoot Group M ± SD	p-value
Lower Extremity Kinematics/Kinetics			
Maximum Ankle PF (°)	-24.3 ± 11	-15.9 ± 10.5	.025
Ankle ROM (°)	37.1 ± 10.7	27.6 ± 11.7	.018
Maximum Ankle Moment (Nm/kg)	1.11 ± 0.13	0.99 ± 0.12	.011
Time Maximum Ankle Moment (%TRC)	19.1 ± 14.6	36.1 ± 20.4	.009
Maximum Ankle Power Generation (W/kg)	2.1 ± 0.5	1.5 ± 0.8	.013
Total Heel Excursion (mm)	72.5 ± 14.1	56.4 ± 15.9	.003
Multi-Segment Foot Kinematics			
Timing Maximum Hindfoot Valgus (%TRC)	22.1 ± 25.8	44.9 ± 31.6	.026
Coronal Hindfoot ROM (°)	10.2 ± 3.1	7.9 ± 3.2	.037
Maximum Forefoot PF (°)	-13.4 ± 8.4	-5.2 ± 6.3	.002
Sagittal Forefoot ROM (°)	18.4 ± 7.9	11.3 ± 5	.002

Notes: PF = Plantarflexion, ROM = Range of Motion, COM = Center of Mass, TRC = Toe Raise Cycle

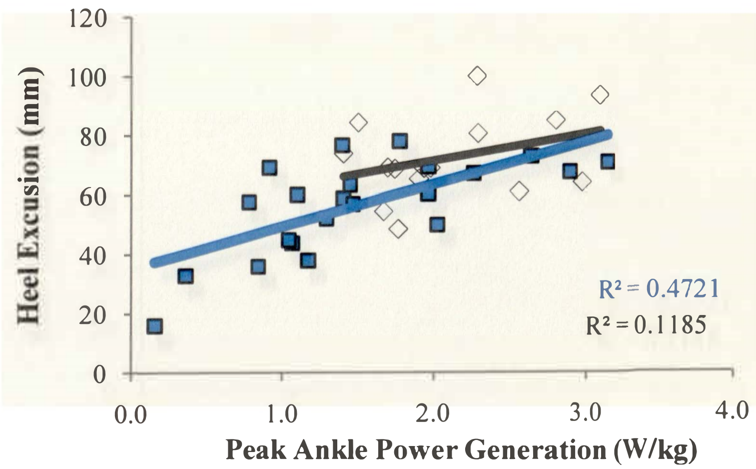


Figure 18: Correlation of heel excursion and maximum ankle power generation during a toe raise test. Blue squares represent children with clubfoot; black diamonds represent children without clubfoot.

During the UP phase, the Clubfoot Group demonstrated less *in-phase* coupling for inter-segment sagittal plane coordination, (41 vs. 65%, $\chi^2 = 82.1$, $p = < .001$, Figure 19). Within the forefoot, the Clubfoot Group demonstrated less forefoot *sagittal-phase* coupling (30 vs.50%, $\chi^2 = 61.7$, $p = < .001$) and more *transverse-phase* coupling (53 vs. 23%, $\chi^2 = 137.5$, $p = < .001$). Inter-segment coordination between hindfoot varus/valgus and forefoot add/abduction also demonstrated this shift towards increased forefoot *transverse-phase* coupling in the Clubfoot Group (44 vs. 27%, $\chi^2 = 46.5$, $p = < .001$).

