THE UNIVERSITY OF CALGARY

Lower Extremity Biomechanics of Children with Clubfoot

by

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ABSTRACT

Clubfoot is a bony deformity characterized by inversion, adduction and equinus which often requires surgical intervention. Functional outcome assessments after surgery often measure passive range of motion at the ankle joint, but no studies to date have examined the biomechanics of the forefoot relative to the hindfoot in clubfoot children. This study used age- and gender- matched normal control subjects to determine the biomechanics of the normal foot using a motion analysis system and compared the results to unilateral and bilateral clubfoot subjects. We assessed outcome by using a motion analysis system to quantify the relative forefoot and hindfoot motion in addition to hip, knee and ankle kinematics and kinetics. We found that push-off was not only affected by the lack of plantarflexion and strength at the ankle, but may be adversely affected by the inadequate amount of plantarflexion and abduction of the forefoot relative to the hindfoot.

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To Mum and Dad who've spent hours on the phone
encouraging me to step back and look at the big picture.

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1 INTRODUCTION

Clubfoot is a bony deformity present at birth and characterized by inversion, adduction and equinus. In many cases, surgery must be performed to release the soft tissue contractures that have resulted as a cause of this bony abnormality. The comprehensive posteromedial release is most typically performed today as it is believed to achieve better correction of the deformity than multiple surgeries (Caroll 1997, DeRosa 1980, Magone 1989, McKay 1983, Porat 1984, Simons 1980, Yamamoto 1994). Although correction is often attained in one procedure, Laaveg and Ponseti (1980) argue that the motion of the foot and ankle may be reduced, thus the functional result is not significantly improved.

To quantify the success of the procedure, a series of outcome measures have been introduced (Bensahel *et al.* 1995, Laaveg and Ponseti 1980). These included radiologic techniques, passive motion assessment and the examination of cadence parameters. Although the radiologic techniques helped define bony improvements, it was hard to assess whether functional normality was attained. Passive motion measurements indicated the range of motion, but did not necessarily relate to function of the foot. Passive motion measurements were also highly variable with both inter-observer and intra-observer errors.

The method of determining function as determined by Ponseti and Laaveg (1980) included a questionnaire answered by the patient, followed by an analysis of the range of motion and characteristic gait patterns. Although gait was awarded 20 points of 100, only the ability to heel walk, toe walk and walk without a limp were taken into account. Without a full gait analysis using a motion analysis system it was difficult to assess how a clubfoot subject compensated especially at the hip, knee and ankle. A more quantitative method of measuring outcomes is needed.

To date only one three-dimensional study has been performed analyzing the kinetics and kinematics at the hip, knee and ankle in clubfoot subjects (Karol *et al.* 1997). This study examined the kinematics and kinetics of unilateral clubfoot subjects but did not offer a comparison to normal age-matched controls. Asperheim *et al.* (1995) have also used three dimensional gait in determining a treatment plan for children with clubfoot and have attained satisfactory results in 87% of their cases.

Although the functional outcome assessments often measure passive range of motion at the ankle joint and of the forefoot relative to the hindfoot, no studies have examined the biomechanics of the forefoot relative to the hindfoot in clubfoot children. Admittedly, there have only been a limited number of studies of normal subjects measuring the three dimensional biomechanics of the forefoot and hindfoot. Lee *et al.* (1997) examined the adduction of the forefoot during walking, running and side shuffling. Scott and Winter (1993) examined the flexion and extension of the transverse tarsal joint using three subjects and a computer model. This study used age and gender matched normal control subjects to determine the biomechanics of the normal foot, then drew a comparison with the clubfoot subjects.

The relative motion between the forefoot and the hindfoot may contribute to the lack of push-off that clubfoot subjects exhibit (Hutchins *et al.* 1995, Karol *et al.* 1997). Karol *et al.* (1997) attributed the lack of push-off to lack of strength in the calf muscles and a lack of dorsiflexion at the ankle. There may be other factors contributing to this phenomenon. One of the other factors we chose to examine was the motion of the first metatarsophalangeal (MTP) joint. Bojsen Moller and Lamoreux (1979) and Hetherington *et al.* (1990) have indicated that to achieve sufficient propulsion, a minimum amount of dorsiflexion of the first MTP joint is required. Since the clubfoot child is born with a bony abnormality that increases the muscle contractures in the foot, there is a possibility that after surgery, full motion of the great toe is not attained.

Knowing how the clubfoot subject functions relative to a normal subject can aid in assessing the type of treatment (Asperheim *et al.* 1995). It is not only necessary to understand the kinematics and kinetics at the hip, knee and ankle, but since this deformity results in deviations of the foot musculature, it is important to examine how the forefoot, hindfoot and first MTP joint mechanics are affected.

Therefore, there were several purposes of this study:

(1) to characterize the kinematics, kinetics and muscle strength of unilateral and bilateral clubfoot subjects and compare them to normal subjects.

(2) to establish a set of normal curve data of the forefoot relative to the hindfoot which was then used to assess the differences in biomechanics of clubfoot subjects.

(3) to determine whether abnormal motion of the first phalange contributed to abnormal push-off in clubfoot subjects.

Chapter 2 describes the pathology and function of the foot and discusses the relevant literature. Chapter 3 describes gait and muscle strength assessments that examined the differences in kinematics, kinetics, and muscle strength and related those differences to a functional outcome questionnaire (Ponseti 1981). Chapter 4 discusses the biomechanics of the forefoot relative to the hindfoot for normal subjects as well as those with unilateral and bilateral clubfoot. Chapter 5 examines the lack of push-off in clubfoot subjects as related to a lack of ankle dorsiflexion and possible insufficient first MTP joint motion.

2 REVIEW OF LITERATURE

2.1 Anatomy of the Foot

2.1.1 Foot Function

The foot plays an important role in all aspects of daily living. There are three parts that are typically described in the foot (Figure 1.1). The hindfoot consists of the talus and the calcaneus, and it acts to convert the torque of the lower limb. The hindfoot motion influences the motion of the midfoot and the forefoot. This motion is dependent on the obliquity of the axes and is highly variable. The midfoot consists of the navicular and the cuboid bones. The midtarsal joint is the major articulation and is formed by the approximation of these two bones in combination with the talus and the calcaneus. Its purpose is to transmit the motion from the hindfoot to the forefoot and to promote stability (Donatelli 1990). Finally, the most distal part of the foot is the forefoot which consists of the cuneiforms, phalanges, and metatarsals. The purpose of the forefoot is to adapt to the terrain and is highly dependent on the function of the hindfoot.

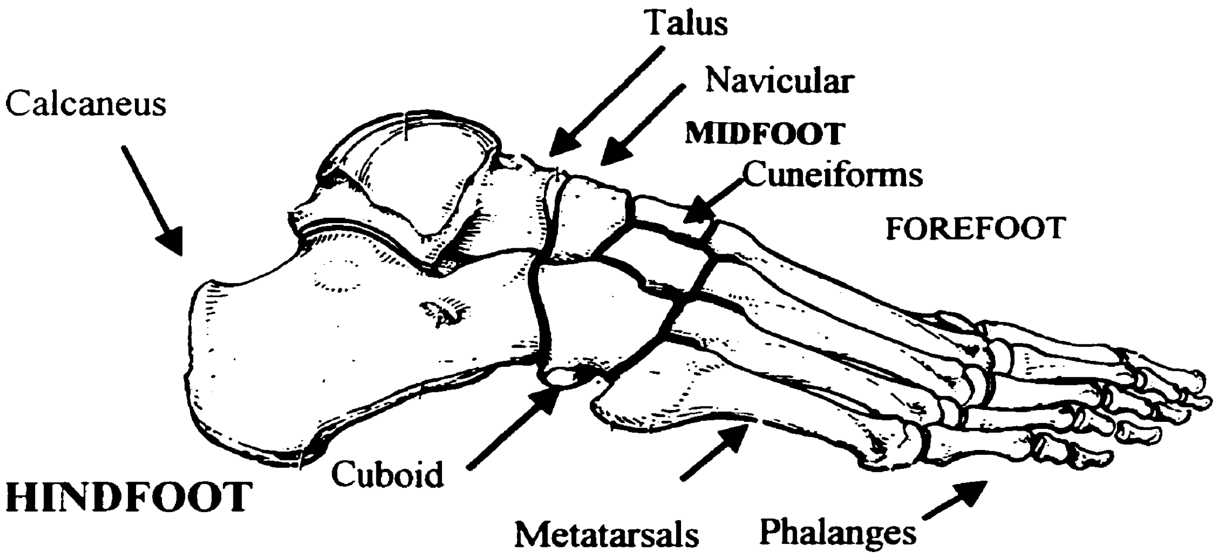


Figure 2.1 **Lateral view of the foot indicating the three different regions (adapted from Donatelli 1990).**

2.1.2 Transverse Tarsal Joint

The transverse tarsal joint is not an anatomical joint, but consists of the motion between the talonavicular and the calcaneocuboid joints. The part which defines the movement is the calcaneocuboid, and the navicular is carried across the calcaneus by its attachment to the cuboid (Lewis 1980). Hicks (1953) believed that the twisting of the forefoot upon this joint was due to the flexion of the first ray. The terms pronation and supination were coined for the twisting of the forefoot relative to the hindfoot about the calcaneocuboid joint. Manter (1941) described two axes of rotation (the oblique and the longitudinal) (Figure 2.2). The longitudinal axis represents the stationary motion of the cuboid on the calcaneus. The oblique axis defines the sliding motion of the cuboid along the calcaneus and acts at a direction 52 ° from the horizontal and 57 ° in the medial direction. Motion about these two axes define supination and pronation. Elftman (1960) also described this saddle joint and determined the resulting “spin” and “swing” about it.

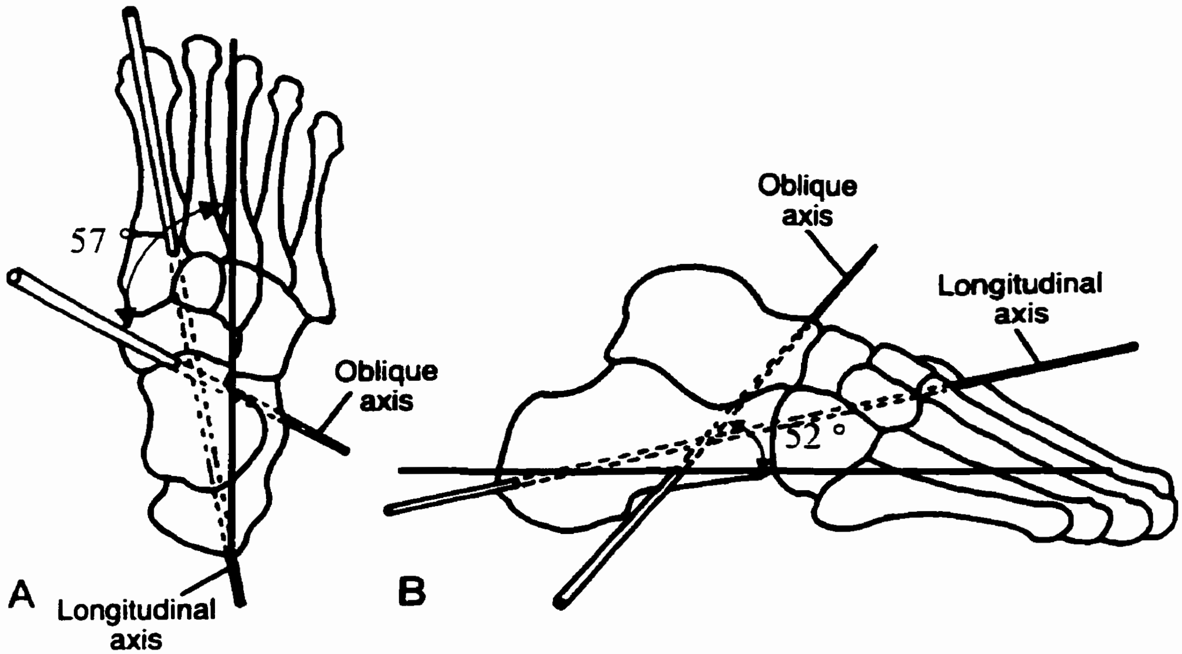


Figure 2.2 **The axes of the foot as defined by Manter (adapted from Seibel 1997).**

2.1.3 Triplanar motion of the foot

Triplanar motion has been used to report the relative movement of the lower extremities, but since the foot mechanical axes are not perpendicular to the cardinal planes, some motions may be uniaxial (Chan and Rudins 1994) when described in three planes. Motions within the sagittal plane of the foot are defined as dorsiflexion and plantarflexion (Figure 2.3.1), those within the transverse plane are abduction and adduction (Figure 2.3.2) and the motions defined within the frontal plane are eversion (Figure 2.3.3a) and inversion (Figure 2.3.3b). Supination is the combined effect of plantarflexion, adduction and inversion. Pronation is the effect of dorsiflexion, abduction and eversion.

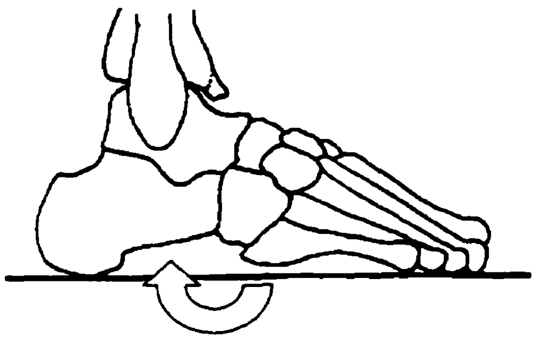


Figure 2.3.1 **Plantarflexion.**

Figure 2.3.2 **Adduction.**

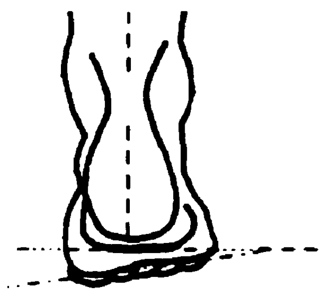


Figure 2.3.3a **Eversion.**

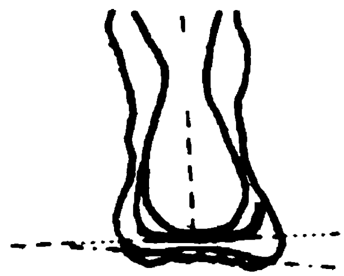


Figure 2.3.3b **Inversion.**

2.1.4 Pathologic Anatomy of the Clubfoot

In the clubfoot, the principal bone affected is the talus. The long body of the talus typically makes an angle of 150° with the neck, but in the clubfoot this angle can be as small as 115° (Turco 1981) (Figure 2.4). As a result, there is medial deviation of the head and neck. The calcaneus bony structure is maintained, but to articulate efficiently, it must rotate inward and downward beneath the talus (Figure 2.5). The soft tissue changes that occur in the clubfoot are a result of this misalignment.

