GROUND REACTION FORCE PATTERNS
IN CHILDREN WITH
IDIOPATHIC UNILATERAL CLUBFEET

By

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ABSTRACT

Clubfoot is a common birth defect affecting 2-3 children per 100 live births. The child is born with a foot in equinus, forefoot adduction, and heel varus. The defect primarily lies within the subtalar joint, the articulation between the talus and calcaneus.

Assessment of the clubfoot, to date, depends upon clinical measurement, radiographic measurements, and observations of the child's gait. The clinical measurements are subjective in nature. While the radiographic measures are more objective, they have shown to be poorly correlated with the clinical outcome. The problem in assessing clubfeet is the lack of a dynamic objective assessment which correlates well with the clinical assessment.

The purpose of this study is examine the differences between ground reaction force patterns in children with normal feet versus children with clubfeet, and more specifically determine whether there is a significant correlation between subtalar motion and vertical moment.

Three groups of feet were used for the study: the first group included one foot from children with normal feet (n=16), the second group included the affected clubfoot of children with unilateral clubfoot (n=7), and the third group included the intact foot of the children with clubfoot (n=7). The children's feet were clinically examined by an orthopaedic resident, measuring ankle and subtalar range of motion, and heel position on stance. Ground reaction force data was collected with 3 trials for each group for each subject.

One way ANOVA's showed significant differences between the clubfoot group and the intact foot group and the normal foot group for all clinical parameters. Regression analysis showed that the net vertical moment correlated highly (r=.84) with the subtalar range of motion and heel position in the clubfoot and intact groups, however, not the normal group. For example, a more rigid, varus foot produced a greater internal net torque. The net anterior-posterior impulse correlated highly (r=.92) with ankle range of motion. Thus, an ankle with a greater range of motion produced a greater propulsive force.

The rigid and varus nature of the clubfoot does reduce the foot's ability to efficiently absorb and transmit the torque produced by the leg. The restricted ankle range of motion in the clubfoot also affects the ability for the foot to produce a normal powerful propulsive force during gait. This

limited propulsion may be cause by the current standard of treatment of the clubfoot. A surgeon could perform an anterior wedge osteotomy of the tibia instead of an achilles lengthening to obtain adequate dorsiflexion and maintain a strong plantarflexor muscle. Before any of these conclusions can be made with confidence, a study with more subjects needs to be undertaken.

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INTRODUCTION

Initially, clubfoot or talipes equinovarus was a term that indiscriminately described all deformed feet. The term is derived from latin, talus (ankle) and pes (foot), to distinguish a foot deformity of equinus and varus.

The gross pathologic changes seen on exam of the clubfoot are characteristic: the foot is plantar-flexed at the ankle, the hindfoot is inverted, and the mid and forefoot are adducted, inverted and in equinus position (Tachdjian, 1985).

The major task in the diagnosis of the clubfoot is determining whether the clubfoot is idiopathic (etiology unknown) or associated with other anomalies. There are many other anomalies or disorders associated with clubfoot, including meningomyelocele, arthrogryposis, cerebral palsy, tarsal coalitions, and congenital absence of the tibia. Treatment varies between these causes of the clubfoot, therefore, they must be ruled out before diagnosing the child to have an idiopathic clubfoot.

Evaluation of the clubfoot is done primarily through clinical examination of the foot, determining its range of motion and flexibility of the foot. Radiographic assessments are done in addition to define precisely the anatomic relationships of talocalcaneonavicular, tibiotalar, midtarsal, and tarsometatarsal joints (Tachdjian, 1985). Description of these relationships are determined by objective measurements from the radiograph.

The evaluation of the management of treatment has been primarily based on clinical measurements and radiographic factors including assessment of function (observing the child's gait), appearance of the foot, presence of pain or limping, standing heel position, joint range of motion, and muscular strength (Outerbridge, et al., 1988). Radiographically and clinically, one is not expected to obtain a normal foot. If the patient has no pain, is able to keep up to his/her peers, and can fit into regular shoes, the management is functionally successful. Overall, the assessment of the clubfoot is primarily static and subjective.

Numerous papers have been published concerning the clubfoot deformity in children. They discuss the specific pathology, etiology, biomechanics and treatment methods of this condition (Outerbridge, et al., 1988). However, little attention has been devoted to objective measurement of the dynamic function in patients with clubfoot (Otis &Bohne, 1986).

Objective measurements of gait of individuals with clubfeet is limited to two studies in the literature. One study only assessed the muscle action during gait using electromyography (Otis & Bohne, 1986). This study concluded that there were minor differences between the normal foot and clubfoot with respect to the medial gastrocnemius and the tibialis anterior muscles. The unilateral clubfoot had no significant differences however, the bilateral clubfoot had increased duration of the medial gastrocnemius. Brand, et al. (1981) examined surgically treated clubfeet with respect to centre of pressure path They concluded that there was no correlation between the centre of pressure path and the severity of the clinical deformity.

Since the advent of computerized gait analysis, many articles have been published to show the usefulness of such analyses for clinical purposes. The force plate, in particular, has been commonly used for measuring ground reaction forces during walking in amputees using prosthetics. The primary purpose of the force plate is to determine how well a person's leg or prosthesis absorbs forces at heel strike and how efficient propulsion is at toe off. If force plate data are combined with kinematic data, joint moments of force can also be calculated.