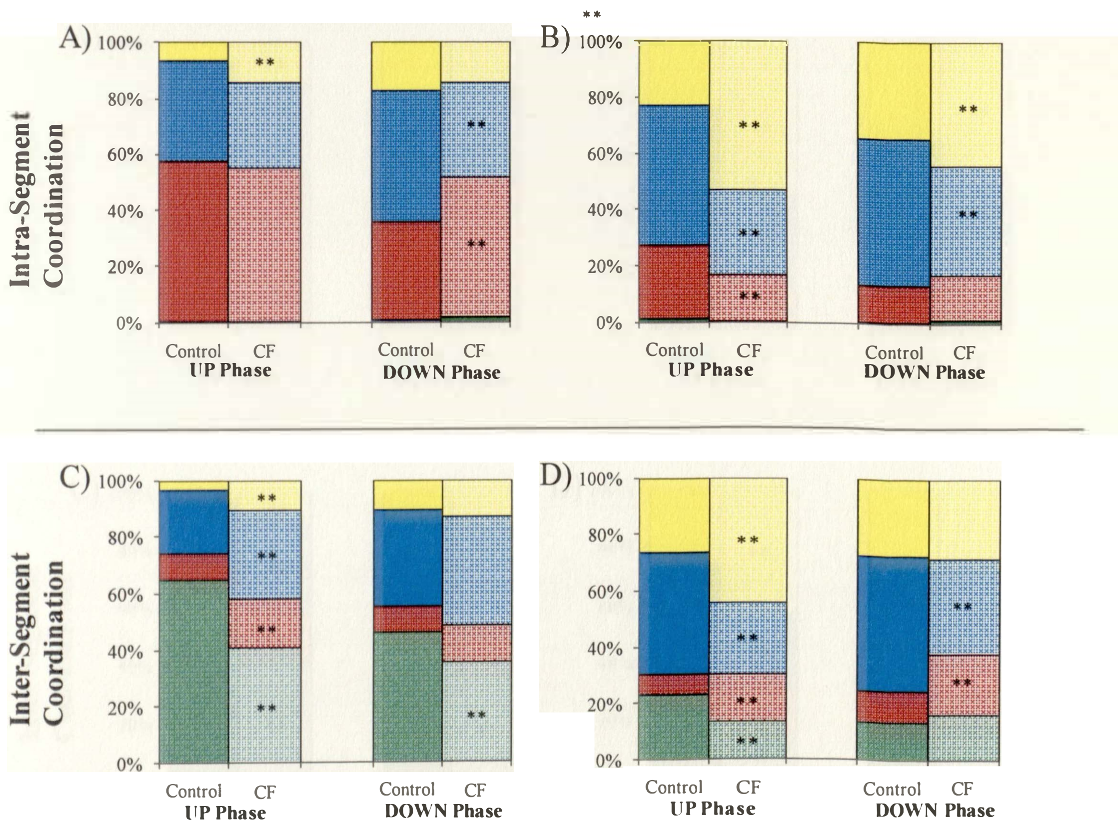


Figure 19: Coupling categorization results for single limb toe raises. A) Coupling patterns between sagittal and coronal hindfoot motion. B) Coupling patterns between sagittal and transverse forefoot motion. C) Inter-segmental coupling between sagittal hindfoot and forefoot motion. D) Inter-segmental coupling between coronal hindfoot and transverse forefoot motion. ** Indicates statistically significant difference between Control and Clubfoot (CF) Groups. Green: *in-phase,* Red: *anti-phase,* Blue: *abscissa-phase* and Yellow: *ordinate-phase.*

There were fewer significant differences between the Clubfoot Group and the Control Group during the DOWN phase. Intra-segment sagittal to coronal hindfoot coordination revealed less *hindfoot-phase* (34 vs. 47%, $\chi^2 = 425.4, p = < .001$) and more *anti-phase* (50 vs. 35%, $\chi^2 = 32.3, p = < .001$) coupling in the Clubfoot Group. Within the forefoot, there was less *sagittal-phase* coupling (39 vs. 52%, $\chi^2 = 25.9, p = < .001$) and increased *transverse-phase* coupling (44 vs. 35%, $\chi^2 = 14.0, p = < .001$) in the Clubfoot Group. Across segments in the sagittal phase, the Clubfoot Group demonstrated less in-phase coupling (36 vs. 46%, $\chi^2 = 17.2, p = < .001$) during the DOWN phase.

Discussion

The purpose of this exploratory study was to assess ankle kinematics and kinetics, multi-segment foot kinematics and joint coupling in children with and without clubfoot. Previous studies have demonstrated decreased ankle strength; therefore hopping and toe raise tests were chosen to challenge the gastrocnemius in an attempt to identify differences in foot mechanics not seen during overground walking. Significant differences were seen between the children with clubfoot and the children without clubfoot using the TSRHC multi-segment foot model which expanded upon those results seen with the Conventional Gait Model. Significant differences in joint coupling were also seen, with decreased *in-phase/anti-phase* coupling during toe raise and hopping tests in children with clubfoot.