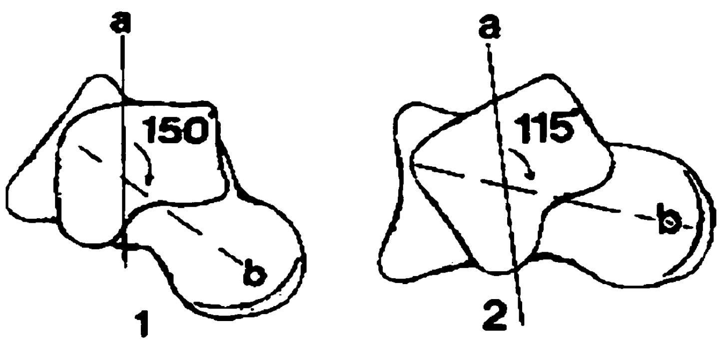


Figure 2.4 **The talus indicating the degree of deformity between the normal and the clubfoot. "a" represents the axis of the neck of the talus, "b" represents the long axis of the body. "1" is the talus of the normal foot and "2" is the talus of the clubfoot.**

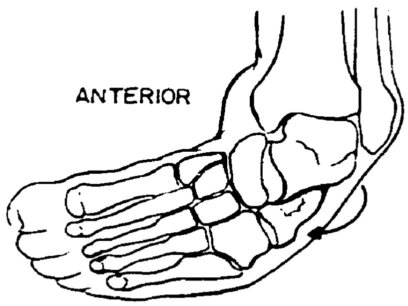


Figure 2.5 **The calcaneus must rotate beneath the talus in order to articulate efficiently.**

2.2 Clubfoot

2.2.1 Characterization of Clubfoot

Talipes equinovarus refers to a patient who has a foot which is both inverted and adducted. This is the most common type of clubfoot and occurs in approximately 1-2 in 1000 births (Lehman 1980). This type of clubfoot may also be accompanied with a cavus component. A cavus deformity indicates a forefoot plantarflexion. An equinus deformity refers to a foot which is fixed in a plantar-flexed position and includes the involvement of both the ankle joint in equinus and the inversion of the talocalcaneonavicular complex. Adduction refers to the condition in which the foot is rotated inward, and there is medial displacement at both the talonavicular and the anterior subtalar joint. A varus deformity has the tarsus rotated inwardly with respect to the lower leg. The medial border of the foot is seen to face upward.

2.2.2 Etiology

There are several schools of thought on the development of clubfoot, but the exact cause is indeterminate. In the past, extrinsic pressure on the embryo *in utero* was thought to be a cause. This belief has since been discarded as the development of clubfoot occurs while the embryo is still encased in amniotic fluid. As well, there does not appear to be an increase in the occurrence of clubfoot between twins, discounting this theory. Idelberger (1939) studied 174 pairs of twins and determined that although lack of space *in utero* is not the cause, there is some component of heredity as the likelihood of clubfoot in identical twins was 33%, whereas in fraternal twins, there was a 3% chance of both having clubfoot. This is only slightly higher than the incidence in the single birth population.

A neuromuscular effect may also be implicated. Isaacs *et al.* (1977) insist that a muscle imbalance occurs which results in clubfoot, thus there is a resistant form of arthrogryposis. Arthrogryposis is the presence of multiple joint contractures at birth. Fibrosis has also been known to limit the amount of stretch that the calf muscles can undergo (Ionescu *et al.* 1974). In the past, spina bifida and clubfoot were thought to be related, but more recently, clubfoot as a neurologic disorder has typically been ruled out. A misshapen foot due to a neurologic disorder, should be more flexible and able to show some improvement if only for a temporary period.

Arrested embryonal development has also been thought to be a contributor since the normal development of the foot occurs in an equinus position which is both adducted and in varus. It is not until the end of fetal development that the hindfoot grows, and as a result, the amount of forefoot varus is greatly reduced.

2.2.3 Incidence

The incidence of clubfoot tends to be greater in males than in females (2.5:1) (Kite 1964), and in about 50-55% of the cases the child has a bilateral condition (Turco 1981). There have been a variety of tests to determine if clubfoot is part of a family history, and these report results of 5-50% (Palmer 1964).

2.2.4 Treatment Methods

Within twenty-four hours of birth, the clubfoot patient is treated with manipulation or manipulative cast application to stretch the muscles. The contractures maintain the abnormal relation of the tarsal bones, and for correction to occur, these contractures must be stretched. Immediately before the cast is applied, manipulations are required to position the foot. A circumferential plaster cast is applied while the foot is held in position. A below knee cast is typically used. Care is taken to mould the cast and use a skin adhesive to keep the cast from being kicked off in the older infants.

If the foot improves with casting, the next step is to splint the foot, often twenty four hours per day (Figure 2.6) until the child is walking. Splinting has been successful in patients who have a long flexible deformity, but not for those who have rigid deformities. Thus there is typically a high failure rate (Lehman 1980).

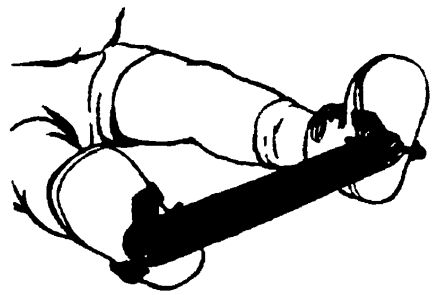


Figure 2.6 **Dennis Browne splint used to attempt to correct a nonrigid clubfoot (from Lehman, 1980).**

If the infant's foot does not respond to manipulation and casting, surgery is required. The most common treatment today for the resistant, rigid clubfoot is the posteromedial release (PMR). This involves the release of several muscle groups in order to ensure that the tarsal bones can be realigned (Yamamoto 1994). By performing a release of the plantar, medial and subtalar contractures at the same time, it is more likely that full correction will be achieved. After performing the release of all muscle groups, Kirschener wires are used to transfix the talonavicular and talocalcaneal joints, and the leg is placed in an above knee cast for stabilization.

The advantages are many for doing a PMR as opposed to doing several different stages of surgery. If all deformities are eliminated in one operation, complete correction is more likely to be achieved. In the past, a medial release was usually followed by a plantar release, but it is now understood that one deformity cannot be corrected without correcting the others. The PMR stabilizes both ends of the calcaneus and the navicular permitting restoration to a "normal" position.

The age at which to perform surgery has been a topic of much debate. Crawford *et al.* (1996) reported that if the operation was performed on an older child there was less likelihood of overcorrecting or undercorrecting the deformity and the axes of ossific nuclei were more easily identified. On the other hand, if correction was achieved early, the bones ossified more nearly normal.

In many cases, relapses have been known to occur until the child has reached approximately ten years of age. There is a greater likelihood of relapse if the initial correction is incomplete. There has also been discussion as to whether a relapse is actually a residual deformity.

2.3 Outcome Measures

It is difficult to determine success of treatment. There are a variety of different classification groups that have not been standardized, and operative procedures are rarely differentiated between. To quantify outcome, it is essential to determine standardized procedures for reporting results. In addition, further operative treatment is often seen as a future success, rather than a failure. There does not appear to be a consensus as to when failure actually occurs.

2.3.1 Rating Systems

The posteromedial release has been common since the 1980's (Lau *et al.* 1989), yet success of treatment is difficult to determine. In the past, different rating systems have been established to define success. There is a general trend that is followed when assessing the outcome measures of the patient. These include radiographic measures, clinical features, and the patient's own assessment.

More recently, Laaveg and Ponseti (1981) developed their own functional rating system which did not include radiographs but instead used the patient's personal rating and effectiveness of treatment based on satisfaction, pain and function in daily activities. This rating system also involved the patient's passive motion of dorsiflexion/plantarflexion, inversion/eversion, and varus/valgus motion of the heel. To qualify their results, they also performed the radiologic tests and found that there was a correlation between the patient satisfaction and the talocalcaneal angles (Laaveg *et al.* 1981). This scoring system was used by Hutchins *et al.* (1995) who found that 81% of their patients were satisfied with results. They too found a correlation between functionality and bone deformity.

Lau *et al.* (1989) used a modified form of the Ponseti and Laaveg system and separated surgery into two types: minimal (which included lengthening of the tendo-Achilles tendon and posterior capsulotomy) and extensive (which included posteromedial release with or without bone surgery). Better results were obtained for the less rigid type of foot, but they noted that a universal method of determining success of treatment should be established, as there were many variations in the surgery itself.

Blakeslee *et al.* (1995) reported good functional assessment of the patients they tested based on a questionnaire that did not include as many gait characteristics as that of Ponseti and used a much more limited interpretation of dorsiflexion; dorsiflexion was defined as less or greater than 90°. They determined that radiographic analysis was essential to assessing success and thus applied 25 points to radiographic analysis. Using these methods, they determined that a good functional assessment was achieved and that an inverse relationship existed between function and follow-up. They determined that a truly normal foot was never achieved.

2.3.2 Radiographic Techniques

Typically three radiographs are taken, one anteroposterior and two lateral radiographs. Of the lateral, one is taken in maximum plantarflexion and the other in maximum dorsiflexion. From these x-rays, several measurement are taken. The bimalleolar axis is determined. The shape and angles of the talus are defined. The amount of navicular displacement both medially and laterally is measured, the calcaneus is characterized and the cuneiform displacement relative to the navicular is quantified. The lengths of the first and fifth metatarsal bones are determined, as are the foot alignment of forefoot to hindfoot, talar to first metatarsus angle, and calcaneal to fifth metatarsus angle. The radiographs can aid in characterizing the success of the surgery, but "a fully functional corrected foot is not necessarily predicted radiographically" (Cohen-Sobel *et al.* 1993).

2.3.3 Clinical Measures

2.3.3.1 Passive Range of Motion

Range of motion is determined by orthopedic examination. Range of motion has been determined to be much smaller in patients with clubfoot than normal patients. For the clubfoot, the range of dorsiflexion and plantarflexion was 20 - 30° lower in clubfoot subjects than in normals (Lau *et al.* 1989, Ponseti 1981).

2.3.3.2 Muscle Strength

Aronson and Puskarich (1990) used isokinetic testing to determine muscle strength differences between the clubfoot side and the contralateral, as well as the clubfoot compared to normal patients. They found that plantarflexor strength was 24% lower than the contralateral side, and the ankle motion was reduced by 42%. They also determined that a longer plantarflexion arc corresponded to stronger dorsiflexors. By observing surgical results, it was also determined that repeated heel-chord lengthenings weakened the plantarflexors, and that a foot with mild equinus with strong plantarflexors was more functional than a weaker plantigrade foot. Karol *et al.* (1997) determined that about 66% of the patients had a weak gastrocnemius, and several had weakness of the anterior tibialis and/or the quadriceps.

2.3.3.3 EMG

Using EMG on the medial gastrocnemius and the tibialis anterior, Otis and Bohne (1986) found that the duration of the medial gastrocnemius activity was 48% of the gait cycle for clubfoot subjects whereas for normal subjects it was 36%. Onset and cessation of the tibialis anterior were not found to be different between the two groups. Karol *et al.* (1997) determined that half the patients had an increased anterior tibialis activity during midstance and an abnormal burst of activity in the peroneus longus or peroneus brevis during the swing phase.

2.4 Gait Characteristics

When a physician assesses gait, an observation of the subject's ability to toe walk and heel walk is included and the gait pattern is classified into several categories: normal, abnormal toe-off, abnormal heel strike or presence of a limp. Cohen-Sobel *et al.* (1993) determined that very few patients actually achieve functional normality in gait. It is more valuable to examine the joint motion to assess gait abnormality. Some studies have looked at simple kinematics and kinetics, and others have looked at pressure paths and muscle strength to aid in identifying the important aspects of clubfoot function or lack thereof (Widhe and Berggren 1994, Sawatzky *et al.* 1994, Brand *et al.* 1981., Karol *et al.* 1997, Otis and Bohne 1986, Hutchins *et al.* 1995)

2.4.1 Previous Gait

Many rating systems include gait as one of the criteria for determining success of treatment. Lau *et al.* (1989) found that push-off was much weaker in only 23 of 153 feet included in their study. Alternatively, Hutchins *et al.* (1995) found that abnormalities in toe off were common, as the subject would supinate the forefoot during heel-walking. Otis and Bohne (1986) assessed stride length and duration of single and double support and concluded that there was no relation between clinical assessment, gait, and radiologic assessment.

Karol *et al.* (1997) were the first to perform a three-dimensional study of gait. Their study examined 23 patients with unilateral clubfoot. Although differences in kinematics were observed between a normal foot of a unilateral subject and a standard set of normals, they did not examine the other parameters (kinetics, muscle strength and EMG) with respect to a normal group.

2.4.2 Kinematic

Using foot switches, Otis and Bohne (1986) found that single limb support times were not different between normal and clubfoot patients, or between each foot of the unilateral clubfoot patients. Karol *et al.* (1997) determined that there was an increased plantarflexion response at the ankle on impact with a decreased dorsiflexion during stance. For those subjects that exhibited abnormal dorsiflexion of the ankle, the knee was hyperextended on the clubfoot side, and the contralateral exhibited greater flexion.

If intoeing is examined, Yngve (1984) determined that 48% of clubfoot patients had inturning greater than two standard deviations from normal. When these were regrouped as those with versus those without intoeing, the mean functional rating was less for those with varus in addition to intoeing than those with intoeing alone. Yamamoto *et al.* (1994) attempted to construct a model for foot progression angle based on radiographs both before and after surgery. They determined that after surgery, 67% of intoeing gait was changed to outtoeing gait.

2.4.3 Kinetics

Widhe and Berggren (1994) conducted 2D analyses of 42 patients but discussed only ground reaction forces and pressure rather than the motion in the coronal, sagittal, and frontal planes. Ground reaction forces were less for the clubfoot as compared to the contralateral. Sawatzky *et al.* (1994) also studied ground reaction forces and found that the ground reaction force of the normal foot of a unilateral patient was similar to that of the ground reaction forces of a normal population. The clubfoot had a large internal moment about the vertical axis of the ground reaction force, whereas the normal foot had a large external moment. During weightbearing, it was found that the normal foot had a 4-6° valgus, whereas the clubfoot only had a 1° valgus. With the anterior-posterior ground reaction force determination, a smaller net anterior force or propulsion was evident for the clubfoot and the unaffected limb as compared to normals. For unilateral subjects, the power at the ankle was less on the side with the clubfoot, and the work done was also much smaller (Karol *et al.* 1997).

2.4.4 Center of Pressure Paths

The pressure of the foot and its relative distribution has been examined and it was found that although clubfoot patients show more variability in their centre of pressure paths and slightly larger contact areas, the centre of pressure path was consistent with normal patients (Brand *et al.* 1981). Heelstrike was less posterior (Figure 1.7) on the clubfoot subjects due to the limited amount of dorsiflexion.

Widhe and Berggren (1994) and Otis and Bohne (1986) used an EMED system to determine pressure at three different sections of the foot and found that the pressure per unit area for the unilateral clubfoot as compared to the contralateral was smaller and more lateral. For the patients with bilateral clubfoot, there was no correlation between radiographic data and gait or foot pressure.

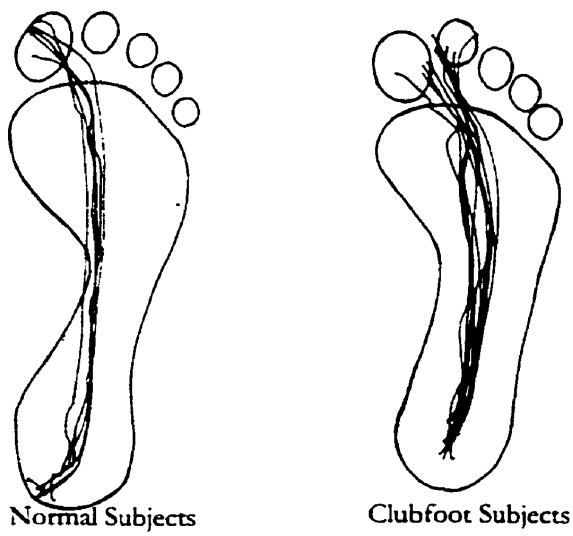


Figure 2.7 Centre of pressure paths of normal and clubfoot subjects (from Brand *et al.* 1981)

2.4.5 Patient Assessment

Satisfaction is typically based on a questionnaire. Determination of satisfaction includes ability to wear shoes of the same size, acceptance of cosmetic appearance of clubfoot, limitation of activities both daily and highly physically demanding, and the degree of pain caused by certain activity levels. Lau *et al.* (1989) determined that there was a correlation between cosmesis and function. It has also been found that females are three times less likely to be satisfied than their male counterparts (Hutchins *et al.* 1995).