In the literature, the force plate has been traditionally used to look at vertical, anterior-posterior, and lateral impulses. The Kistler force plate also measures the degree of vertical moment produced. However, only two studies in the literature have used this variable (Close & Inman, 1953; Schoenhaus, et al., 1979). Both of these studies suggested that the degree of moment is a reflection of internal and external rotations of the leg during the stance phase in gait. Only Scheonhaus, et al. (1979) has tried to relate subtalar function specifically to the vertical moment (Mz) patterns obtained from the force plate. Their findings showed an initial external rotation at heel strike followed by a greater internal moment before mid stance, changing to an external moment ending with a small internal moment. The amplitudes of the moments remained relatively small which they explained to show the functional absorption of the rotational forces by the subtalar joint. They also studied several individual's gait with various pathological conditions of the hindfoot and compared the effects their disability had on torque. They found increasing amplitudes with increasing rigidity of the subtalar joint. In the clubfoot, pathological examination has shown the primary deformity lies within the subtalar joint. Thus, gait differences between the clubfoot and the normal foot could possibly be observed by examining the vertical moment patterns (Mz)

Statement of the Problem

Children with clubfeet appear to do well functionally based upon the subjective evaluation in the clinical setting. This study was aimed to address this subjective nature of evaluation by analysing the children's gait with the aid of a force plate to measure ground reaction forces. The study was designed to analyse the relationship between the clinical range of the motion data and the data obtained from the force plate (vertical, anterior-posterior, and vertical moment). However, it was felt to be imperative to first establish ground reaction force patterns and clinical range of motion norms for children with no functional abnormalities. Then, it is possible to compare the ground reaction force patterns between normal children and children with a clubfoot.

Hypothesis

The hypothesis in this study was that the net vertical moment would correlate significantly with the degree of valgus or varus during standing and the total range of motion in the subtalar joint. The expectation was that a foot in valgus will have a net external moment and varus foot will have a net internal moment. A foot with more rigidity would have greater moment peak amplitudes. The data obtained from the force plate would help differentiate between the children with a clubfoot and normal feet, and also the severity of clubfeet.

Significance

Children's Hospital and Sunny Hill Hospital in Vancouver, British Columbia are working together to develop a gait analysis laboratory. If vertical moment, as determined from the force plate, is a true indicator of subtalar motion, this could then be a tool for evaluation of treatment in children with clubfeet or other anomalies involving the hindfoot. Further objective research could then be done to compare different treatment methods.

Definitions of Terms

Clubfoot. A common congenital disorder of the foot which presents with the foot in equinus, the heel in varus and forefoot adduction.

Ground Reaction Force. The four orthogonal components of the ground reaction force are measured by a force platform. They represent the net vertical, anterior-posterior, medial-lateral forces, and vertical moment (torque) applied to the foot during the stance phase of gait.

Normalization. As subjects are unique in height, body mass, and cadence, the data are normalized to produce universal patterns which may be compared across subjects. Temporal data, expressed as a percentage of total stance duration allow the relative timing of events to be assessed. Components of the ground reaction force and moments of force for each subject are normalized to individual body mass (Winter, 1987).

Coefficient of Variation. The stride-to-stride variability in kinetic profiles may be quantified by the Coefficent of Variation (CV). This CV is equal to the root mean square of the standard deviation at each time interval divided by the mean magnitude of the signal over the entire stride. It is, therefore, a variability to signal ratio (Winter, 1983).

Assumptions

Sutherland (1986) studied the gait of children ages 1-7 years, examining all aspects of gait : velocity, cadence, stride length, kinematics, and kinetics, including joint moments of force. He showed that mature gait patterns are established by age 6. The assumption is made in this study that the differences seen in the gait parameters examined in this study will not be related to differences in development of the children.

Chapter 2

REVIEW OF LITERATURE

The clubfoot is one of the most common congenital foot deformities and was first described by Hippocrates around 400 BC. The average incidence of clubfoot is approximately 2.3 per 1000 births. The ratio of male to female is 2:1, and nearly 50% of all clubfeet are unilateral (Perlman, et al., 1987). The child is born with a foot in equinus, forefoot adduction and heel varus. Varying degrees of the deformity can be seen in the newborn. It may appear mild, being a slight exaggeration of the normal equinovarus position, or it may be so severe that the foot lies almost in contact with the medial border of the tibia (Turco, 1974).

Over the past 5 years, many papers have been published concerning the clubfoot deformity in children. This reflects the lack of understanding regarding the specific pathology, etiology, biomechanics and appropriate treatment methods for this condition (Outerbridge, et al., 1988). The management ranges from conservative casting and splinting to surgical intervention of soft and bony tissues with the goal of obtaining as normal a foot as possible. However, little attention has been devoted to objective measurement of gait in individuals with clubfoot (Otis & Bohne, 1986).

This section will examine the complexity of the clubfoot, briefly outlining the pathology, the theories behind the etiology, the diagnosis, and the treatment strategies of the clubfoot. A discussion will follow reviewing recent biomechanical studies of the clubfoot, considering the problems of analyzing gait in this population along with how more indepth investigations of the clubfoot may assist in the treatment of this condition.

PATHOLOGIC ANATOMY

A brief outline of the pathologic anatomy as described by (Turco, 1981) is included to give an overall understanding of the underlying changes and the relationships of the bones in the clubfoot.

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Of all the bones in the clubfoot, the talus is the least displaced but has the most changes. The most important and constant distortion is found in the neck of the talus. The neck has an increased medial deviation (15-30 degrees greater than normal) with the neck foreshortened and the usual constriction of the neck absent. The head of the talus is usually broader and flatter, and the facet for the navicular faces medially. The ankle is positioned in equinus with the anterior aspect of the talus out of the ankle mortice; thus, the talus has an abnormal surface and failed development of normal articulation contour.

The calcaneus is abnormally positioned rather than abnormally shaped. The posterior tuberosity of the calcaneus is displaced upwards and laterally, while the anterior end is displaced downward, medially, and inverted under the head of the talus. The normal shape is maintained except for the changes around the sustentaculum tali, which is displaced medially from its normal location under the head of the talus.

The navicular articular surfaces face medially to articulate with the medially deviated head and neck of the talus. In the severe clubfoot, the navicular may even articulate with the medial malleolus.

The cuboid involvement is controversial. Turco feels the changes at the calcaneocuboid joint are minimal when compared to the displacement of the calcaneus and navicular. Others emphasize a significant medial displacement of the cuboid.

The cuneiforms show minimal changes and the metatarsals even less.The medial migration and inversion of all five metatarsals cause the forefoot adduction. Plantar flexion of the forefoot on the hindfoot contributes to the composite equinus deformity and cavus.