The Conventional Gait Model quantifies ankle motion using a single-rigid body model, therefore the use of a multi-segment model allowed for more advanced identification of changes in kinematics by assessing motion of the hindfoot and forefoot independently. Multi-segment foot kinematics revealed that the significant reductions in ankle range of motion seen in the children with clubfoot using the Conventional Gait Model during walking were most likely due to decreases in hindfoot motion, with reduced peak hindfoot plantarflexion, delayed peak hindfoot dorsiflexion and overall decreased hindfoot sagittal range of motion. Theologis et al. (2003) found similar results with decreased hindfoot dorsiflexion in their study examining outcomes in children with clubfoot. The Oxford Foot Model used in their study includes a midfoot segment, and as such, they found significant increases in midfoot dorsiflexion in the children with clubfoot. Graf et al, (2010) used a foot model similar to the TSRHC model, and found increased hindfoot plantarflexion, increased forefoot dorsiflexion and increased forefoot adduction during walking in a group of adults with clubfoot, all of which had been treated surgically.

Previous work by Karol et al. (1997, 2005) has suggested that surgical treatment leaves the foot stiff and weak, and nonoperative treatment may be associated with improved outcomes in patients with clubfoot. In the current study, children with clubfoot demonstrated fewer significant differences from their peers without clubfoot compared to results previously reported by Theologis et al. (2003) and Graf et al. (2010), both studies in which all subjects underwent extensive surgical releases. Only 8 of 23 feet (35%) in the current study underwent surgical treatment beyond a percutaneous tendo-Achilles lengthening, which is part of both the Ponseti casting and physical therapy treatments offered at TSRHC. This suggests that children with clubfoot in the current study may be more heterogeneous. Those children treated successfully with nonoperative methods may have fewer biomechanical deficits than those feet with failed nonoperative treated and required further surgery. For example, residual forefoot adduction is often seen in patients with clubfoot and was seen in young adults with clubfoot by Graf et al., (2010) using the multi-segment Milwaukee Foot Model. Although there was a trend for increased adduction during walking in children with clubfoot in the current study, there were no significant differences between subjects with and without clubfoot. With a larger sample size, a comparison of children who received only nonoperative treatment for clubfoot to those children who required comprehensive surgical release may reveal more significant findings and identify those with significant residual deformity.

In addition to overground walking, the testing protocol in the current study included the assessment of the foot biomechanics during single limb hopping and single limb toe raises. These tests are often used to assess gross motor function in children as part of more comprehensive physical therapy evaluations. Play is an important element of socialization in children, and the ability to keep up with their peers is an integral component of their interactions with others. Hopping, jumping, and overall agility are used in many areas of play, from hopscotch and dodgeball to basketball and volleyball. Ankle plantarflexion strength and foot and ankle range of motion may be necessary to successfully execute hopping and toe raise tasks. The unilateral performance of these tests in the current study was aimed to isolate the affected limb in children with clubfoot in order to elicit deviations in foot kinematics not identified during overground walking.

During walking, foot and ankle motion has previously been described as occurring about three rockers: heel rocker, as the foot lands with heel contact and the forefoot lowers to the ground through plantarflexion at the talocrural joint; ankle rocker where the tibia (and proximal body segments) advances over the flat foot, primarily through talocrural joint dorsiflexion; and forefoot rocker where the heel comes off the ground and the body is propelled forward using a combination of ankle push-off power and hip pull-off power (Perry & Burnfield, 2010). Observationally, it was noted that children without clubfoot tend to use a forefoot strategy to go up on the toes during the hopping tasks. As both the hopping and toe raises tests tend to isolate forefoot rocker type movement patterns, significant changes focused in the forefoot during these tasks compared to walking were expected. Significant reductions in sagittal plane forefoot range of motion were found during these activities, which were not seen during overground walking.