2.5 Summary

Qualitative rating systems have been established retrospectively, but no comparison with gait characteristics and compensation measures has been established. Studies of other patient populations have shown that weak push off occurs when there is insufficient dorsiflexion of the first metatarsal. Clubfoot patients sometime have a smaller first metatarsus and weak tibialis anterior muscle which may contribute to weak push off. This study assessed the gait kinetics and kinematics of unilateral and bilateral clubfoot subjects and compared them to normal subjects. It also examined patient satisfaction using the Ponseti questionnaire and evaluated the muscle strength at the ankle and the knee. An understanding of clubfoot function relative to function of a normal foot may be used in assessing outcomes of further surgery.

3 KINEMATICS AND KINETICS OF THE HIP, KNEE, AND ANKLE OF CLUBFOOT CHILDREN FOLLOWING POSTEROMEDIAL RELEASE

3.1 Introduction

Although a relatively large percent (0.1%) of the population is born with clubfoot (Lehman 1980), little has been done to analyze the function of the foot several years after surgery once the child has started walking. Present outcome measures include questionnaires and radiographs. A few researchers have looked at foot pressure and ground reaction forces (Brand *et al.* 1981, Widhe and Berggren 1994), but only one study to date has examined the three dimensional kinematics and kinetics of these subjects. Karol *et al.* (1997) examined the kinematics and kinetics of unilateral clubfoot subjects. Although they compared the kinematics of the contralateral limb to normal subjects, they did not draw a direct comparison between normal subjects and the contralateral limb of the unilateral subjects with respect to kinetics or muscle strength, or to bilateral subjects who underwent similar surgery. Since they did show that kinematics were different, we believe that the kinetics and the strength of the contralateral limb of unilateral subjects and normal subjects should also be compared. The clubfoot limb may be used less often than the contralateral, there is a possibility that the clubfoot limb biomechanics are different to those that have bilateral clubfoot.

The purpose of our study was to examine the kinematics, kinetics, muscle strength and functional rating score of bilateral and unilateral clubfoot subjects who had undergone a posteromedial release as compared to normal subjects. We predicted that there would be significant differences in the hip, knee and ankle dynamics among the three different groups.

3.2 Methods

3.2.1 Subjects

An attempt was made to contact all 65 children who had undergone a comprehensive posteromedial release for congenital clubfoot between 1980 and 1990 at Alberta Children's Hospital. Of these, 25 agreed to participate in the study. Ten (3 female and 7 male), had undergone posteromedial release for each of their bilateral clubfeet, and 15 (6 female and 9 male) underwent posteromedial release for unilateral clubfoot. These subjects were between 8 and 17 years of age, with a mean of 12.1 and a standard deviation of 3.0 years. The age at first surgery was between 3 and 31 months. For those who required further surgical correction, at least 5 years had passed since the last intervention. In addition, 16 age- and gender-matched normal subjects volunteered to participate in this study. All individuals and their parents signed an informed consent approved by the Conjoint Medical Ethics and Science Review Committees of the Alberta Children's Hospital and the University of Calgary (Appendix 1).

3.2.2 Functional Rating

The functional rating system of Laaveg and Ponseti was used to compare function to other studies (Appendix 2). Each clubfoot subject completed a brief questionnaire regarding activity levels, pain and satisfaction which constituted 70% of the assessment. This questionnaire in addition to range of motion measurements was used to obtain a functional rating score for each clubfoot subject. Range of motion of the forefoot relative to the hindfoot was obtained both by passive and active measurements. The amount of ankle dorsiflexion, varus-valgus heel motion and inversion/eversion of the forefoot relative to the hindfoot was measured (all by the same investigator) passively using a goniometer. The active measurement of dorsiflexion and plantarflexion was obtained using a motion analysis system to record marker motion while the subject fully dorsiflexed and plantarflexed the foot with the leg extended. Function was determined by the number of points scored on the questionnaire. Classification of function was divided into four categories. If the score for the Ponseti questionnaire (1981) was between 90 and 100, the function of the foot was considered excellent. If the score was between 80 and 90 the function was good, an assessment was fair if the score was between 70 and 80 and poor if the foot was scored lower than 70. The study performed by Hutchins *et al.* (1995) and the studies performed by Laaveg and Ponseti (1981) used this rating system to determine success of treatment.

3.2.3 Muscle Strength

Isokinetic strengths at the knee and ankle were measured using a KinCom (Chattanooga, Inc.). The quadriceps and hamstrings were tested at 60 °/s (Karol 1997), and the plantarflexors and dorsiflexors of the ankle were tested at 30 °/s for three cycles of five repetitions. Maximum strength was obtained for each cycle, and these were averaged to obtain muscle strength.

3.2.4 Gait Analysis

3.2.4.1 Data Acquisition

For gait analysis, three spherical reflective markers were placed on each lower extremity segment using double-sided adhesive tape. Each segment was defined using three markers including the pelvis (defining the front and the upper and lower pelvis using a hip belt), the thigh (greater trochanter, the front of the thigh, and the lateral epicondyle), the leg (distal fibula, front of fibula and proximal fibula) and the foot (posterior superior protrusion of calcaneus, head of first metatarsus and head of fifth metatarsus).

Video data were collected using four high speed cameras (Motion Analysis Corporation, Santa Rosa, CA, USA) and 8 mm lenses. The cameras were placed to allow at least two cameras to see each marker at any given point in time. These cameras were linked to a SUN station which used EVa software (Motion Analysis Corporation, Santa Rosa, CA, USA) to collect the data from all four cameras. Calibration was performed using a cubic frame (1m x 1m x 1m) with eight spherical markers at known distances. Using this calibration, the Cartesian coordinate system for the laboratory was defined. A wand calibration was also performed using a 1 m length wand with three markers at known distances.

Force data were collected using one force platform (Kistler model 9865 B) at a sampling frequency of 1200 Hz. Three spherical markers were used at three of the four corners of the forceplate to define the x and y coordinates of the forceplate. The collection of data from the forceplate was timed in conjunction with the cameras to be able to synchronize the forces with the positions.

A standing trial was performed to define the neutral position of the subject. Since three markers defined a rigid segment, these markers remained equidistant during the gait cycle. The motion from the neutral position was used to determine the relative angles between segments. All kinematic and kinetic data obtained used this position as the zero value for angles obtained.

Each trial consisted of video acquisition for 2 s. during which 240 frames of data were obtained. Collection of the data was triggered by a handheld button which the researcher pressed as heel strike was about to occur. The subject was allowed several practice trials along a runway (1.2 x 6 m) at a self-selected pace to feel comfortable with the procedure and to strike the forceplate without changing his/her gait. The speed of the subject was determined by 2 photocells which were placed 1.94 m apart. Since the height and age of the subjects were so variable, each subject chose a comfortable pace for the first five trials, then walked as fast as possible, without breaking into a run, for the next five trials. All trials for each patient at each pace were within 0.03 m/s of the other trials.

3.2.4.2 Data Analysis

Expert Vision software was used to track the position-time trajectories of each of the reflective markers. Three dimensional positions of each of the markers were determined based on at least two camera views using a Direct Linear Transformation technique (Abdel Aziz *et al.*, 1971). The 3 D data were smoothed using a fourth order Butterworth low-pass digital filter with a cutoff frequency of 12. These data were imported to KINTRAK (University of Calgary). The beginning of the stance phase was determined by initial contact with the force plate and the beginning of the next stance phase, or the end of the swing phase was defined as the velocity of the calcaneal marker reaching zero.

Transformation measurements were performed in order to represent the motion of each segment in an inertial laboratory coordinate system. To use KINTRAK to analyze the data, the origin was defined as the proximal joint center with the x-axis from the origin to the distal joint centre. The joint centre of the ankle was determined using the marker placed on the distal fibula to obtain the position in the sagittal and transverse planes. The distance in the frontal plane was measured to the centre of the ankle joint from the distal fibula marker. A similar approach was used to determine the knee joint centre using the marker located on the lateral epicondyle. The sagittal and transverse plane positions of the hip joint centre were determined from the marker on the greater trochanter and the position in the frontal plane by a measurement to the pubic symphysis. The medial/lateral and anterior/posterior directions were defined following the right hand rule. The relative motion of each of the segments from the neutral position was obtained and the kinematic and kinetic variables were determined using the Cardanic angle sequence of hinge-cross-long to determine relative movement between each of the segments. The rotation first occurs about the medio-lateral axis followed by the vertical axis and finally the anterior-posterior axis of the segment. Five trial mean values were calculated of the angles and moments at the pelvis, the hip, the knee, and the ankle joints for a full gait cycle at each of the two speeds.

Ground reaction forces in the anterior/posterior, vertical and lateral/medial directions were also determined using the data from the forceplate. Inverse dynamics were used to calculate the moments at the ankle, followed by the knee and finally the hip.

Minimal and maximal values of kinetic and kinematic data during the gait cycle were used to determine statistical significance. Figures 3.1-3.3 indicate the variables of interest for the kinematics and Figures 3.4-3.7 indicate the variables of interest for the kinetics.

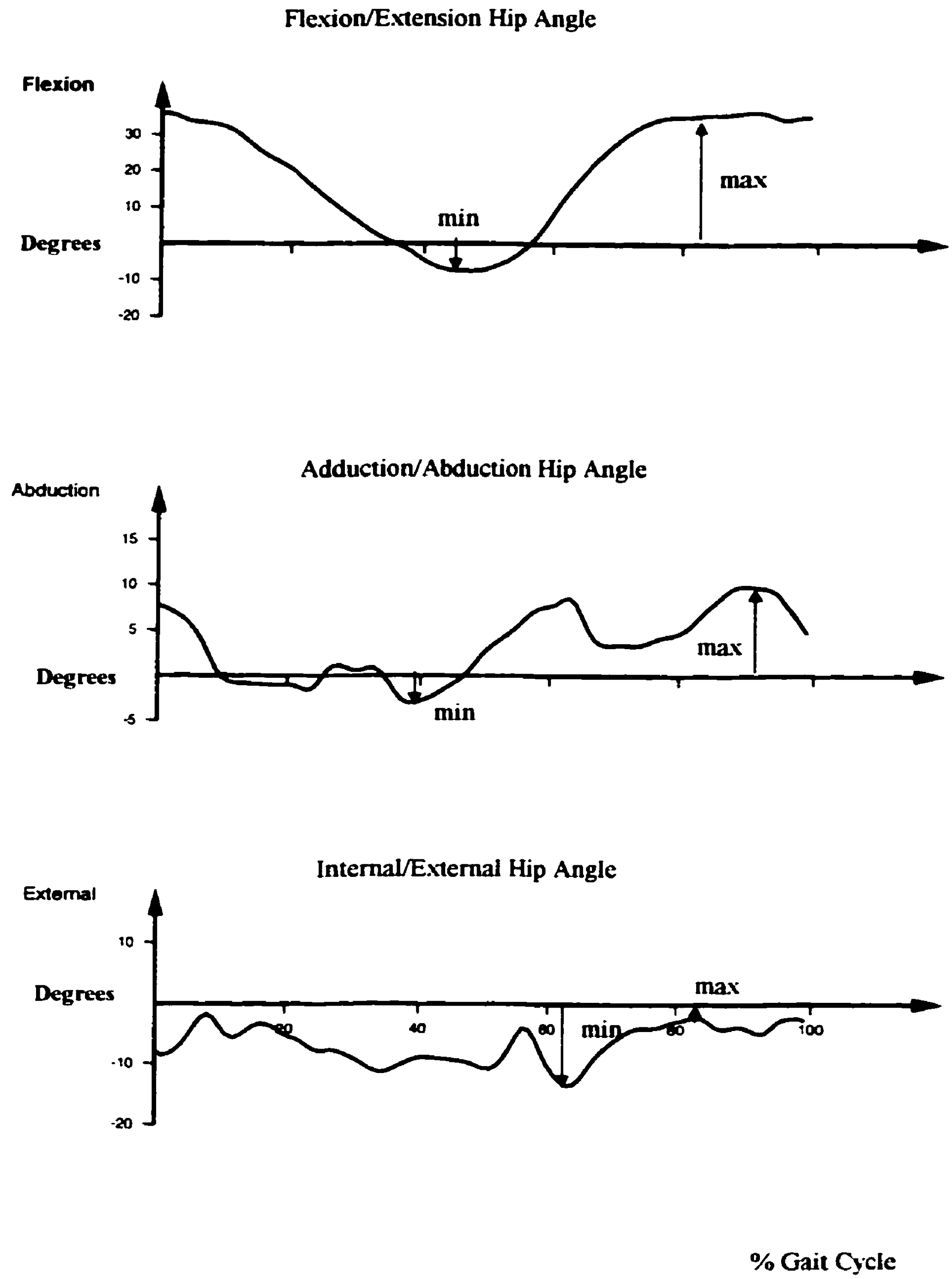


Figure 3.1 **The maximal and minimal values used to calculate significance at the hip are indicated.**

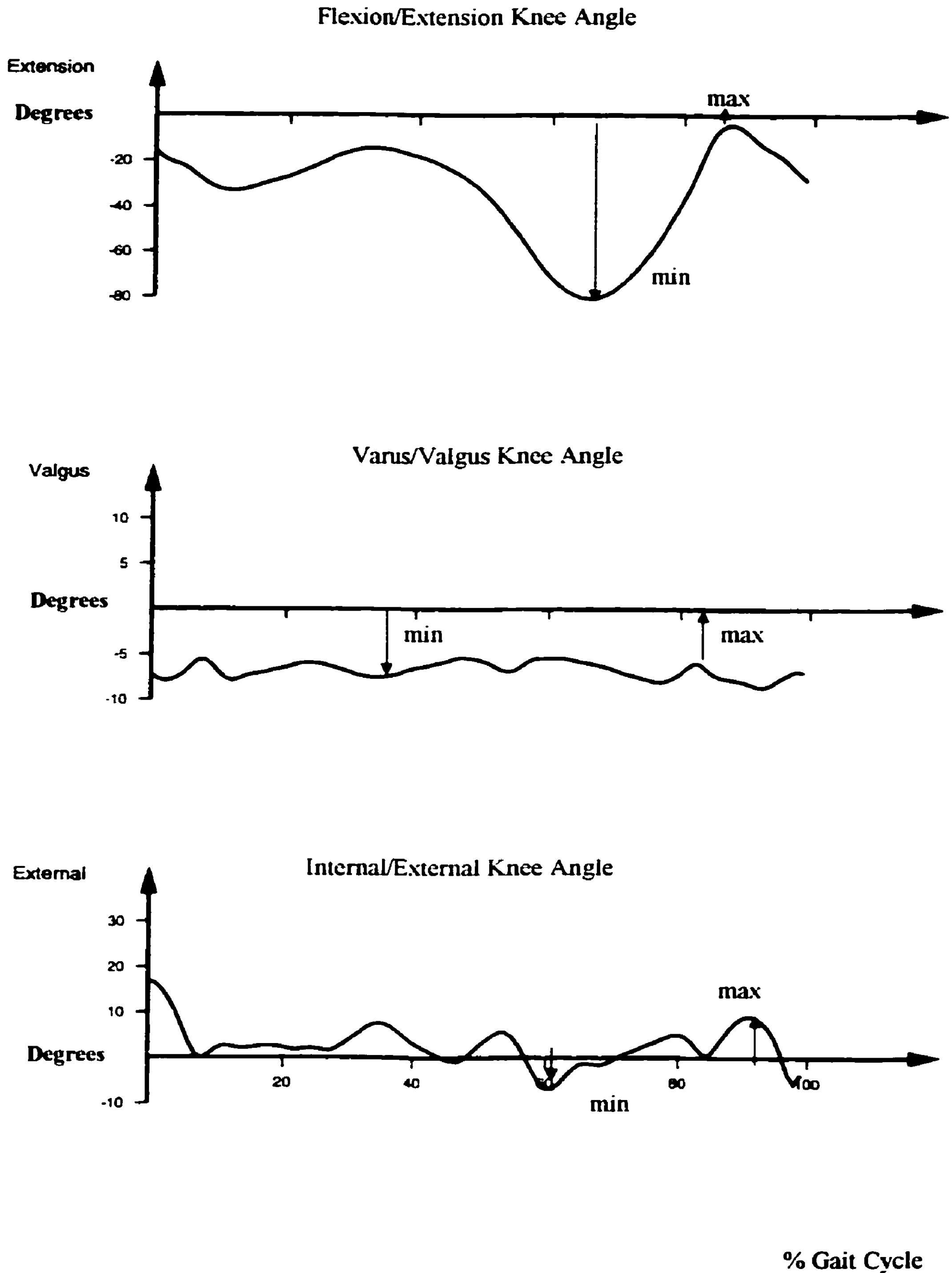


Figure 3.2 **The maximal and minimal values used to calculate significance at the knee are indicated.**