Soft Tissue Contractures:

Posterior Contracture. (Tendo Achillis, tibiotalar capsule, talocalcaneal capsule, posterior talofibular ligament, calcanealfibular ligament): The posterior contractures resist correction of the equinus deformity. The posterior capsules of the tibiotalar and tibiocalcaneal joints are shortened. The talocalcaneal articulation is usually more shortened. The Achilles tendon is always contracted. The attachments are broader and are attached more distally on the medial surface of the calcaneus, thus the varus position of the heel.

Medial Plantar Contractures. (Tibialis posterior tendon, deltoid ligament, talonavicular capsule and spring ligament): The medial plantar contractures are the most important and resistant in the clubfoot. The fibrosis of the medial and plantar structures form a massive indistinguishable scar which maintains the navicular tuberosity and sustentaculum tali in close proximity with the medial malleolus. The tibialis posterior is shortened and its sheath is hypertrophied. The tendon insertions are abnormal and usually blends with the common mass of scar tissue. The flexor digitorum and hallicus longus muscles are shortened causing the flexion contractures of the toes. The contracted Henry's Knot restricts mobility of the navicular by its attachment to the undersurface of the navicular.

Subtalar Contractures. (Talocalcaneal interosseous ligament, bifurcated "Y" ligament): Fibrosis and shortening of talocalcaneal interosseous ligament increases with age. In the older child, this ligament may appear as an extremely thickened, dense mass of scar tissue that firmly binds together the calcaneus and talus.

Plantar Contractures. (Abductor hallicus, intrinsic toe flexors,quadratus plantae, plantar aponeurosis): The cavus deformity is seen in some of the newborns with a severe deformity but it is more commonly seen in the older child with an uncorrected foot. The plantar aponeurosis is contracted and is palpable as a tight subcutaneous fibrous band along the medial plantar surface of the foot of the older child. In the severe foot, the hallicus has accessory abnormal attachment or origin from the tendon sheaths of the tibialis anterior in addition to its normal medial plantar surface of the calcaneus. The calf is atrophied and diminished in bulk, which becomes more obvious as the child grows.

ETIOLOGY

The exact cause of talipes equinovarus is unknown, however, several theories have been described in the literature. The four most common theories are the intrauterine mechanical factors, a neuromuscular defect, an arrest of fetal development, and a primary germ plasm defect.

Intrauterine Mechanical Factors

The mechanical theory is the oldest theory advocated by Hippocrates (Tachdjian, 1985). He claimed that the fetal foot was forced into the equinovarus position by external mechanical forces which pressure the fetus against the uterine wall. Due to the rapid skeletal growth, the ligaments and muscles develop adaptive shortening and the tarsal bone, especially the talus, responding with a subsequent articular malalignment (Tachdjian, 1985). This theory was supported by subsequent studies done by Parker and Shattock (1884), Nutt (1925), and Browne (1934). However, this theory is not supported from the fact that the incidence of clubfoot is not increased in prenatal conditions that tend to overcrowd the uterus such as twinning, high birth weight, and hydramnios (Tachdjian, 1985).

Neuromuscular Defect

There are many theories that explain the clubfoot to be secondary to a neuromuscular dysfunction. Examples of some these theories are: a peroneal lesion caused by pressure at the intrauterine stage (McCauley, 1951); maldevelopment of striated muscle (Middleton, 1934); muscle imbalance due to dysplasia of the peroneals (Flinchum, 1953); and relative shortening of the degenerating muscle fibres during growth (Bechtol, 1950). Irani and Sherman (1963) sought to disprove this theory by demonstrating through routine histologic studies the absence of muscular, neural, or tendonus abnormalities. However, a more recent study by Issacs, et al. (1977), indicated evidence of neurogenic disease by histochemical and electron microscopic analysis of muscles from clubfeet.

Arrest of Fetal Development

The third theory is that talipes equinovarus is a result of an arrest of development of the foot in one of the physiologic phases of its embryonic life (Huter, 1863). Bohm (1929) demonstrated that there are physiologic positions of the embryonic development which resemble the clubfoot. He outlined four stages in the evolution of the human foot in the first half of prenatal life.

The first stage (2nd month) is characterized by marked equinus and severe adduction of the hind and forepart of the foot. The second stage (beginning 3rd month) shows the foot rotating into marked supination, with some equinus, and the first metatarsal is markedly adducted. In the third stage (middle 3rd month) the equinus decreases slightly but the marked supination and the metatarsus varus persists. By the fourth stage (4th month), the foot is in midsupination and slight metatarsus varus. The foot begins to rotate towards pronation and the leg gradually assumes the relative position seen in the adult human.

This theory is difficult to accept because Bohm could not explain the medial displacement of the talocalcaneonavicular joint, for this is not seen in any stage of development. In addition, the embryonic foot does not show distortion of the tarsals bones found in the clubfoot (Tachdjian, 1985).

Primary Germ Plasm Defect

A consistent finding in the clubfoot is the medial and plantar tilting of the head and neck of the talus, thus, the speculation was made of primary bone dysplasia (Tadchjian, 1985). The cartilagenous anlagen of the tarsal bones are fully formed by six weeks in the embryo. Therefore, Irani and Sherman (1963) proposed that the clubfoot is a result of a defective cartilaginous anlage produced by a primary germ plasm defect of the talus, developing in the first trimester of pregnancy.

According to Tadchjian (1985), there is more than one cause of congenital talipes equinovarus. In some cases it is due to primary germ plasm defect of the talus. In others, there may be a neuromuscular type of clubfoot in which the the paralysis, imbalance and fibrotic contracture of paralyzed muscles are the primary cause. There may be a primary ligamentous disorder with excess of myofibroblasts as the cellular cause of soft-tissue.