Changes in foot kinematics were not isolated to the sagittal plane. Coronal plane hindfoot range of motion was decreased in children with clubfoot, with delayed peak hindfoot varus during the toe raise test. Heel excursion, or the height of the heel during the toe raise test, and center of mass excursion during the flight phase of hopping, were also limited in children with clubfoot; therefore their ability to perform these tests was reduced. Decreases in ankle strength have been previously identified in long-term outcomes of patients with clubfoot (Karol et al., 1997 and Graf et al., 2010). Maximal ankle power generation was greatest during hopping and lowest during the toe raise test in children with and without clubfoot. A direct comparison of test variables between the three tasks was not conducted; however, qualitative examination showed the toe raise task had the lowest speed of movement which could result in lower power generation. Future work aimed at comparing these activities should evaluate the work done (area under the power curve) by the ankle as this may provide a more useful comparison of the demand on the posterior calf musculature during these tasks. During the toe raise test there was a higher correlation between peak ankle power generation and heel excursion in the children with clubfoot compared to their peers without clubfoot. This may be indicative of the role that ankle weakness has in this patient population, as the range of peak ankle power seen in the children without clubfoot was smaller than that seen in the children with clubfoot. In addition, without formal strength testing, it is not possible to determine if the reduced forefoot range of motion during these tasks are due to anatomical restraints (static or dynamic) or simply a lack of strength to 'get up higher' on the metatarsal heads.

Differences in inter- and intra-joint foot coupling patterns were seen between children with and without clubfoot for all three activities. During walking the largest differences in coupling patterns were seen during early stance, prior to foot flat and prior to the forefoot rocker. In the children without clubfoot, hindfoot motion primarily consisted of plantarflexion and slight hindfoot valgus in early stance while the forefoot slightly dorsiflexes and remains neutral in the coronal and transverse planes. This results in more *sagittal-phase* coupling across planes within both the hindfoot and forefoot. In children with clubfoot, there was more *in-phase* coupling between the sagittal and coronal planes within the hindfoot during walking. This may be due to decreased hindfoot motion or variations in subtalar and/or other joint axes of rotations.

The orientation of many of the axes of rotation within the foot is oblique, and results in coupled motion patterns across planes within a joint (intra-segment, inter-planar motion). Imaging studies have shown abnormal radiographic findings in adults following extensive surgical release for clubfoot and noted arthritic joints within the foot in patients who had undergone multiple surgeries (Dobbs, Nunley, & Schoenecker, 2006; Roche et al., 2006). Changes in the bony anatomy and joint articulations in patients with clubfoot may lead to alterations in the overall alignment of the oblique axes of rotations, and therefore have a significant effect on coupled motion (Ledoux et al., 2006). During walking trials in the current study, joint coupling metrics were able to identify significant differences in forefoot motion between children with and without clubfoot that were not seen using kinematic time-series variables. Children with clubfoot demonstrated a shift towards *transverse-phase* coordination of the forefoot during early stance. The anterior tibialis fires during early stance to decelerate the lowering of the forefoot towards the ground. If the line of pull of the anterior tibialis muscle is altered due to changes in foot alignment or variations in axes of rotation, the forefoot may invert as well as dorsiflex, causing in an increase in forefoot transverse plane motion, and a shift towards *transverse-phase* coupling patterns. These findings support the use of coupling analysis to identify gait deviations not seen using the discrete time-series variables in the assessment of children and adults with foot pathology, particularly when gait differences are minimal.

During the toe raise and hopping tasks there was a reduction in the sagittal plane *in-phase* coupling between the hindfoot and forefoot during the power generation phases (UP for toe raises and PROP for hopping), most likely due to the reduction in forefoot range of motion and/or gastrocnemius muscle weakness. In addition, changes in the coupling patterns across planes within the forefoot segment were seen in the children with clubfoot during these activities. Compensations for decreased ankle strength and decreased range of motion in the forefoot may lead to changes in the mechanics and strategies used to perform these tests, particularly once fatigue begins. In this study, only the first three hops or toe raises were assessed to eliminate the influence of fatigue; however, decreased ankle power generation even in the early repetitions suggest significant weakness of the posterior calf muscles. Formal evaluation of muscle strength, however, is needed in future work.