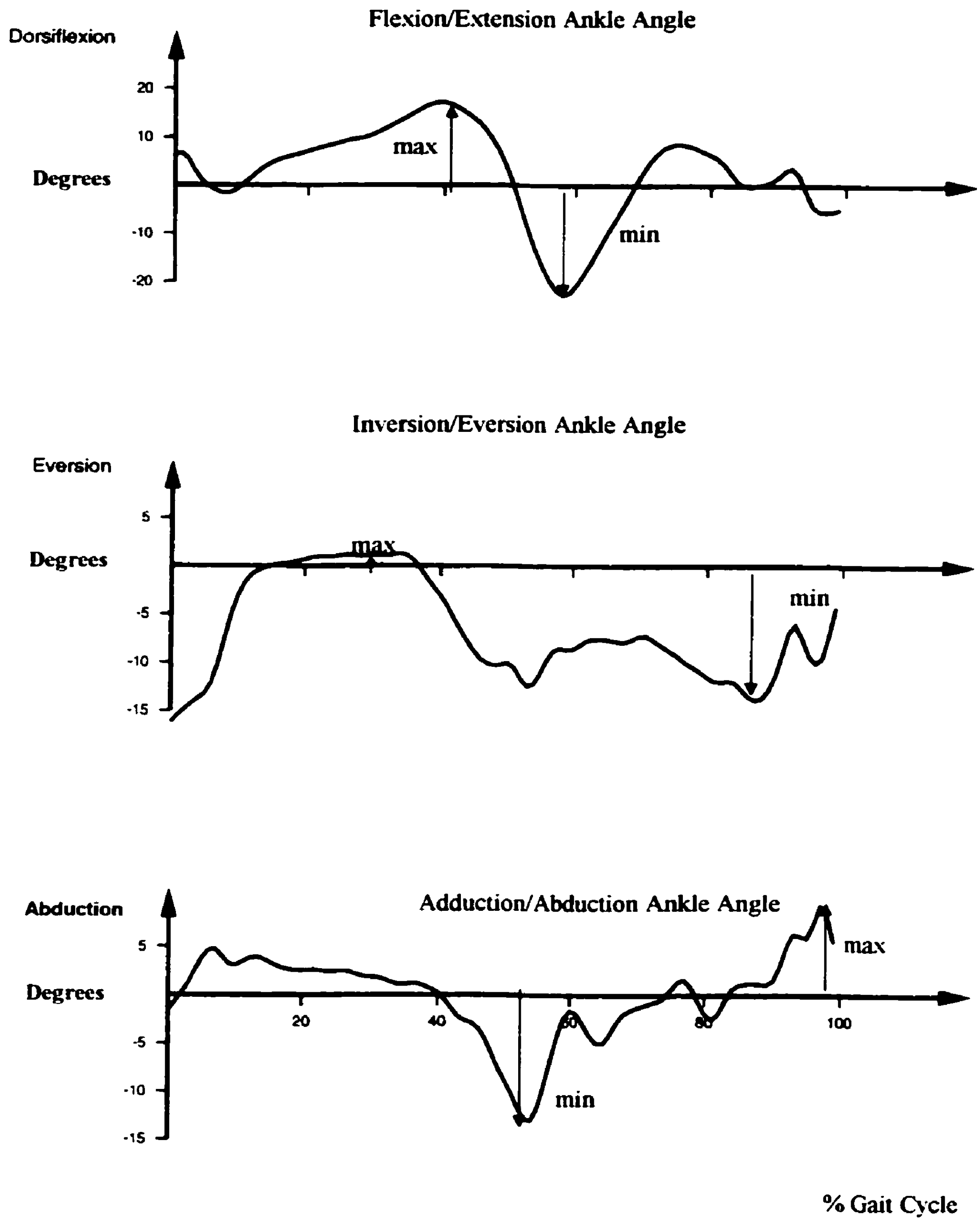
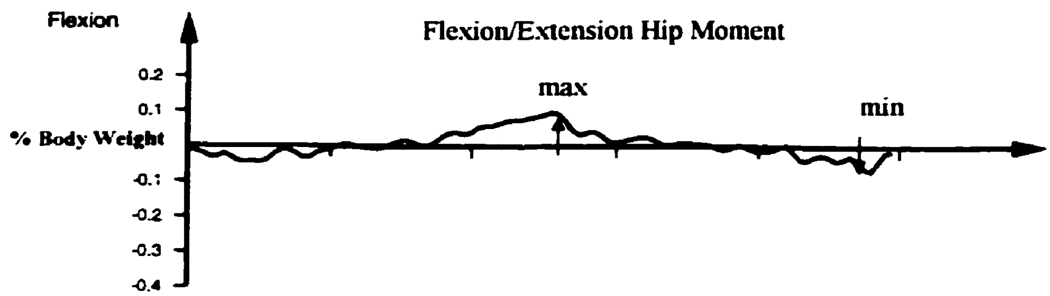
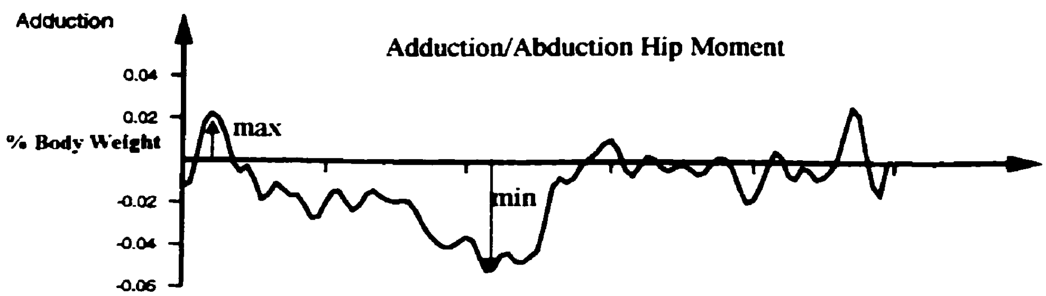


Figure 3.3 **The maximal and minimal values used to calculate significance at the ankle are indicated.**





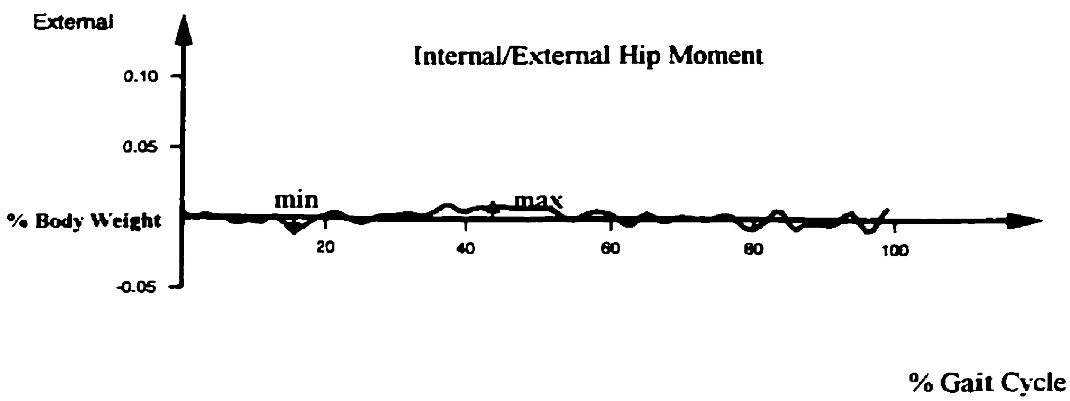


Figure 3.4 **The maximal and minimal values of moments used to calculate significance at the hip are indicated.**

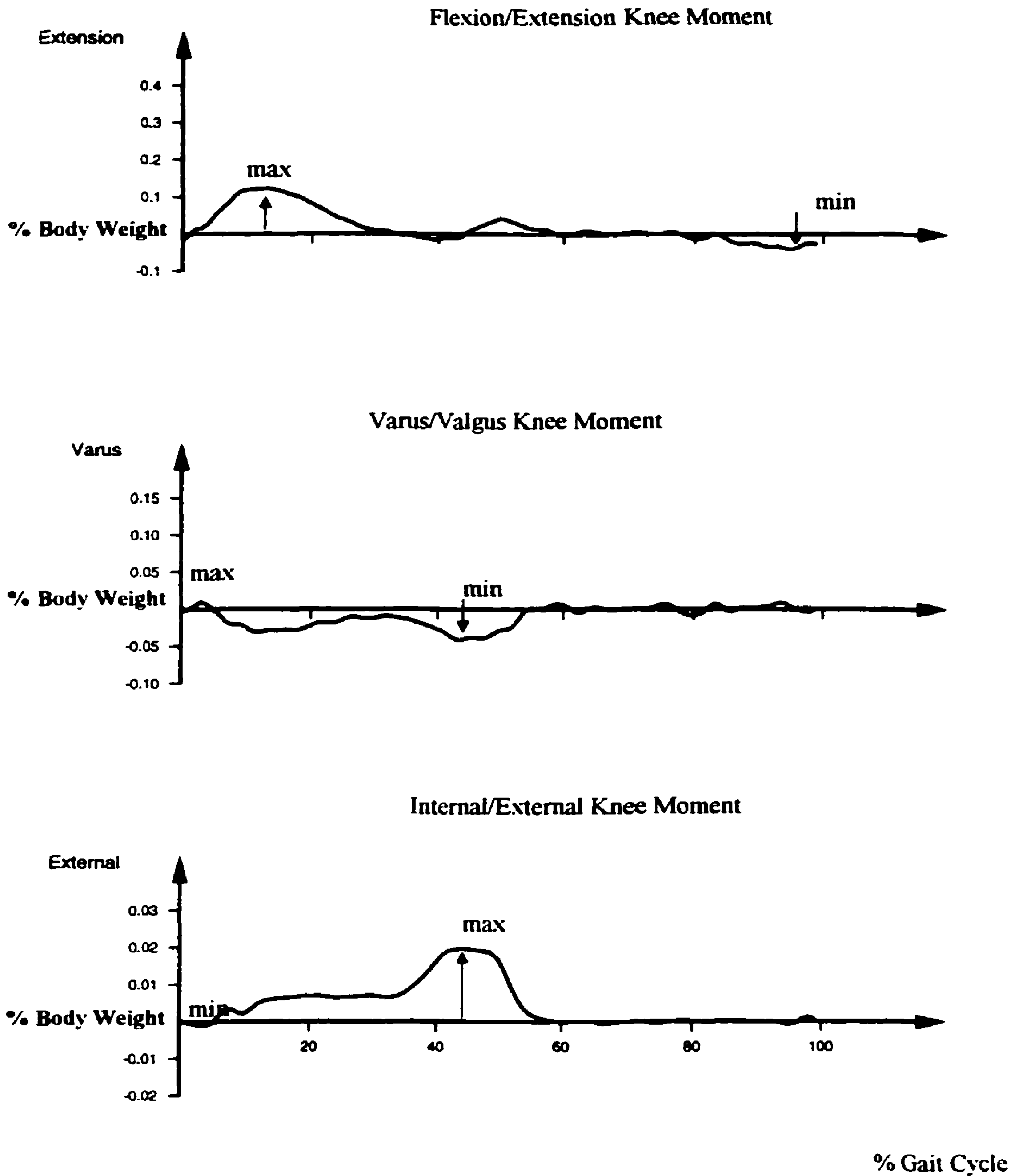


Figure 3.5 **The maximal and minimal values of moments used to calculate significance at the knee are shown.**

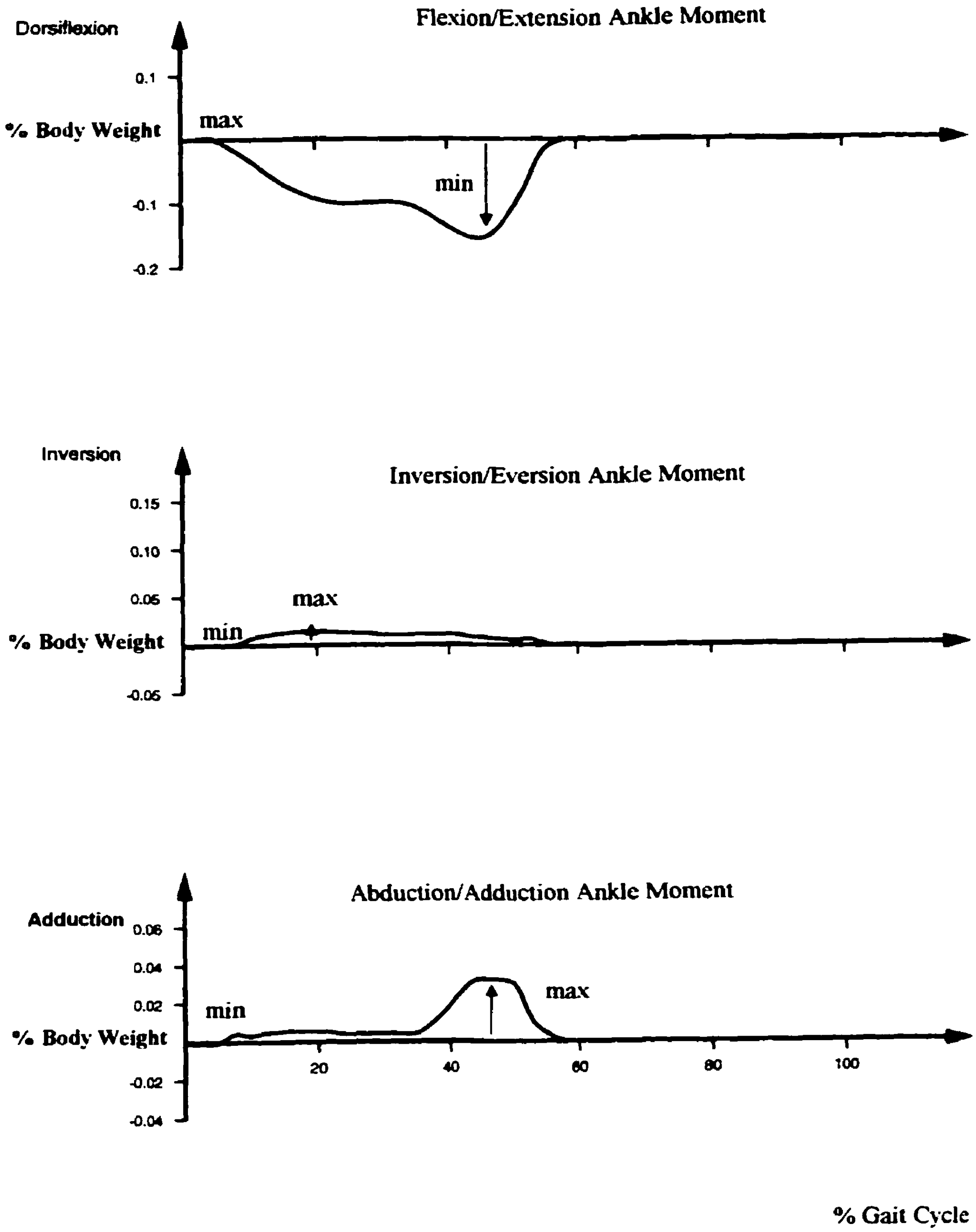


Figure 3.6 **The maximal and minimal values of moments used to calculate significance at the ankle are indicated.**