With respect to the etiology and the pathology of the clubfoot, Turco (1981) concludes that there are many factors responsible for the disagreement. A major reason for the disagreement has been the failure to differentiate idiopathic clubfoot from the deformity associated with multiple congenital anomalies. Because many conditions can cause talipes equinovarus, it is not surprising that the abnormalities will vary and will not be consistently the same in all feet. Another reason for the differing hypotheses is the inability and failure to distinguish secondary adapted changes from primary defects, especially from failure to appreciate that all the pathology evident at birth is not necessarily primary.

Further disagreement has occured because most dissections have been done on premature fetuses born with a clubfoot that is a local manifestation of a systemic syndrome, a neurologic disorder , or multiple congenital anomalies. Very few dissections have been carried out on true idiopathic clubfeet. Many of the specimens had spinal cord defects, which are notorious for creating variability in the clubfoot.

DIAGNOSIS AND EVALUATION

The major tasks in the diagnosis of the clubfoot is determining whether the clubfoot is idiopathic or associated with other anomalies, and whether the clubfoot is intrinsic (rigid) or extrinsic (flexible) (Perlman, et al., 1987).

There are many other anomalies or disorders associated with clubfoot, and a few to mention are: meningomyelocele, arthrogryposis, cerebral palsy, tarsal coalitions, and congenital absence of the tibia. Treatment varies between these origins to the clubfoot; therefore, they must be ruled out before diagnosing the child to have idiopathic clubfoot.

Comparing the two types of congenital clubfoot, the rigid form does not respond well to conservative treatment, and surgical intervention is almost inevitable. Unfortunately, the rigid intrinsic form is more common (Somppi, 1984).

Evaluation of the clubfoot is done primarily through clinical examination of the foot, determining the range of motion and the flexibility of the foot. Radiographic assessments are done in addition to define precisely the the anatomic relationships of talocalcaneonavicular, tibiotalar, midtarsal, and tarsometatarsal joints (Tadchjian,1985). Description of these relationships are determined by objective measurements from the radiograph. These are summarized in the following table.

Table 1. Average angular measurements of anterior-posterior and lateral projection of feet in normal and clubfeet (degrees)

Angle	Normal	Clubfoot
Anterior-posterior talocalcaneal	20 - 40	<15
Talar first metatarsal	0 --20	>15
Lateral talocalcaneal	35 - 55	<35

MANAGEMENT

Management of the clubfoot has been successful in many cases with manipulation of the foot and application of a cast, preferably within 24 hours after birth (Otis & Bohne, 1986). The foot treated successfully using conservative means has been assumed to result in a less rigid foot. However, this conservative treatment is not successful in a large number (60%) of feet, and surgical treatment must be performed. The goal of medical intervention is to correct the forefoot adduction, hindfoot varus, and finally the equinus in that order for maximal success. Initial surgery is performed on soft tissue (ie. Achilles tendon lengthening or posteromedial release), and if the foot is still resistant then bone surgery (ie. osteotomy or arthrodesis) is performed (Turco, 1986), thus resulting with a considerably rigid foot.

BIOMECHANICS

It is important to examine the anatomy of the normal foot and ankle as compared to the clubfoot with respect to the joint articulations involved before we can understand the biomechanics of the structure and the implications of any abnormalities.

Anatomy and Articulations of the Normal Foot

The ankle joint is an articulation between the talus, the tibia, and the fibula. The tibia articulates with the superior surface (trochlea) and the medial side of the talus, while the fibula articulates on the lateral side. The talus is wider anteriorly, thus securing the talus into the ankle mortise during dorsiflexion. The ankle joint articulates only in the sagittal plane.

The subtalar joint is the articulation between the talus and the calcaneus. There are three articulations involved in this joint. The posterior articulation is between the concave facet of the talus and the convex facet of the calcaneus. The middle articulation is between the facet on the undersurface of the talus and that on the sustentaculum tali of the calcaneus. The anterior articulation is between the convex undersurface of the head of the talus and a small concave facet on the calcaneus (Riegger, 1988). This joint is a simple single-axis joint which behaves like a mitered (oblique) hinge (Morris, 1977). As a result of the oblique rotation at this joint, the net articulation is in both the sagittal and the coronal planes.

The transverse tarsal joint consists of the talonavicular and the calcaneocubiod joints. The flexibility and angle of axes of these joint are directly related to the position of the subtalar joints. When the hindfoot is everted the axes of the joints are parallel and motion is quite free. However, during inversion, the axes are no longer parallel and the motion is restricted . Movement of this joint is primarily in the plane of abduction/adduction (Czerniecki, 1988).

<u>Anatomy and Articulations of the Clubfoot</u>

The primary differences in the clubfoot compared to the normal foot appear in the subtalar joint. Of all the bones in the clubfoot, the talus is least displaced but has the most changes. The bones surrounding the talus are adapting to these changes.

The neck of the talus has an increased medial deviation (15-30 deg.> normal), thus the articulation with the navicular is oriented in a more sagittal plane compared to the normal coronal plane. The medially displaced navicular may even articulate with the medial malleolus in very severe cases.

The posterior concave facet of the talus body is less well developed and more shallow and the plantar facets of the head often appear as one continuous flat surface which correlate with similar findings on the superior surface of the calcaneus. In addition the calcaneal posterior tuberosity is displaced upwards and laterally while the anterior end is displaced downward, medially, and inverted under the head of the talus. In the clubfoot, the articulations of the subtalar joint are considerably limited with increasing rigidity in the severe clubfoot (Turco, 1981).

Due to the equinus nature of the foot, only the posterior surface of the talus articulates with the ankle mortise. The anterior portion of the talus never articulates in the mortise, therefore, not developing the normal contours to articulate with the medial and lateral maleoli, thus restricting normal range of movement in the ankle.

Biomechanics of the Normal Foot

The motions of the foot are not independent of the rest of the lower extremity, but more importantly the foot must accommodate for what is happening proximally. During walking, rotation of the pelvis causes the femur, tibia and fibula to rotate about the long axis. The magnitude of this rotation increase progressively from pelvis to tibia (6 - 18 deg).