The results of this report form the basis for a larger scale study of outcomes in children with clubfoot. Heterogeneity in the subjects with clubfoot was most likely due to initial treatment (nonoperative versus surgical) and current severity of residual deformity. Changes in coupling patterns found in this study suggest that differences in bony anatomy and residual deformity may greatly impact one's ability to perform tests such as toe raises or hopping. Expanding upon that proposed by Graf et al. (2012), a comprehensive protocol to evaluate foot function in children or adults with clubfoot should include biomechanical assessment of more challenging tasks to gain a better understanding of the mechanics of the intrinsic foot joints. In addition, it is recommended that radiographic measures or advanced imaging should be correlated with coupling mechanics within the foot, as well as examined to quantify severity of residual deformity. Another method to assess residual deformity is the use of dynamic plantar pressures to determine residual adductus, and categorically define foot contact patterns (heel contact, forefoot contact) and arch type. Ankle strength, measured using manual muscle test or isokinetic dynamometry, should be correlated to peak ankle power generation during tasks which challenge the posterior musculature. Further investigation into variations in coupling mechanics during concentric and eccentric muscle activity is warranted, as differences in statistical findings were seen between the UP/PROP and DOWN/CM phases of the toe raises and hopping, respectively.

Limitations of the current study include, but are not limited to, potential measurement errors and effects of fatigue. Markers were placed on the surface of the skin to represent the bony anatomy underneath. While it is acknowledged that skin motion artifact may exist, the only method to eliminate it is through the use of bone pins, which are not feasible in this population of children. Furthermore, it is assumed that each segment is a rigid body and intra-segment marker motion is negligible. Fatigue most certainly played a role in the overall performance of the hopping activity as subjects were asked to hop as long, as high and as fast as possible. For this initial study, assessment was limited to the first few hopping and toe raise cycles to eliminate potentially confounding variability due to fatigue.

Statistical testing using Student's t-test was conducted with alpha set to .05. As this is an exploratory study to evaluate the application of coupling analysis and utility of the additional tasks of hopping and toe raises in the biomechanical evaluation of patients with clubfoot, Bonferroni correction/adjustment was not used. While multiple comparisons were conducted in this analysis, correlations or dependences exist at some level for some of the variables evaluated.

Furthermore, while reduction of alpha based on the number of comparisons made will reduce the number of false positives (Type I error), Bonferroni correction tends to be extremely conservative. This may cause a substantial increase in false negatives (Type II error) and ultimately reduce the power of the study. As further work is conducted however, with more defined subject treatment/groups, adjustment to limit Type I error will be necessary.

In conclusion, children with clubfoot demonstrated a significant reduction of hindfoot range of motion during walking, and forefoot range of motion during toe raises and hopping. Children with clubfoot also exhibited decreased ankle power generation during all three activities compared to children without clubfoot. Reductions in *in-phase* coupling during hopping and toe raise activities were seen with reduced center of mass excursion and reduced heel height, respectively. Outcomes in clubfoot can vary greatly; however, the combination of multi-segment foot kinematics, inter-joint and intra-segment foot coupling, and challenging, age appropriate, protocols which include tasks other than overground walking, can provide a means to define foot function and mobility in both children and adults.

CHAPTER V

CONCLUSIONS

Study Purpose

The purpose of this study was to demonstrate the use of vector coding in assessing motion in the pediatric foot, and to compare the multi-segment foot biomechanics during (a) overground walking, (b) single limb hopping and (c) single limb toe raises between a group of children previously treated for congenital clubfoot and age-matched children without clubfoot.

Null Hypotheses

$H_0 1$: *There will be no differences in multi-segment foot kinematics and coordination during overground walking at a self-selected speed in children previously treated for clubfoot when compared to age-matched children without clubfoot.* Children with clubfoot had significantly decreased ankle kinematics, and demonstrated decreased hindfoot plantarflexion (p = .014), delayed peak hindfoot dorsiflexion (p = .014) and decreased overall sagittal hindfoot range of motion (p = .012) compared to children without clubfoot. Coupling mechanics were most affected during early stance, with decreased *sagittal-phase* dominant patterns (χ^2 = 73.1, p = < .001) and increased *in-phase* coordination (χ^2 = 67.7, p = < .001) for intra-hindfoot sagittal-coronal plane coupling.