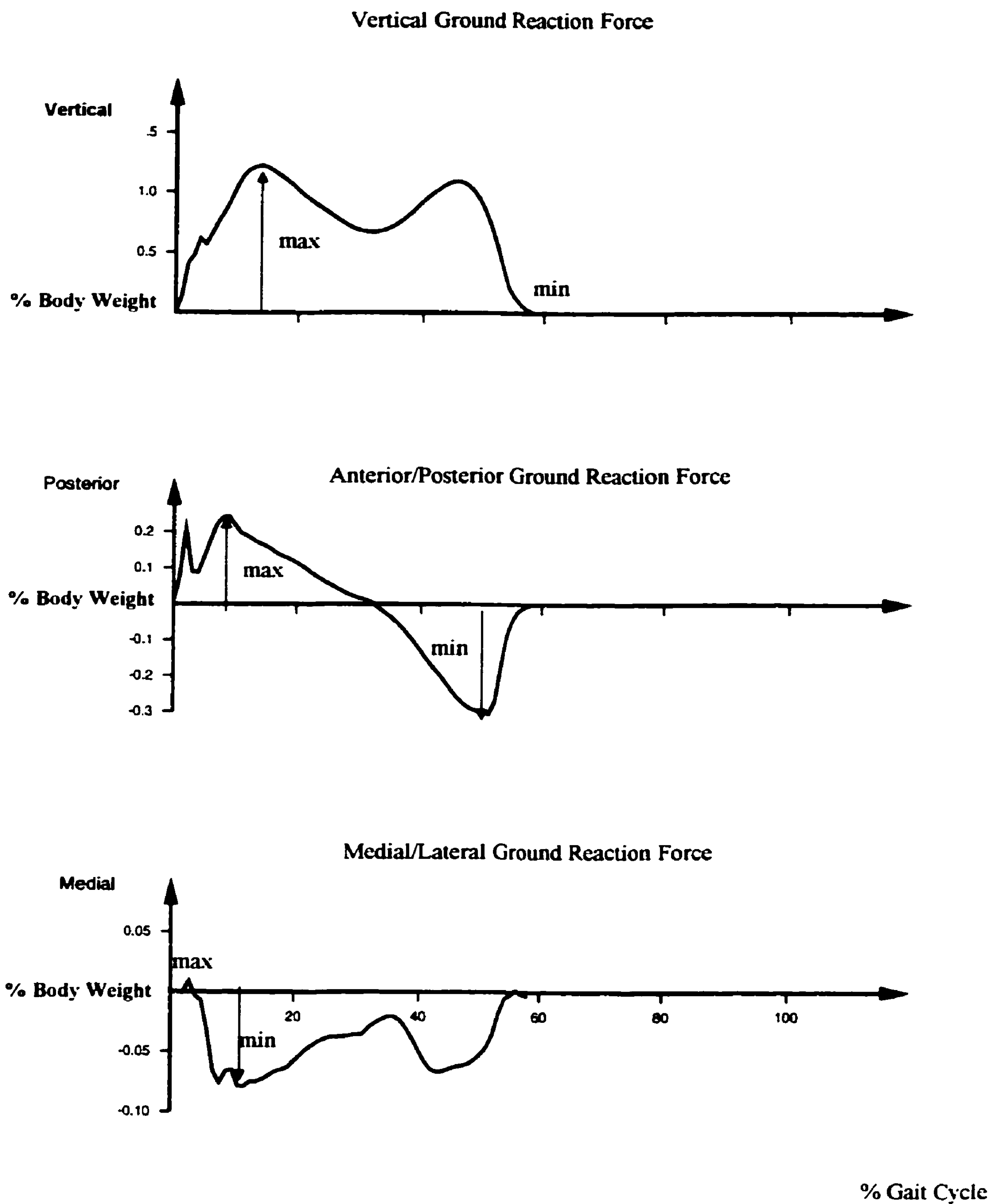


Figure 3.7 **The maximal and minimal values of the ground reaction forces.**

In order to determine whether there were significant differences between lower limbs of the bilateral and normal subjects, a paired t-test was performed. A significant difference was found between limbs, and further analysis treated these independently. A paired t-test was also performed between speeds. Since these were also found to be significantly different with a 95% confidence interval, all the analysis was conducted at the self chosen pace, then repeated for the fast pace. A MANOVA was performed for each of the angles and moments at the hip, knee and ankle joints. In order to find differences between groups, a Hotelling's trace test and a Wilks' lamda test were performed. If significant differences were found among the groups, post-hoc analysis involved a Student-Neuman Keuls test to determine which groups were significantly different. A similar MANOVA was conducted for all ground reaction forces.

3.3 Results

3.3.1 Functional Rating

There were twenty five subjects of which one chose not to complete the personal assessment. Thus, a Ponseti questionnaire was completed for 34 feet. Based on the Ponseti rating system none of our subjects had excellent results, 6% had good results, 41% had fair results, and 53% had poor results.

3.3.2 Muscle Strength

There was a significant difference in the strength of the plantarflexors between the good limb of the unilateral subjects and the normals, between the clubfoot limb of the unilateral subjects and the bilateral subjects as well as between the normal and bilateral subjects. No significant differences were observed among groups in the strengths of the dorsiflexors of the ankle, quadriceps, or hamstrings. For the bilateral and normal subjects there was a very good correlation between the left and right limb for the plantarflexors (Pearson correlation coefficient (PCC) = 0.51), dorsiflexors (PCC = 0.81), quadriceps (PCC = 0.85) and hamstrings (PCC = 0.63).

3.3.3 Kinematics

There were several kinematic variables at the hip, knee and ankle that were significantly different. These variables are listed in Table 3.1.

Table 3.1 Mean values (Std. Error of Mean) of variables which showed significant differences.

* represents the groups that were significantly different from normal. ** represents a significant difference from the CF unilateral limb. ^ represents the groups that were significantly different from the bilateral group.

Angles (°)	Group 0 unilateral contralateral	Group 1 unilateral CF leg	Group 2 normal	Group 3 bilateral CF
Knee Varus	9.1 (1.4)	15.7* (2.4)	8.4 (0.9)	13.6* (1.9)
Knee Valgus	5.3 (1.2)	1.4* (1.5)	5.7 (1.0)	0.8* (1.0)
Knee Internal Rot	7.4** (1.3)	16.3* (2.7)	7.1 (0.1)	12.6 (1.8)
Ankle Plantarflexion	10.2 (2.0)	9.3* (1.2)	15.1 (1.4)	7.8* (1.4)
Ankle inversion	12.4^ (1.3)	12.9 (1.2)	16.5 (1.1)	18.3 (1.9)
Ankle Adduction	13.3 (1.2)	11.0 (0.6)	13.2 (0.8)	9.7* (1.0)

3.3.4 Kinetics

Significant differences in the ground reaction forces were found at the 95% confidence level among the groups. These differences are listed in Table 3.2. Significant differences were also found among the groups at the knee and ankle. All the significant kinetic effects are shown in Table 3.3.

3.3.5 Speeds

Significant differences were found at the hip, knee and ankle between the two speeds. These speeds were treated independently for further analysis. At the faster pace, similar results as at the self-selected pace were observed in the kinematics and kinetics at the hip, knee and ankle, with several exceptions. At a faster speed, the hip internal angle was greater between the clubfoot and the normals and the knee flexion angle was greater. The same trends were evident for the moments between the two speeds.

Table 3.2 Of the ground reaction forces that were calculated, only the ones listed below exhibited significant differences among the groups.

* represents the groups that were significantly different from normal. ** represents a significant difference from the CF unilateral limb. ^ represents the groups that were significantly different from the bilateral group.

Ground Reaction Forces (normalized to body weight)	Group 0 unilateral contralateral	Group 1 unilateral CF leg	Group 2 normal	Group 3 bilateral CF
Vertical GRF Maximum	1.36 ^ (0.04)	1.30 ^ (0.04)	1.44 ^ (0.03)	1.59 (0.07)
Anterior GRF	0.263 (0.011)	0.239 * (0.011)	0.282 (0.008)	0.248 (0.016)
Lateral GRF	0.067 **,^ (0.005)	0.091 (0.008)	0.076 (0.004)	0.096 (0.004)

Table 3. 3 Of the kinetic parameters that were tested, several showed significant differences among the groups. These kinetic parameters (S.E.M) x10^{-3} are listed below.

* represents the groups that were significantly different from normal. ** represents a significant difference from the CF unilateral limb. ^ represents the groups that were significantly different from the bilateral group.

Moments (normalized to body weight)	Group 0 unilateral contralateral	Group 1 unilateral CF leg	Group 2 normal	Group 3 bilateral CF
Hip Extension Moment	170 (7.7)	147^ (4.7)	164 (7.8)	185 (4.5)
Hip Adduction Moment	44.7** (2.05)	41.7 (2.3)	56.8 (4.6)	48.4 (4.3)
Hip Internal Moment	27.7 (2.7)	31.8 (3.9)	25.4 (1.6)	34.5* (3.5)
Knee Valgus Moment	32.4^ (3.3)	44.6* (5.2)	28.6 (2.2)	50.0* (6.3)
Knee Varus Moment	19.5 (2.1)	19.5* (1.6)	31.9 (3.8)	10.2* (2.0)
Knee Internal Moment	4.0* (0.5)	4.6 (0.1)	10.2 (2.0)	7.4 (1.3)
Ankle Eversion Moment	7.8 (1.8)	5.0^ (0.9)	7.0 (1.3)	13.6 (4.2)
Ankle Inversion Moment	18.0* (2.6)	27.2 (3.3)	37.8 (5.2)	25.9 (2.7)
Ankle Internal Moment	3.5* (0.6)	3.6 (0.6)	8.4 (1.4)	7.0 (1.5)
Ankle Adduction Moment	27.7 (1.7)	20.7* (2.2)	31.4 (2.9)	16.3* (2.3)

3.4 Discussion

3.4.1 Functional Rating

Based on the Ponseti rating system, in the current study 6% had good results, 41% had fair results, and 53% had poor results. Hutchins found that 81% of their patients were satisfied, Blakeslee *et al.* had a 95% satisfaction. Our rates are very low in comparison.

Ponseti and Laaveg also found that of the 104 clubfeet and 70 patients, 53% had no relapse, 47 % had one relapse and 10 % had at least one additional relapse. These results are consistent with ours. Of those with unilateral clubfoot, 40 % had one repeat surgery, and 7% had an additional relapse. The bilateral subjects had similar results as well, with 30% having additional surgery on both legs, 40% had additional surgery on one leg, and 20% had more than one additional surgery.

Although the functional ratings of our subjects were lower than that of other studies, the number of repeat surgeries were consistent indicating a possible difference in the personal and societal expectations, since 60% of the score is based on self satisfaction.

3.4.2 Muscle Strength

Karol *et al.* (1997) found that there was a relative weakness of the plantarflexors at the ankle on the side of surgery in unilateral clubfoot subjects. We too found that there was a significant weakness at the ankle on the side of surgery. Also, there was a significant weakness of the plantarflexors of the ankle when compared to the strength of subjects with two normal limbs and when bilateral clubfoot subjects were compared to normal subjects. Aaronson and Puskarich (1990) performed similar tests using a dynamometer and found significant differences ($p<0.05$) between the clubfoot side and the normal side of unilateral clubfoot subjects. Their study also showed that there were no significant differences between the normal side of the unilateral clubfoot subjects and the normal subjects in their study. This may be due to the different methods of testing. They performed three trials and used the maximum measurement of torque. We performed three sets of five extensions, took the maximum from each of these sets and averaged them together to find the average maximum strength. We found that the strength results were variable (standard deviation of the trials ranged from 0-370 N), and three individual trials would not be representative of the true force.

3.4.3 Kinematic and Kinetics

When the speeds were treated independently, at a faster speed, subjects compensated at the knee for the lack of motion at the ankle as they flexed to a greater amount. Otherwise, the same kinetic and kinematic differences were observed at each speed.

At the hip, no significant kinematic differences were observed, whereas Karol *et al.* (1997) found differences in 15 of 23 of the children and a lack of hip extension. It is possible that our lack of observation was due to the use of a pelvis belt rather than markers directly attached to the skin. The artefact motion of the belt moving while walking may be too high to detect differences.

The knee exhibited greater varus angles as well as increased internal rotation for the clubfoot subjects. This type of malrotation would have caused the ground reaction force to act toward the medial side of the knee and may have required increased muscle support to stabilize the knee during stance. Increased muscle balance when walking may aid in maintaining muscle strength at the knee similar to that of normals.

The ankle exhibited deviations in all three planes. Plantarflexion was significantly smaller in the clubfoot of both unilateral and bilateral subjects. Since normal plantarflexion is required for push-off, insufficient ankle plantarflexion may be a factor causing difficulty with propulsion. This lack of plantarflexion may also be due to weak plantarflexors. Karol *et al.* (1997) found similar results indicating that the lack of propulsion may be due to factors other than range of motion at the ankle including lack of muscle strength. A decreased internal rotation was also evident at the ankle. Since this would cause the ground reaction force to be rotated outside the plane of progression, the abnormal torques at the hip and knee were expected. As the extension moment at the knee is affected by the decreased internal rotation at the ankle, we also saw abnormal varus and internal moments at the knee.

At the hip, we saw kinetic deviations in all three planes. The hip extension moment was different between the unilateral clubfoot limb and bilateral clubfoot limbs, probably because the unilateral subjects could attain more normal motion with the help of their contralateral hip. Also, the internal moment was only different between bilateral and normals, indicating that the compensation technique at the hip on unilateral subjects was successful in creating more normal moments.

3.4.4 Ground Reaction Forces

The vertical ground reaction force for the bilateral clubfoot subjects was higher than any other group. We did not see any significant differences between the clubfoot and the contralateral of the unilateral subjects. This contradicted the observation of Widhe and Berggren (1994), but this may be due to the small sample size. (A power analysis based on their study showed that 16 subjects in each group are required).

The anterior ground reaction force was lower for clubfoot. This same phenomenon was also shown by Sawatzky *et al.* (1994). This is the force required to propel forward. The lack of anterior ground reaction force verifies the lack of push-off observed in clubfoot subjects on which this and many other studies are based (Hutchins *et al.* 1995, Karol *et al.* 1997).

Finally, the lateral ground reaction force of the clubfoot subjects was greater than the normal subjects. Aaronson and Puskarich (1990) also reported increased stress along the fifth metatarsal, while Widhe and Berggren (1994) showed a shift towards the lateral. The inversion angle which is evident at the ankle also indicated that there would be a residual inversion deformity of the foot which caused lateral border walking.

3.5 Summary

A lack of push-off occurred in the clubfoot subjects. This lack of push-off is related to a lack of strength of the plantarflexors and insufficient ankle range of motion in all three planes. Insufficient range of motion caused an extension moment at the knee accompanied by abnormal valgus moments. Hip adduction was different between the normal and contralateral limb of unilateral subjects which indicated compensation on the normal side. The internal hip moment was higher for the bilateral than the normal subjects due to the increased valgus moments at the knee.

4 HINDFOOT AND FOREFOOT BIOMECHANICS OF CHILDREN WITH CLUBFOOT

4.1 Introduction

Clubfoot is a foot deformity due to an abnormal relation between tarsal bones, such that the navicular and the calcaneus are displaced medially around the talus. Surgery is often required to release the soft tissue contractures that have resulted due to this bony abnormality. Many rating systems have been used to quantify the outcome several years after surgery. X-rays have been used to characterize the results after surgery by examining the shape and possible articulation of each of the talus, the calcaneus, the navicular and the metatarsal bones. Function is also determined by the amount of passive motion that the foot can achieve. More recently, gait analysis of clubfoot subjects involves observation of toe-walking and heel-walking at various speeds to observe gait characteristics. Widhe and Berggren (1994) examined the ground reaction forces of these children. Karol *et al.* (1997) examined the three dimensional kinematics of unilateral clubfoot children, and we examined the three dimensional gait characteristics of unilateral and bilateral clubfoot children as compared to age- and gender- matched normal subjects. Although it is interesting to examine the compensation measures at the hip, knee, and ankle, the motion of the forefoot relative to the hindfoot is also important to examine.