During the swing phase and early stance the tibia internally rotates. To keep the weight distributed over the long axis of the leg and to absorbed the forces at heel strike, the foot compensates with an eversion of the calcaneus. Eversion is initiated by two mechanisms. First, the point of contact between the floor and heel is lateral to the center of the ankle joint, where the weight of the body is transmitted to the talus. Second, loading the limb creates a valgus thrust on the subtalar joint (Perry, 1983; Wright, 1964). This eversion results in a pronation of the tarsalphalangeal joints which creates a supple midfoot for absorption of increased forces.

During midstance and push-off, the pelvis begins to rotate externally. Because the forefoot is now fixed on the ground, the lateral rotation is transmitted to the talus in the ankle mortise. The calcaneus in response, inverts under the talus resulting in supination of the foot. (Rodgers, 1988). The strong contractions of the triceps surae also tighten the plantar aponeurosis to create a rigid lever for push-off (Perry, 1983).

The ankle and foot act together in an oblique nature. During dorsiflexion, the hindfoot is often everted and and the midfoot pronated. During plantarflexion, the heel is inverted and the midfoot supinated. For normal kinematics during gait the ankle moves to a maximum of 9.6 deg of dorsiflexion and 19.8 deg of plantar flexion (Winter, 1987). The hindfoot moves into 10 degrees of valgus during heel strike and then returns to neutral or occasionally slight varus during push-off (Perry, 1983).

Biomechanics of the Clubfoot

The talus is an integral component to the biomechanics of the foot. Because the talus is involved in articulations on all of its sides, any changes to the shape of the talus will affect these articulations and the overall biomechanics of the foot.

In preparation for this study, a pilot study was performed to look at ground reaction forces in a sample of children with idiopathic clubfeet. There were two subjects with clubfeet- one subject had bilateral clubfeet, one had a unilateral clubfoot. These two were compared with the vertical torque patterns obtained from data existing in the lab from normal adult walking trials (n=9) The purpose of the study was to observe the ground reaction force children with clubfeet generate and how they differed from the normal data. Examined were the vertical (Fz), anterior-posterior (Fy) and medial-lateral (Fx) forces, and the vertical moment (Mz). All the force patterns showed relatively little difference between the type of feet examined. However, the vertical moment (Mz) was quite different. There were significant differences in gait patterns found in Mz (Figure 1). The vertical moment is the amount of rotational torque exerted around the vertical axis.

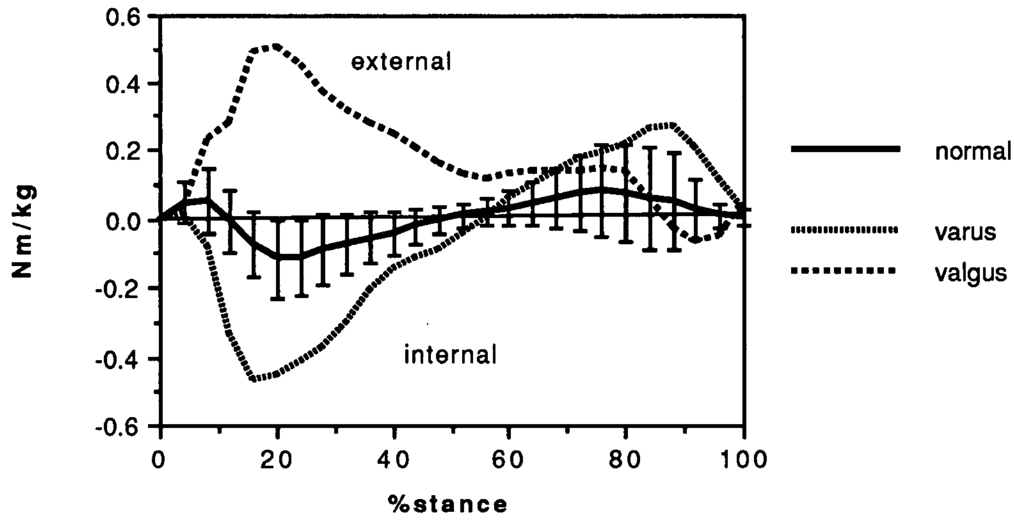

Figure 1. Vertical moment of the normal adults (n=9) and children with clubfeet (n=2)

The child with unilateral clubfoot had restricted dorsiflexion being only able to attain neutral position on his affected side, in addition to a varus heel position and rigid hindfoot and forefoot. The child with bilateral clubfeet had minimum active plantar flexion against body weight. She, too, had a rigid hindfoot held in considerable valgus, but had a supple forefoot.

If the role of the foot is to accommodate for the moment being produced at higher segment levels, the ideal foot should produce a small resultant net moment. In the normal child and the child with unilateral clubfoot's normal foot, the net resultant moment was relatively small compared to the clubfeet. For bilateral clubfeet there was a net residual external moment in both feet implying the foot's inability to compensate for the external moment created in the tibia and femur. For the more rigid subtalar joint, the net impulse was doubled. Because her feet were oriented in the valgus position, she could compensate for the internal moment but not the external moment. The opposite case was true for the unilateral clubfoot. Due to the varus nature and the rigidity of the hindfoot, the foot could not compensate as well for the internal moment.

The subtalar joint acts as a directional moment transmitter. The axial moments about the long axis of the foot or tibia induces moments about the long axis of the other segment (Czerneicki, 1983). For example, with the internal moment produced in the tibia during the initiation of stance, the foot rapidly pronates under the load of body weight. In contrast, the external rotation moments produced in the lower extremity induced from the accelerating swing in the contralateral limb results in a supination of the foot. The foot's primary role is to absorb and transmit forces (Tiberio, 1988). The restriction of the subtalar to absorb and transmit force in both of these children was apparent in the vertical free moment.