$H_0 2$: *There will be no differences in multi-segment foot kinematics and coordination during single limb hopping in children previously treated for clubfoot when compared to age-matched children without clubfoot.* Children with clubfoot demonstrated decreased sagittal forefoot range of motion (p = .015), peak forefoot plantarflexion (p = .041), delayed peak forefoot abduction (p = .006) and delayed peak forefoot dorsiflexion (p = .003). During the propulsive phase of the hop, children with clubfoot demonstrated decreased *in-phase* coupling (χ^2 = 208.3, p = < .001) between the hindfoot and forefoot in the sagittal plane, with increased *hindfoot-phase* coordination (χ^2 = 186.9, p = < .001).

$H_0$3: *There will be no differences in multi-segment foot kinematics and coordination during single limb toe raises in children previously treated for clubfoot when compared to age-matched children without clubfoot.* Children with clubfoot demonstrated decreased maximum forefoot plantarflexion (p = .002), decreased sagittal forefoot range of motion (p = .002) and a trend for decreased coronal plane hindfoot range of motion (p = .027). Children with clubfoot had less *in-phase* coupling between the hindfoot and forefoot in the sagittal plane (χ^2 = 82.1, p = < .001), during the concentric UP phase, however there were no differences in coupling patterns during the eccentric DOWN phase. Intra-forefoot segment coupling patterns between the sagittal and transverse plane were predominantly more *transverse-phase* (χ^2 = 137.5, p = < .001) in the children with clubfoot compared to those children without clubfoot. These changes in foot mechanics led to a significant reduction in heel excursion (p = .003) in the children with clubfoot.

Conclusion

Evaluation in children 10 years following treatment for clubfoot revealed significant differences in foot mechanics when compared to age-matched children without clubfoot. During walking children with clubfoot had reduced hindfoot range of motion and hindfoot plantarflexion The addition of toe raises and hopping tests revealed limitations in forefoot motion not seen during overground walking. In this study, children with clubfoot demonstrated decreased ankle power generation during all three activities compared to children without clubfoot, supporting findings of decreased ankle plantarflexion strength in previous long-term outcomes studies. Reductions in *in-phase* coupling during hopping and toe raise activities were also seen leading to reduced center of mass excursion and reduced heel height, respectively. The assessment of coupling patterns during these activities was able to identify changes in foot mechanics that were not seen using discrete kinematic variables. The combination of multi-segment foot kinematics, categorization of foot coupling, and challenging tasks in addition to walking can provide clinicians with a comprehensive method to evaluate foot function in patients with pathology, and specifically, those with clubfoot.

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APPENDIX A

TWU Institutional Review Board Approval Letter

TWU
TEXAS WOMAN'S UNIVERSITY
DENTON DALLAS HOUSTON

Institutional Review Board
Office of Research and Sponsored Programs
P.O. Box 425619, Denton, TX 76204-5619
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email: IRB@twu.edu

September 16, 2011

Ms. Kirsten Tulchin
2229 Overlook Ln.
Denton, TX 76207

Dear Ms. Tulchin:

Re: Multi-segment Coordination Within the Foot in Children Previously Treated for Congenital Clubfoot and Children Without Clubfoot During Walking, Toe Raises and Single Limb Hopping (Protocol #: 16796)

The above referenced study has been reviewed by the TWU Institutional Review Board (IRB) and was determined to be exempt from further review.

If applicable, agency approval letters must be submitted to the IRB upon receipt PRIOR to any data collection at that agency. Because a signed consent form is not required for exempt studies, the filing of signatures of participants with the TWU IRB is not necessary.

Any modifications to this study must be submitted for review to the IRB using the Modification Request Form. Additionally, the IRB must be notified immediately of any unanticipated incidents. If you have any questions, please contact the TWU IRB.

Sincerely,

Rhonda R Buckley

Dr. Rhonda Buckley, Co-Chair
Institutional Review Board - Denton

cc. Dr. Charlotte Sanborn, Department of Kinesiology
Dr. Young-Hoo Kwon, Department of Kinesiology
Graduate School