Dynamic motion of the forefoot and rearfoot *in vivo* is difficult to measure, but recently, Scott and Winter (1993) examined the amount of flexion of the forefoot relative to the hindfoot in normal subjects using a motion analysis system and compared it to a mathematical model. Lee *et al.* (1997) examined the amount of adduction of the forefoot in normal subjects while running, walking and side shuffling. Recently, Carson *et al.* (1998) presented the preliminary results of a method of quantifying forefoot versus hindfoot motion in three cardinal planes.

We chose to expand on these recent studies and look at normal and clubfoot subjects to examine the different foot biomechanics among the groups. To examine the clubfoot biomechanics in greater detail, our study examined forefoot and hindfoot kinematics of unilateral and bilateral clubfoot children who underwent posteromedial release as compared to normal subjects.

4.2 Methods

4.2.1 Subjects

An attempt was made to contact all 65 children who had undergone a comprehensive posteromedial release for congenital clubfoot between 1980 and 1990 at Alberta Children's Hospital. No other abnormalities were present in these subjects. Of these, 25 agreed to participate in the study. Ten (3 female and 7 male), had undergone posteromedial release for each of their bilateral clubfeet, and 15 (6 female and 9 male) underwent posteromedial release for unilateral clubfoot. These subjects were between 8 and 17 years of age, with a mean of 12.1 and a standard deviation of 3.0 years. The age at first surgery was between 3 and 31 months. For those who required further surgical correction, at least 5 years had passed since the last intervention. In addition, 16 age- and gender-matched normal subjects volunteered to participate in this study. All individuals and a parent signed an informed consent approved by the Conjoint Medical Ethics and Science Review Committees of the Alberta Children's Hospital and the University of Calgary (Appendix 1).

4.2.2 Data Acquisition

Spherical reflective markers (1 cm in diameter) were attached to the skin using double-sided tape. Three markers were placed on the calcaneus and three on the forefoot: head of the first metatarsus, head of the fifth metatarsus, and second cuneiform. (Figure 4.1). It was assumed that both the forefoot and the hindfoot were rigid bodies. Scott and Winter (1993) noted that skin markers are highly reliable, but did report concern for motion of the extensor hallucis longus when a marker was placed on the first MTP. To reduce the amount of skin movement, the marker was placed slightly medial to the extensor.

Video data were collected using four high speed cameras (Motion Analysis Corporation, Santa Rosa, CA, USA) and 8 mm lenses. The cameras were placed to allow each marker to be seen by at least 2 cameras at any given point in time. These cameras were linked to a SUN station which used EVa software (Motion Analysis Corporation, Santa Rosa, CA)

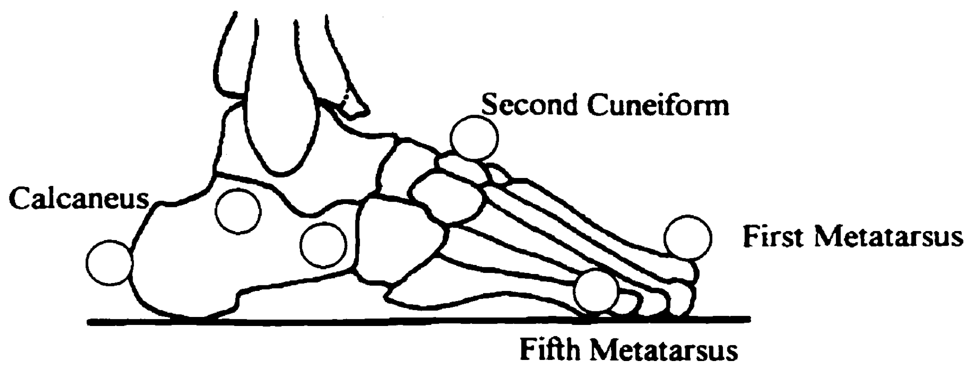


Figure 4.1 **Lateral view of marker placement defining forefoot and rearfoot.**

to collect the data from all four cameras. Calibration was performed using a cubic frame (1m x 1m x 1m) with eight spherical markers at known distances. Using this calibration, the Cartesian coordinate system for the laboratory was defined. For the right foot, the positive direction of the x-axis corresponded to the anterior direction, the positive y-direction was defined as the medial direction and the positive z corresponded to the superior direction. Thus, for the right foot, adduction was defined as a positive (clockwise) rotation about the z-axis, inversion was a positive rotation about the x-axis and plantarflexion was the positive direction about the y-axis. For the left foot, the direction of progression was reversed. Thus, in the laboratory coordinate system, the directions of motion were as follows: adduction was negative about the z-axis, inversion was positive about the x-axis, and plantarflexion was negative about the y-axis. A wand calibration was also performed using a 1 m length wand with three markers at known distances to calibrate the area more accurately.

Force data were collected using a force platform (Kistler 9865 B). This was synchronized with the cameras to superimpose the forces with the positions to determine the stance phase of gait.

Each subject performed five trials at a self-selected pace and five additional trials at a fast pace. Since the cameras were situated on one side of the subject, these trials were performed first with the markers on the left leg, then repeated with markers on the right leg.

A standing trial was performed to define the neutral position of the subject. Since three markers defined a rigid segment, these markers remained equidistant during the gait cycle. The motion from the neutral position was used to determine the relative angles between segments. All kinematic data obtained used this position as the zero value for calculated angles.

Each trial consisted of video acquisition for 2 s. during which 240 frames of data were obtained. Collection of the data was triggered by a handheld button as heel strike was about to occur. The subject was allowed several practice trials along a runway (1.2 x 6 m) at a self-selected pace to feel comfortable with the procedure and to strike the force plate without changing his/her gait. The speed of the subject was determined by 2 photocells placed 1.94 m apart. Since the height and age of the subjects were so variable, each subject chose a comfortable pace for the first five trials, then walked as fast as possible, without breaking into a run, for the next five trials. All trials for each patient at each pace were within 0.03 m/s of the other trials.

4.2.3 Data Analysis

Expert Vision software was used to track the position-time trajectories of each the reflective markers. Three dimensional positions of each of the markers were determined based on at least two camera views using a Direct Linear Transformation technique (Abdel *Aziz et al.*

1971). The 3 D data were smoothed using a fourth order Butterworth low-pass digital filter with a cutoff frequency of 10 Hz. Data were tracked using EVa software (Motion Analysis Corp., Santa Rosa) and analyzed using Matlab code to determine the relative motion of the hindfoot and forefoot throughout the stance phase of gait. A relative transformation matrix $T_{rel} = T_{rf}^{-1}T_{ff}$ was computed, and the Cardanic angle sequence recommended by Cole *et al.* (1993) consisting of a rotation about the medial-lateral axis, then the vertical axis, followed by the anterior-posterior axis was used to extract the relative angles throughout the stance phase. The beginning of the stance phase was determined by initial contact with the force plate, and the end of stance was defined as lift off from the force plate. Thus stance was defined using contact of the foot with the force plate.

The values of adduction, inversion and flexion throughout the gait cycle were determined. The maximal amount of abduction and adduction, inversion and eversion, flexion and extension from heelstrike were also computed. Finally the total range of motion during the stance phase was determined. These kinematic variables of interest are shown on Figure 4.2 and described below:

α = value of ab/adduction at heelstrike

α_{max} = value of abduction from heelstrike

α_{min} = value of adduction from heelstrike

$\Delta\alpha$ = total range of ab/adduction motion from α_{max} to α_{min}

β = value of in/eversion at heelstrike

β_{max} = value of inversion from heelstrike

β_{min} = value of eversion from heelstrike

$\Delta\beta$ = total range of in/eversion motion from β_{max} to β_{min}

ϕ = value of dorsi/plantarflexion at heelstrike

ϕ_{max} = value of dorsiflexion from heelstrike

ϕ_{min} = value of plantarflexion from heelstrike

$\Delta\phi$= total range of dorsi/plantarflexion motion from ϕ_{max} to ϕ_{min}

Using these values, paired t-tests were performed between limbs of the bilateral and normal subjects and between speeds. Since there were no significant differences between limbs, the data for each variable of the bilateral and normal subjects was combined. A MANOVA was conducted with the different groups to determine if there was significance among the groups using a Hotelling's trace and a Wilks' lamda test. Post-hoc analysis using a Student-Neuman-Keuls test was performed to determine which groups were significantly different.

4.3 Results

Forefoot adduction at push-off was lower in the clubfoot patients than their normal counterparts. Mean values of the variables of interest for the ab/adduction curves for each group are shown in Figure 4.3 . At heel-strike, the forefoot was inverted relative to the hindfoot, although slight eversion occurred during flatfoot phase. During push off, there was inversion of the forefoot relative to hindfoot. Mean values for the in/eversion curves are provided in Figure 4.4.

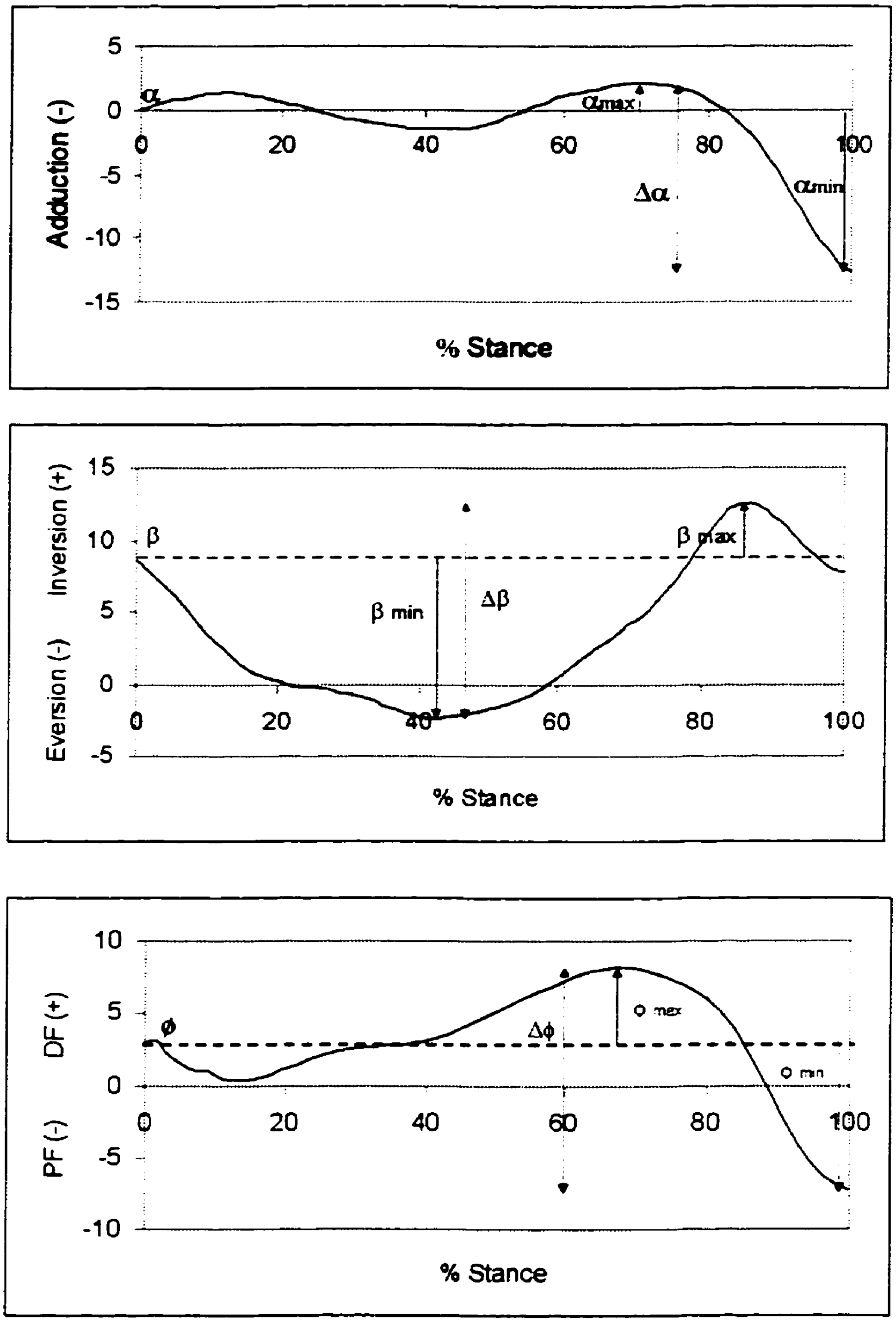


Figure 4.2 **Representative curves of left leg showing ab/adduction, in/eversion and dorsi/plantarflexion of the forefoot relative to the hindfoot.**

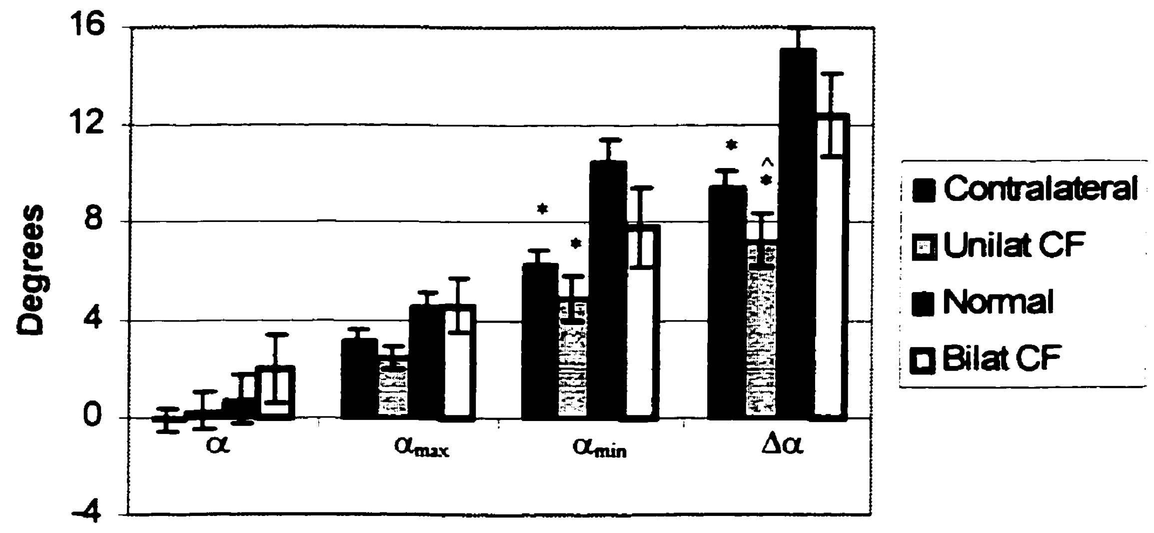


Figure 4.3 **Results of Ab/Ad motion among the groups for the variables of interest.**

* represents the groups that were significantly different from normal.

^ represents the groups that were significantly different from the bilateral group.