Loss of subtalar motion appeared to deny the leg the use of its horizontal rotational component. The horizontal moment between the leg and the foot increases, unless another source of horizontal rotation becomes available. In many patients who have had a triple arthrodesis or subtalar arthrodesis, deformity develops in the ankle joint. The talus becomes looser in the mortise. Traumatic arthritic changes are often then found (Close, et al.,1967). The growth potential in children allows joint remodelling leading to a "ball and socket ankle joint" (Perry, 1983)

In summary, in the normal child and in addition to the adult data, the net resultant moment is relatively small compared to the children with clubfeet. For clubfeet there appeared to be considerable differences in the net residual moment in implying the foot's inability to compensate for the moment created in the tibia and femur. This varied depending upon the suppleness of the subtalar joint and its varus or valgus nature. Therefore, because the subtalar joint was the primary deformity in clubfeet it seemed reasonable to relate the vertical moment as measured by a force platform to the severity of the clubfoot

Chapter 3

PROCEDURES

The project included three groups of children - one group of children had a unilateral idiopathic clubfoot., one group had two normal feet, and the third group had a foot with a subtalar tarsal coalition.

There is no mention in the literature of normal goniometric measures of the subtalar joint in children nor any studies that include force platform vertical moment measurements. However, it is noted that children's feet become more rigid as the foot develops towards a mature adult foot. A young child (10-15 mos) who has just learned to walk, has not developed the musculature in the foot for rigid propulsion, therefore, still has a relatively supple flat valgus foot. As the musculature develops, the foot becomes less flexible and maintains a more neutrally aligned foot. It was important to develop a baseline and a range of subtalar motion for children with normal feet across the developmental stages. Therefore, in addition to studying children with clubfeet and their normal foot, a group of children with normal feet was used, to compare the results of the children with clubfeet versus those with normal feet.

In order to ensure that it is indeed the subtalar joint that is producing the various results in the moment measured, an additional control group of children was included who have a tarsal coalition (a bony bridge) in the talocalcaneal joint which restricts movement only in this joint.

SUBJECT SELECTION

Normal feet group

Twenty children with normal feet were chosen from the general population. An emphasis in the selection was to find children that will be equally distributed across the range in ages from 5 to 13 years.

Clubfoot group

The selection criteria for this group was a child with idiopathic unilateral clubfoot who was between 5 and 13 years of age. Ten subjects were to be chosen for this study.

They were selected from the Orthopaedic clinics at BC Children's Hospital. The parents were asked for their children to be part of the study during routine clinical visits, at which time permission for further contact regarding the study was sought.

Tarsal coalition group:

Five children were to be chosen for this group. The selection criteria for this group were children who have a unilateral talocalcaneal coalition, who were currently asymptomatic, and have 10 degrees or less of total subtalar range of motion. They, too, were selected from the Orthopaedic clinics at BC Children's Hospital.

Parents of all the children were phoned to set up an appropriate time for them to come to the Biomechanics Lab at UBC. Any child who had a history of musculoskeletal injury or other anomalies in the lower extremities were excluded from the study.

DATA COLLECTION

Clinical data collection

Each subject was brought into the lab for orientation of the facilities and protocol. Prior to the gait analysis a clinical assessment of the feet was performed. This was performed by an orthopaedic resident who was well trained in clinical assessment of foot deformities. The variables measured were ankle dorsiflexion and plantar flexion, subtalar inversion and eversion, standing heel position, and thigh foot angle.

Both the ankle measurements and the subtalar measurements were performed as described by Oatis (1988) and Elveru, et al., (1988b). Elveru, et al.,(1988a) showed intratester reliability for goniometer measures of the foot and ankle of .85. The ankle range of motion measures were passive ranges using a plastic goniometer. The subtalar motion was defined as the degree of total passive range of motion from maximum varus to maximum valgus (see Figure 2).

The weightbearing heel position in standing was measured with a plastic goniometer to determine degree of varus or valgus deformity on stance. The measurement was put on a continuum with neutral being "0". A degree of measure in the valgus direction was negative, and in the varus direction was positive. Both feet of the all children were used for all measurements and recorded.

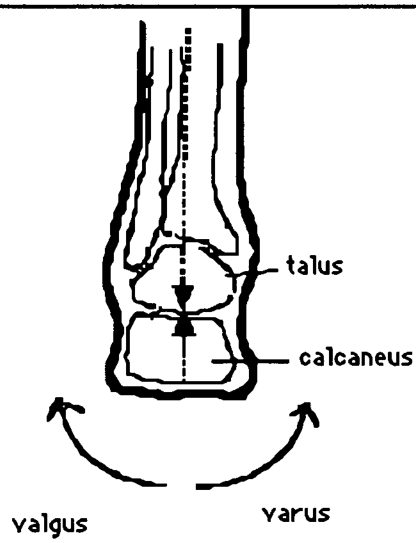

Figure 2. Total subtalar motion is the degree of motion from maximum varus to maximum valgus measured passively.

In several studies there have shown to be significant differences between the clubfoot side and the normal side of patients with a unilateral clubfoot (Aronson & Puskarich, 1990; Brand, et al., 1981; Otis & Bohne, 1986). It has been suggested that the calf girth represents plantarflexor power in these patients. Therefore, we included this measurement in our study.

Kinetic Data Collection

The most common force acting on the body is gravity, which acts on the foot during standing, walking, or running. This force vector is three-dimensional and consists of a vertical component plus two shear components acting along the force plate surface.

Ground reaction forces were measured using a Kistler Model 9261-A multi-component force platform flush mounted in a 12 metre indoor walkway. This is a piezoelectric force plate (Figure 3).

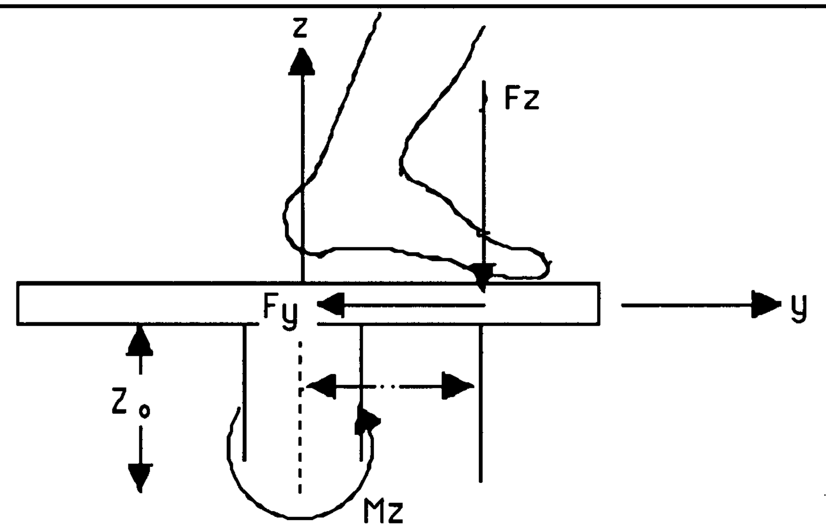

Figure 3. Central support type force plate showing the location of the centre of pressure of the forces and the moments involved. (adapted from Winter,1990)

The action of the foot acts downward (Fz) , and the anterior-posterior shear force of the foot (Fy) can act either forward or backward. If we sum the moments acting about the central axis of the support, we get:

$$Mz - Fz(y) + Fy(z_o) = 0 \qquad \text{Eq. 1}$$

where Mz = bending moment about axis or rotation of support
z_o = distance from support axis to force plate surface

This study analyzed the three components recorded from this device: vertical force (Fz), anterior-posterior force (Fy), and the vertical moment (Mz).

The force plate output was sampled through a 12 bit analog-to-digital converter at the rate of 100 Hz/channel, interfaced to a Data General 20 desktop computer. The child's natural walking speed was measured using photocells placed 3.25 m apart on each side of the platform.

Sufficient practice was permitted to ensure that contact with the force platform was made with a smooth, unbroken stride at the subjects' natural walking cadence while barefoot. Trials which differed more than 5% of subject's average speed or for which targeting was evident were rejected. The goal was to attain data from 3 successful trials from each leg at walking speed for all subjects.

DATA ANALYSIS

The ground reaction force data was initially manipulated on the Data General 20 desktop computer. In order to compare between subjects, the total stance duration was normalized to 100% (50 data points) and the three components of the ground reaction force were normalized by individual body mass. The normalized data were averaged for the three components from three accepted trials of each leg for each subject. The above calculations were performed using the Ensemble program of the UBC Biomechanics Lab. The program's output provided a spreadsheet for each averaged ensemble containing the mean, the standard deviation, minus one standard deviation and plus one standard deviation. These spreadsheets were then transferred to a Macintosh SE/30 computer through a telecommunications program, BLAST.

Once the data were transferred onto the Macintosh, the spreadsheets were manipulated and organized for a graphics program using Microsoft Excel 2.2. The individualized Excel spreadsheets were then imported into a graphics program called Deltagraph. The averaged plots for the three components of ground reaction force for each leg on each subject were done (Appendix B). For comparisons between groups of subjects, the mean force data for the groups: normals (left and right), clubfoot (clubfoot and intact) and tarsal coalition (coalition and intact) for the three force patterns were calculated in Excel and plotted using Deltagraph.

The statistical analysis were performed using Statview II and Systat 5.0 for the Macintosh. Due to the inter-dependency of the normal right and left feet, statistical comparisons to the normal group should only be made to either the right or left measurement. By the flip of a coin it was decided that the left leg be used for statistical analysis.

Chapter 4

RESULTS

GROUP DESCRIPTIONS

The **normal** group consisted of 22 children for enrollment into the study. Five children were excluded from the study. These children were excluded for two reasons: technical difficulties in data collection due to computer problems, or difficulties due to a child's cooperation in walking at a consistent speed or targeting the force plate. The data from the remaining 17 children were used for analysis. Sixteen of these children were normal, healthy children who had no history of injury or illness that would affect their gait.

One child (#12) was born with mild tibial torsion that was treated with Denis-Browne boots and bar. She was an athletic girl involved in track and field, and long distance running. Her clinical assessment did not reveal any obvious deformity, therefore, we included her in the group of normals. For this group, the average age of the children was 8.9 years (range 5-13). There were 9 females and 9 males.

The **clubfoot** group consisted of 8 children. One child was excluded due to lack of cooperation. He was the youngest child to be tested (4.8 yrs). The data from the remaining 7 children were used for analysis. All these children were born with an idiopathic unilateral clubfoot for which they were treated at birth at the BC Children's Hospital. Four children had a right clubfoot and three had a left clubfoot. There were 2 females and 5 males. The average age was 7.7 years (range 6-11). Since birth one of the children has had a postero-medial tendon lengthening, two had the tendo-achilles lengthened, and the remaining four children had only serial manipulation and casting for management of their clubfeet. All the children's outcome were considered good to excellent from a orthopaedic perspective. All the children were active in sports or clubs and felt they could keep up with their friends at school. None of the children had problems with pain during walking.

The **tarsal coalition** group consisted of only 2 children. It was difficult to find children with this problem who had not been treated or fit into the specified age group. The female subject (age 13 yrs) had bilateral tarsal coalition which included both the subtalar and the calcaneal -navicular joint. She had not yet been treated but was scheduled for surgery for her left foot following the assessment. On clinical exam, the left foot was more symptomatic and rigid, particularly in the subtalar joint and on ankle dorsiflexion. On the day of assessment she was not experiencing any pain.

The male subject (age 14yrs) had an unilateral subtalar tarsal coalition which had been treated, but on clinical examination the subtalar joint was still considerably rigid. He was totally asymptomatic.

Due to this heterogeneous group and the small numbers, this group could not be included into the comparative statistical analyses between the different groups. This group could only be used for descriptive and more subjective comparisons.

Summary: It was difficult to obtain data on some children due to their lack of cooperation and short attentions span; thus, a couple of normal children have only data for one side. Also, there were some technical difficulties with the amplifier used for the force plate for the last two children with clubfeet (subject #'s 39 & 40). Data was obtained for the vertical and A-P forces; however, the computer could not calculate the vertical moment. Therefore, the statistics in this study are based on 16 normal children's left foot and 7 children with clubfeet (intact and clubfoot) for vertical and A-P forces. Vertical moment statistics is based on 16 normal left feet and only 5 children with an intact and clubfoot.