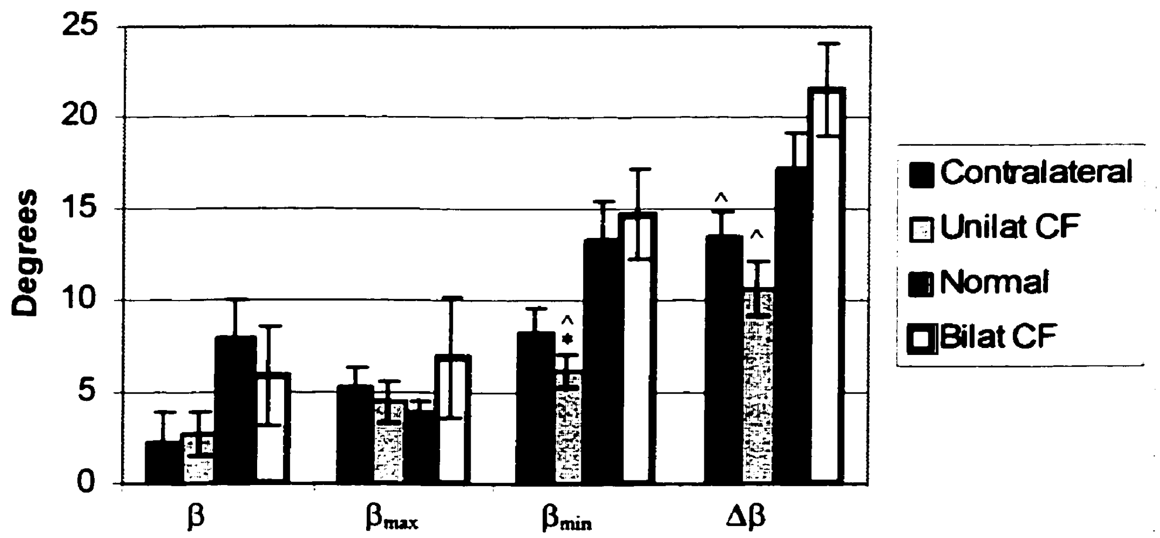


Figure 4.4 **Results of In/Eversion motion of the variables of interest among the groups.**

* represents the groups that were significantly different from normal.

^ represents the groups that were significantly different from the bilateral group.

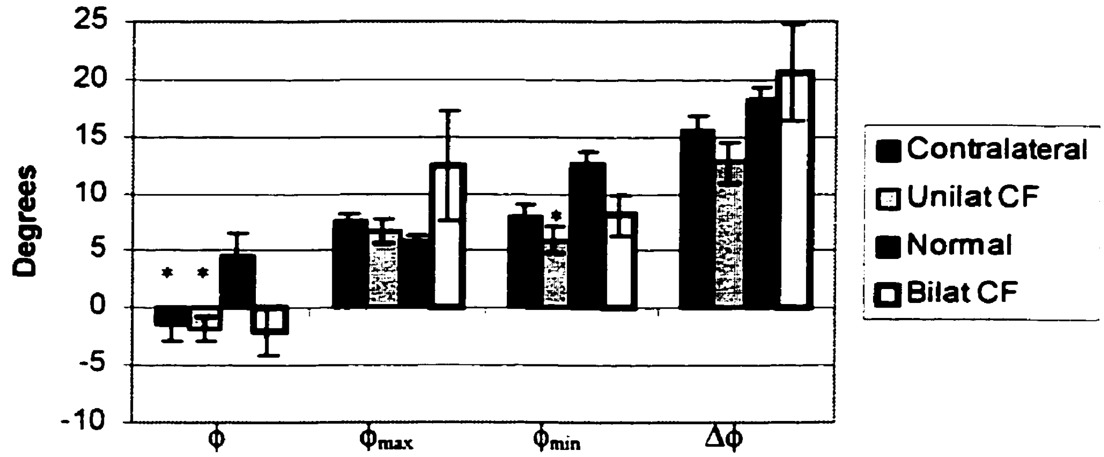


Figure 4.5 **Results of Dorsi/Plantarflexion motion of the variables of interest among the groups.**

* represents the groups that were significantly different from normal.

During mid-stance, all subjects extended the hindfoot relative to the forefoot, then all flexed during push-off. There was greater plantarflexion at heelstrike of the clubfoot than the normal subjects. The variables of interest for the dorsi/plantarflexion motions are in Figure 4.5.

There were no differences in the trends of motion between the different speeds.

4.4 Discussion

Generally, the forefoot gradually becomes abducted for the first 70% of stance which is followed by adduction during push-off (Lee *et al.* 1997). This was evident for our normal subjects, whereas the clubfoot subjects had relatively little motion of the forefoot relative to the hindfoot during the flatfoot phase followed by only slight adduction at push-off. Lee *et al.* (1997) found that normal subjects with a rigid foot had less adduction when compared to subjects with a flexible foot. The clubfoot subjects may also be compared to those with a rigid foot, which Freychat described as having a "stiff" spring which resists abduction (Figure 4.6). Cohen-Sobel (1993) believed that one of the greatest reasons for children not attaining normal function of the foot was due to forefoot adductus.

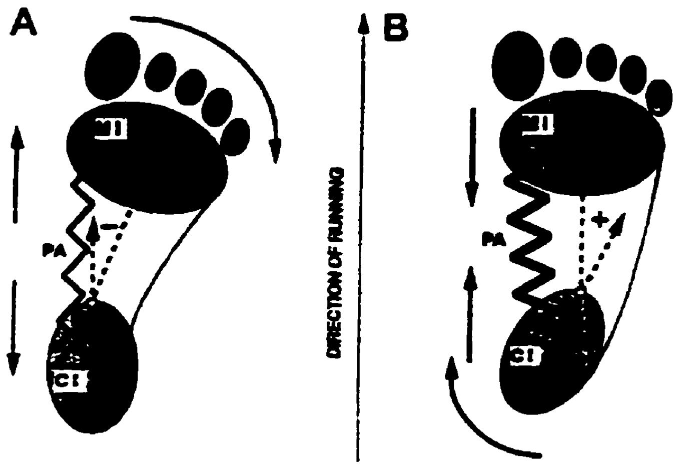


Figure 4.6 **Freychat's explanation of a foot with a flexible spring which can abduct (A) and a rigid spring in which the forefoot stays adducted (B). (From Freychat et al. 1996)**

Forefoot adduction may also be attributed to calcaneal inversion. Calcaneal inversion, in addition to adduction of the forefoot, was one of the clinical features defining clubfoot (Turco 1981). Although surgery has been performed to reduce this inversion, many of the evaluations of outcome include an assessment of heel position relative to the tibia. It has been found that the deformity still existed several years after treatment and sometimes calcaneal osteotomies were performed to reduce this inversion. This residual deformity may result in increased overall adduction and decreased abduction during stance.

All forefeet were inverted upon heel strike, everted throughout stance and inverted just prior to push-off. The unilateral clubfoot limb had less inversion, less eversion and less range of in/eversion motion than normal. As the unilateral subject can compensate with the contralateral, they may not attempt to restore full function in the clubfoot. Since inversion is a major component of talipes equinovarus prior to surgery, it is expected that the residual deformity will be present after surgery. There was more inversion of the bilateral subjects although not significant. Brand *et al.* (1981) found that lateral border walking was common for children with clubfoot by performing centre of pressure studies. Widhe and Berggren (1994) and Otis and Bohne (1986) used an EMED system to examine the pressure at different sections of the foot, and also found that walking on the lateral border was common. For lateral border walking to occur, the forefoot was likely rotated in inversion.

During push-off, with the exception of one subject who had arthrogryposis, flexion was observed from 0-33° (with the mean values being between 8.5 and 13°). This is a slightly greater range than Scott and Winter (1993) reported (from 5 -20°), but they used only three normal subjects. The general trend of extension just after heelstrike followed by flexion at push-off was similar to that of Scott and Winter (1993). Less plantarflexion from heelstrike of the clubfoot subjects was evident. Since a clubfoot is typically characterized by equinus, this residual plantarflexion may be causing the decreased amount of plantarflexion from heelstrike of the clubfoot subjects during push-off.

The windlass effect of the plantar aponeurosis is known to contribute to this flexion which also increases the height of the longitudinal arch. The plantar aponeurosis acts as a tie or a truss which is wrapped around the calcaneus and reaches to the proximal phalanges (Figure 4.4). As the hallux extends, both the transverse tarsal joint and the tarsometatarsal joint flex.

Although clubfeet are characterized by the bony deformity of the tarsal bones, the resulting tissue contractures may also affect the ability of the foot to flex during push-off. The plantar aponeuorosis responsible for the windlass mechanism may be more rigid in clubfeet than in normal feet possibly reducing the amount of flexion.

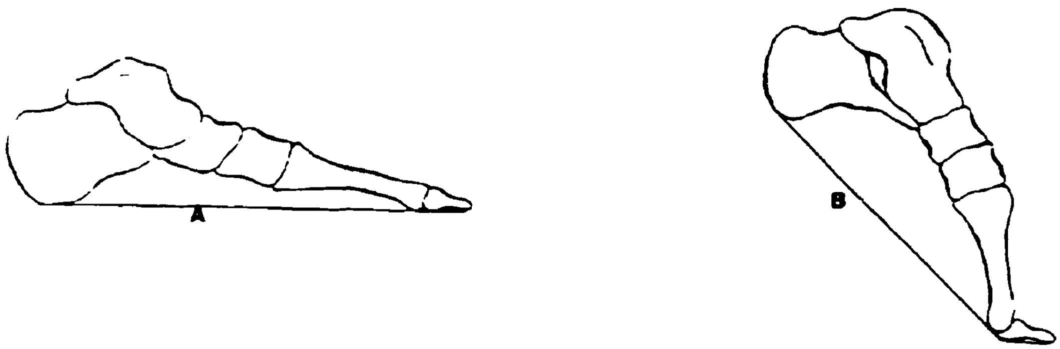


Figure 4.7 **The windlass mechanism as described by Hicks (1954).**

"A" represents flatfoot position of the plantar aponeurosis. As the hallux extends, the transverse tarsal and tarsometatarsal joints flex, acting as a rigid lever for push-off.

4.5 Summary

Weak push-off which has been observed in clubfoot patients may be linked to abnormal kinematics of the foot itself. Greater adduction, more inversion and residual plantarflexion were evident when relative motion of the forefoot and the hindfoot in clubfoot subjects were examined. The plantar aponeurosis responsible for both dorsiflexion and adduction of the forefoot relative to the hindfoot may be more rigid causing an inability of the foot to function efficiently as a rigid lever at the time of push-off.

5 ANKLE AND FIRST METATARSOPHALANGEAL JOINT DORSIFLEXION IN CHILDREN WITH CLUBFOOT

5.1 Introduction

Clubfoot is a foot deformity due to an abnormal relation between tarsal bones, such that the navicular and the calcaneus are displaced medially around the talus (Turco 1981). It is characterized by equinus, varus and adductus of the foot preventing normal function. Due to this bony structure abnormality, tissue contractures result. To modify the foot from its equinus position, surgery is performed. The most common type of surgery today is the posteromedial release, in which the posterior and medial muscles of the foot are lengthened. Although the foot attains a normal appearance after surgery, its function as compared to normal subjects has not been quantified. Attempts have been made to evaluate success of surgery using radiographs and passive motion measurements, but the results from these have been found to be highly variable.

Several studies (Laaveg *et al.* 1981, Ponseti 1981, Lau *et al.* 1989, Cohen-Sobel *et al.* 1993) have shown that the passive motion at the ankle is much lower for clubfoot subjects than for normal subjects when measured with a goniometer, but to date, active motion at the ankle joint has not been examined. This lack of dorsiflexion at the ankle has been correlated with qualitative functional results using the questionnaire of Ponseti and Laaveg (1980).

It has been shown that clubfoot children have abnormalities in toe-off (Hutchins 1985). A minimal amount of dorsiflexory motion of the great toe, 60 - 65°, is required to permit the foot to act as a rigid lever and to promote propulsion (Hetherington 1990). Although the first metatarsophalangeal (MTP) joint has not been examined in the clubfoot subject in the past, there is a possibility that the lack of propulsion of clubfoot children results due to a lack of dorsiflexion of the first MTP joint in addition to a lack of dorsiflexion at the ankle.

The purpose of this study was to examine the ankle and first MTP joint motion actively in a seated position as compared to gait kinematics in the sagittal plane. Bilateral and unilateral subjects who underwent a posteromedial release were compared to normal age- and gender-matched subjects to determine how active dorsiflexion of the ankle and first MTP joints affected dorsiflexion during stance and subsequent push-off.

5.2 Methods

5.2.1 Subjects

Six bilateral clubfoot subjects, 13 unilateral clubfoot subjects and 14 age- and gender-matched normal subjects participated in this study. Prior to their participation, written informed consent was obtained from each subject and a parent (Appendix 1). Ethics approval was obtained from the Conjoint Medical Ethics Board of the University of Calgary and the Alberta Children's Hospital. Each bilateral and unilateral clubfoot subject was age- and gender-matched with a normal subject.

5.2.2 Data Acquisition

5.2.2.1 Setup

Spherical reflective markers (1 cm in diameter) were attached to the skin using double-sided tape. Three markers were placed on the lower leg (head of fibula, mid-tibia, and distal fibula), three on the foot (head of the first metatarsus, posterior protrusion of the calcaneus, and head of fifth metatarsus), and one on the tip of the first phalange (Figure 5.1).

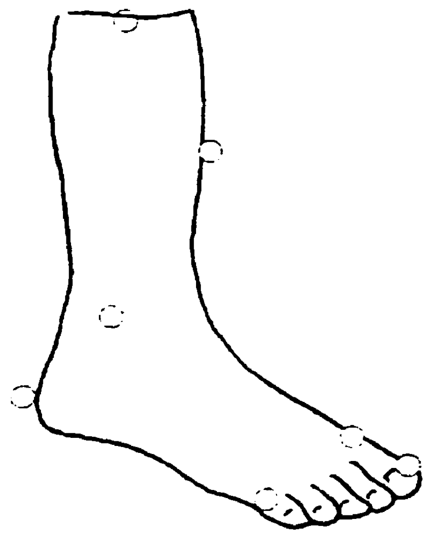


Figure 5.1 **Lateral view of the marker placement defining tibia, foot, and first MTP joint.**

Video data were collected using four high speed cameras (Motion Analysis Corporation, Santa Rosa, CA, USA) and 8 mm lenses. The cameras were placed to allow at least two cameras to see each marker at any given point in time. These cameras were linked to a SUN station which used EVa software (Motion Analysis Corporation, Santa Rosa, CA, USA) to collect the data from all four cameras. Calibration was performed using a cubic frame (1m x 1m x 1m) with eight spherical markers at known distances. A wand calibration was also performed.

5.2.2.2 Active Motion

In the past, passive motion of the ankle has been measured manually with the use of a goniometer. This type of motion has inherent errors associated with it as there are considerable inter-observer and intra-observer errors. Instead of examining the passive motion, our study examined the active motion at the ankle and the first MTP joint using a motion analysis system. Each subject was seated in a chair, then shown how to completely dorsiflex and plantarflex his/her ankle. Active motion of the first MTP joint was also obtained, by permitting the subject to rest his/her foot on a box, and plantarflexing and dorsiflexing the big toe.

Data collection consisted of video acquisition for 2 s. during which 240 frames of data were obtained while the subject was dorsiflexing and plantarflexing. Two trials were obtained, and the maximal amount of dorsiflexion and plantarflexion were used for statistical analysis.

5.2.2.3 Gait Data

The subject was allowed several practice trials along a runway (1.2 x 6 m) at a self-selected pace to feel comfortable with the procedure and to strike the force plate without changing his/her gait. The speed of each subject was determined by 2 photocells placed 1.94 m apart. Three trials for each leg were recorded at two walking speeds: self-selected walking speed and a fast pace. Each trial consisted of video acquisition for 2 s. during which 240 frames of data were obtained. Collection of the data was triggered by the researcher who used a handheld button to start recording as heel strike was about to occur.

Force data were collected using one force platform (Kistler 9865 B). This was synchronized with the cameras to be able to superimpose the forces with the positions in order to determine the stance phase of gait.

5.2.3 Data Analysis

Expert Vision software was used to track the position-time trajectories of each of the reflective markers. The data were smoothed using a fourth order Butterworth low-pass digital filter with a cutoff frequency of 12 Hz. These data were imported to KINTRAK (University of Calgary) and the angles at the ankle and first MTP joint during active motion and during gait were determined. The beginning of the stance phase was determined by initial contact with the force plate, and the end of stance was defined as lift off from the force plate. Thus stance was defined using contact of the foot with the force plate.

5.3 Results

Curves for the relative angles throughout the stance phase of gait for both the ankle and the first MTP joint were obtained (Figures 5.2 and 5.3).

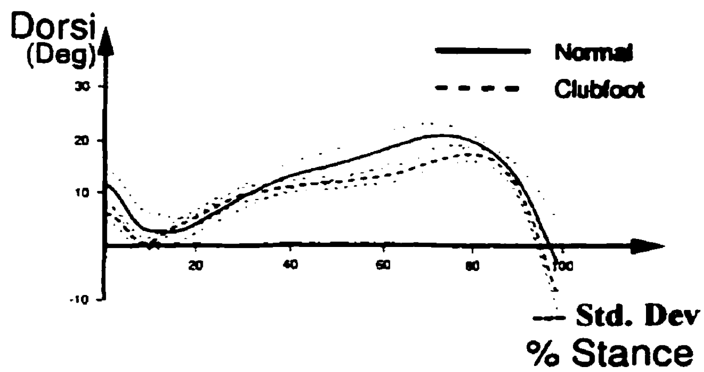


Figure 5.2: **Typical curves of ankle motion throughout the stance phase of gait for normal and clubfoot subjects.**

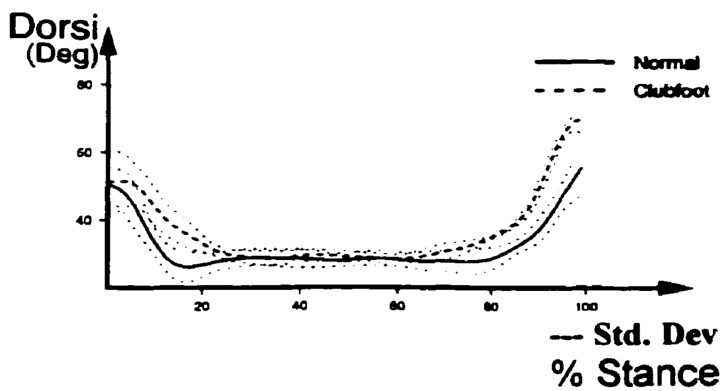


Figure 5.3 **Representative curves of toe dorsiflexion during gait.**

Using a two way analysis of variance, the maximal and minimal values were compared for plantarflexion (PF) and dorsiflexion (DF) of both the first MTP joint and the ankle. No significant differences were found between the right and left limb of any of the groups. There were however, significant differences between the normal limb of the unilateral clubfoot and the normal subjects, as well as between the clubfoot limb of the unilateral clubfoot subjects and their bilateral counterparts at the ankle joint (Table 5.1).

Table 5.1 Ankle motion during active measurements and gait.

* groups that were significantly different from normal.
^ groups that were significantly different from the bilateral group.

Motion (°)	Group 0 contralateral	Group 1 unilateral CF leg	Group 2 normal	Group 3 bilateral CF
Active Ankle PF	36.4 ^ (1.8)	29.4 * (2.7)	38.1 (1.6)	22.0* (3.6)
Active Ankle DF	18.0 (2.5)	9.1* (2.3)	22.3 (1.5)	12.2* (4.1)
Gait Ankle PF	18.6 (0.8)	17.8 (1.4)	18.7 (0.5)	17.5 (1.5)
Gait Ankle DF	8.8* (1.3)	8.4* (1.5)	15.0 (1.0)	7.9* (1.3)

Table 5.2 Toe motion during active measurements and gait.

	Group 0 contralateral	Group 1 unilateral CF leg	Group 2 normal	Group 3 bilateral CF
Active Toe PF	30.7 (3.2)	35.9 (3.2)	28.7 (2.0)	33.0 (3.5)
Active Toe DF	69.1 (5.2)	78.3 (6.8)	63.4 (1.8)	72.4 (6.3)
Gait Toe PF	30.3 (2.8)	27.5 (2.9)	22.0 (1.6)	21.6 (2.1)
Gait Toe DF	77.5 (2.9)	72.1 (3.6)	70.7 (1.8)	71.6 (4.7)

No significant differences in MTP joint motion were found at the self-selected pace (Table 5.2). At the faster of the two speeds, there was significantly greater plantarflexion of the first MTP joint of the contralateral leg of the unilateral clubfoot subjects than of the normal subjects.

5.4 Discussion

Both the active dorsiflexion and plantarflexion at the ankle were significantly less between the clubfoot limb of the unilateral clubfoot subjects and the bilateral clubfoot subjects as compared to normal subjects. Many studies have reported these differences using a passive motion technique with the leg extended (Karol *et al.* 1997, Hutchins et al. 1985, Laaveg and Ponseti 1980), as well as with radiographic techniques (Aronson *et al.* 1990). Determination of active motion using a Motion Analysis system gives results similar to those obtained by other techniques, yet the degree of plantarflexion and dorsiflexion can be obtained without the inter-observer and intra-observer errors.

The results obtained can be compared directly to gait analyses to indicate the function of the foot in a quantitative manner as the marker set is the same. Karol *et al.* (1997) found no significant decrease in the range of motion at the ankle of the clubfoot subject during gait as compared to the contralateral. We found similar results when comparing the clubfoot limb to the contralateral. We did find however, that there were significant differences in dorsiflexion at the ankle between the contralateral limb of unilateral clubfoot subjects and normal subjects. This suggests that the contralateral cannot be used as a normal comparison when reporting the success of treatment or ability to function normally in unilateral subjects. On the other hand, no significant differences were found between the plantarflexion motion at the ankle of our clubfoot subjects and their normal counterparts, or between the limbs of unilateral subjects.

As with previous studies (Bojsen-Moller and Lamoreux 1979, Joseph 1954, Mann and Hagy 1979), we found that the great toe was typically extended 20° from the axis of the metatarsal bones during the flatfoot phase of gait and was dorsiflexed during push-off. Our results indicated that dorsiflexion was about 70° during push-off for both the normal population (Mann and Hagy 1979) and the clubfoot subjects. The lack of push off in clubfoot subjects cannot be attributed to first MTP joint motion. This also agrees with Mann and Hagy (1979) and Stefanyshyn (1996) who suggest that propulsion does not occur at the MTP joint during push-off, since the toe is still dorsiflexed and would have to be extended in order to do work.

5.5 Summary

Although clinical measures of range of motion are used in assessing outcome of clubfoot surgery, the methods that have been commonly used were not reproducible. A method in which four motion analysis cameras are used to obtain three dimensional positions may provide a more accurate and better indication of the functional range of motion that occurs.

A lack of push-off has been found in clubfoot subjects. Dorsiflexion of the first MTP joint is unaffected by the clubfoot pathology and appears normal. The ankle joint dorsiflexion during both active motion and gait is lower for the clubfoot subjects than the normal subjects agreeing with the observations of Aronson and Puskarich (1990) and Cooper and Dietz (1995). Thus, the active range of motion of the ankle is a better indication of the functional success.

Finally, significant differences during the stance phase of gait were found between the contralateral limb of unilateral subjects and normal subjects. In future studies, it is necessary to examine the contralateral limb of a unilateral clubfoot subject in addition to normal subjects.

6 DISCUSSION

Although there are many different methods for testing surgical outcome of clubfoot, very few of these relate to the actual motion of the foot while undertaking everyday activities. In the past, radiological methods were always key factors in determining outcome. More recently, outcome measures have started incorporating patient satisfaction and functional measures. We performed a comprehensive gait analysis by looking at

a) kinematics and kinetics of the hip, knee and ankle to determine how the more proximal segments were compensating for lack of motion at the ankle.
b) the hindfoot and forefoot biomechanics to understand the differences between the clubfoot and the normal foot.
c) the motion of the first metatarsophalangeal joint to determine if limited motion may have caused the lack of push off that has been reported in the past.

By looking at the ground reaction forces, we showed that there was a weakness in push-off. Therein, we attempted to determine the cause of this weakness. By looking at the kinematics, it was important to note that deviations occurred at the ankle of clubfoot subjects. The differences in kinematics and kinetics between normal and clubfoot subjects at the hip and knee were a result of this lack of motion at the ankle. This lack of motion may be caused by residual bony deformities and muscle tightness from the original condition. In addition, the strength in the ankle plantarflexors was weak reducing the ability to plantarflex during push-off.

By examining the motion between the hindfoot and the forefoot, we found that in addition to the lack of ankle plantarflexion, there was also an insufficient amount of abduction and plantarflexion between the forefoot and the hindfoot. Both of these motions have been attributed to the windlass effect of the plantar aponeurosis. If there are residual contractures within the foot that interfere with the action of the plantar aponeurosis, a lack of push-off may result.

Finally, since the function of the plantar aponeurosis appeared to be affected, it was important to determine if first MTP joint motion also affected push-off. By examining the motion of the first MTP joint using a motion analysis system and passive motion techniques then correlating these with gait characteristics, we found that the first MTP joint was not affected in clubfoot children. We did find during this study that a motion analysis system could be used to determine accurately range of motion.

Generally, there is a lack of push-off in clubfoot children, but to relate this push-off to insufficient ankle motion simplifies the problem. Not only is there a lack of plantarflexion at the ankle, but there is also a lack of abduction and plantarflexion of the forefoot relative to the hindfoot. Although lack of ankle plantarflexion is evident, the lack of motion at the transverse tarsal joint may also be an important factor affecting push-off or lack thereof in clubfoot children.

7 CONCLUSIONS AND RECOMMENDATIONS

The outcome of clubfoot treatment can be assessed using a motion analysis system which can be used to quantify the relative forefoot and hindfoot motion in addition to hip, knee and ankle kinematics and kinetics. We found that push-off is not only affected by the lack of plantarflexion and strength at the ankle, but may be due to the insufficient amount of plantarflexion and abduction of the forefoot relative to the hindfoot.

By examining clubfoot treatment using a motion analysis system, different types of surgeries can be examined, and a quantifiable measure of outcome can be determined. This method is more reproducible than the methods that have been used in the past and instead of assessing motion in a passive manner, the motion of the foot in a functional situation is examined.

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Consent Form

Research Project: Three dimensional gait analysis of patients with clubfoot who have undergone posteromedial release.

Investigators: Claire Davies, Ron Zernicke, Gerhard Kiefer
Funding Agency: ATCO and TransAlta Utilities-on going support for ACH and Motion Analysis Laboratory at McCaig Centre.

This consent form, a copy of which has been given to you, is only part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. If you would like more detail about something mentioned here, or information not included here, please ask. Please take time to read this form carefully and understand any accompanying information.

Purpose:
We are studying the walking patterns of people who have had surgery to correct their clubfoot. The purpose of this study will be to see how the length of your foot affects your walking.

Explanation of your involvement:
First, you will fill in a brief questionnaire about your satisfaction with your clubfoot function. This will be used for comparison with other clubfoot studies.

You will be asked to change into a pair of loose shorts (which will be provided) and remove your shoes in an examination room. Your weight and height will then be recorded as well as the circumference of the calf on each of your legs. Your foot will also be examined to determine the length of your forefoot and then your ankle and toe range of motion will be measured using a goniometer.

Once changed, you will be asked to sit in a chair in which you will perform a series of leg exercises to determine the muscle strength in each of your legs. You will be strapped into this chair with two seatbelts so the chair can be moved around. You will have one ankle strapped to a piece of exercise machinery, and you will be asked to perform 20 leg extensions; this will be repeated with the other leg. The same procedure will be undertaken with your foot strapped into the device so the strength of your ankle can also be found.

You will go into the Human Motion Analysis Laboratory (Rm 492) in the Heritage Medical Research Building adjacent to Foothills Hospital. A total of 15 reflective balls (2 cm in diameter) will be taped on your hip, thigh, shank and foot to record the movement of each lower extremity segment as you walk. The placement of the markers will require that you wear shorts that may be rolled up. This may be somewhat embarrassing to you, but we will try to make you feel comfortable by providing you with privacy during testing. Only the researchers and technicians directly involved in the study will be allowed to view the videotape after the session is completed. The Human Motion Analysis Laboratory is in a private room of the McCaig Centre.

The data collection will involve walking along a 6 metre walkway while your motion is videotaped. You will be asked to walk along the runway approximately 5 times in each direction at a normal walking speed. You will also be asked to walk along the runway an additional 5 times in each direction at a fast pace. You will have sufficient time between trials to avoid fatigue.

The data collection involves the use of complex electronics equipment, and because of equipment problems, you might experience delays in data collection. Every effort will be taken to minimize this potential inconvenience, but if it occurs, you will be given the option of waiting while we fix the problem, rescheduling the data collection, or withdrawing from the study.

Potential Risks and Discomforts:
There is a possibility that a skin rash may develop from adhesive material used to apply the markers. The risk of long term irritation is very small. During the walking trials, you may trip and fall, but you are at no more risk than in a normal walking situation.

Confidentiality:
Only those persons directly involved with the project will have access to the data we collect from you. At no time during the description of our findings will your identity be revealed. When the findings are presented in oral or written form, only your age, gender, and the information collected in the study will be revealed. Without your separate written permission, no one other than the investigators will view your videotaped walking trials. After completion of the data collection and analysis, you will be welcome to review our findings and conclusions and to view your videotape.

Benefits:
Clubfoot has been treated using different surgical techniques for several decades, but it is difficult to assess function after the treatment. Gait analysis can be used to determine how a person compensates for the clubfoot and to understand strengths and weaknesses relative to an unaffected limb. These data can then be used in assessing outcomes of further surgery as well as understanding where weakness of the foot occurs.

Costs: There are no costs or fees associated with the participation in this study.

In the event that you suffer injury as a result of participating in this research, no compensation (or treatment) will be provided for you by ATCO, TransAlta Utilities, University of Calgary, the Calgary Regional Health Authority, Dr. Zernicke, Dr. Kiefer, or C. Davies.

You still have all your legal rights. Nothing said here about treatment or compensation in any way alters your right to recover damages.

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Your signature on this form indicates that you have understood to your satisfaction the information regarding participation in the research project and agreed to participate as a subject. In no way does this waive your legal rights nor release the investigators, sponsors, or involved institutions from their legal and professional responsibilities. You are free to withdraw from the study at any time. Your continued participation should be as informed as your initial consent, so you should feel free to ask for clarification or information throughout your participation. If you have any further questions concerning matters related to this research please contact:

Claire Davies 220-4327
Dr. Ron Zernicke 220-8666
Dr. Gerhard Kiefer 229-7824

If you have any questions concerning your participation in this project you may also contact the Office of Medical Bioethics, Faculty of Medicine, University of Calgary, at 220-7990.

Participant's Signature	Date
Parent's Signature	Date
Investigator's Signature	Date
Witness' Signature	Date

The investigator will, as appropriate, explain to your child the research and his or her involvement, and will seek his or her ongoing cooperation throughout the project.

Questionnaire for Determining Function of Clubfoot

Section I: To be filled in by subject

Please answer the following questions:

1) What is your birth date?___/___/___

2) I am
    a) very satisfied with the end result
    b) satisfied with the end result
    c) neither satisfied nor dissatisfied with the end result
    d) unsatisfied with the end result
    e) very unsatisfied with the end result
3) In my daily living, my clubfoot
    a) does not limit my activities
    b) occasionally limits my strenuous activities
    c) usually limits me in strenuous activities
    d) limits me occasionally in routine activities
    e) limits me in walking
4) My clubfoot
    a) is never painful
    b) occasionally causes mild pain during strenuous activities
    c) usually is painful after strenuous activities only
    d) is occasionally painful during routine activities
    e) is painful during walking

Section II

Position of heel when standing

a) heel varus, 0° or some heel valgus
b) heel varus 1-5 °
c) heel varus 6-10°
d) heel varus greater than10°

Passive Motion

a) Dorsiflexion
b) Total varus-valgus motion of heel _______°
c) Total anterior inversion-eversion of foot _______°

Gait

a) Normal
b) Can toe-walk
c) Can heel-walk
d) Limp
e) No heel-strike
f) Abnormal toe-off