CLINICAL ASSESSMENT

For the clinical measurements, it was not surprising to see the significant reduction in range of motion for the ankle and subtalar joints in the clubfoot (Table 2). The clubfoot had significantly less range of motion in all parameters except calf girth (Table 3). The intact leg of the children with clubfeet also had a significant decrease in range of motion on dorsiflexion, and subtalar inversion.

Table 2. Group means for clinical measurements

	Clubfoot	Intact	Normal L	Normal R
Dorsiflexion	-.714	7.57	15.72	15.44
Plantarflexion	34.14	49.0	45.6	46.33
Ankle ROM	33.28	56.57	61.33	61.78
Eversion	5.57	16.86	16.78	13.78
Inversion	18.14	26.57	28.94	32.23
Subtalar ROM	23.7	43.14	46.17	47.0
Heel position	1.14	6.0	5.89	4.39
Calf Girth	24.5	28.1	27.9	27.4

Table 3. Significant difference between group means for clinical measurements ranked by progression of score

Dorsiflexion	-0.71	7.57	15.44	15.72
Plantarflexion	34.14	45.60	46.33	49.00
Ankle ROM	33.28	56.57	61.33	61.78
Eversion	5.57	13.78	16.78	16.86
Inversion	18.14	26.57	28.94	32.23
Subtalar ROM	23.70	43.14	46.17	47.00
Heel position	1.14	4.39	5.89	6.00
Calf Girth	24.5	27.4	27.9	28.1

* cells underlined showed significant difference p<.05

The findings on clinical examination of the children with a clubfoot and children with normal feet demonstrate the clubfoot is rigid in the subtalar joint and the ankle joint. Many of the clubfeet do not attain even a plantigrade foot.

It is interesting to note the the restricted ankle range of motion is not only with the clubfoot but also with the intact foot of the children with clubfeet. The intact foot is significantly restricted in dorsiflexion.

The normal children demonstrate no significant differences between one side to the other side for any of the measurements.

The children with clubfeet walked on average 1.30 m/s while the normal children walked 1.48m/s. This is a non-significant difference using a one tailed student's t-test (p=.055).

GROUND REACTION FORCES

The ground reaction force (GRF) data were examined in several ways. Initially, the data were analyzed quantitatively by determining the peak forces for the three components at heel strike and toe off, and the net vertical moment for each individual and averaging them across the groups (Table 4).

Table 4. Average peak forces and net impulses for each group

	Clubfoot (n=5)	Intact (n=5)	Normal (n=16)
Internal Moment (Nm/kg)	.304	.241	.154
External Moment (Nm/kg)	.109	.196	.232
++ Net Moment (Nms/kg)*	.031	-.012	-.034
++ Vertical at Heel Strike (N/kg)	10.89	11.62	12.76
Vertical at Toe Off (N/kg)	10.34	11.1	10.38
Anterior (N/kg)	2.07	2.08	2.34
++ Posterior (N/kg)	2.28	2.73	2.8
Net Anterior-Posterior	-.15	-.19	-.12

* positive value implies internal direction and negative implies external direction
++ ANOVA post hoc (Fisher PLSD) test finds significant difference between the clubfoot and normal groups (p<.05).

Using a one-way Anova, the Fisher PLSD post hoc test indicated a significant difference between the clubfoot and the normal foot for net moment, the vertical force at heel strike and the posterior force at toe off. These differences are illustrated in the following graphs of the three groups with respect to the different ground reaction forces (Figure 4-6).

The anterior-posterior forces (A-P) (Figure 4) show an obvious amplitude difference in both the braking (anterior) force and propulsive (posterior) force between the normal and the clubfoot. However, a statistical analysis indicated a larger difference in propulsion. The net anterior-posterior forces showed a larger net posterior force or propulsion for the clubfoot and intact group over the normals. The propulsive phase begins a little earlier in the clubfoot and intact groups compared to the normals.

The peak vertical forces (FZ) (Table 4) showed a significant decrease for the clubfoot at heel strike compared to the normal foot. This can be seen on the graph (Figure 5). The heel strike and toe off peaks are consistent for all three groups.

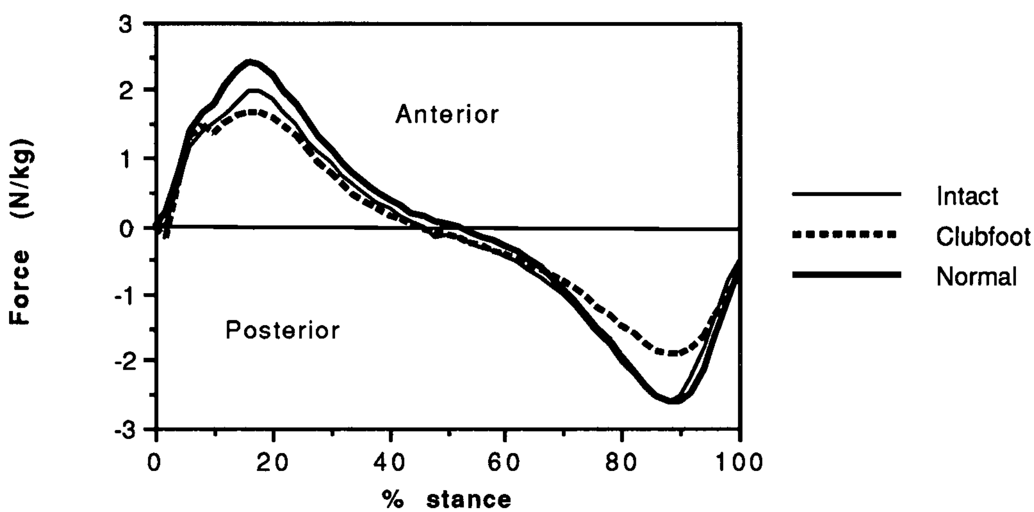

Figure 4 Averaged anterior-posterior forces

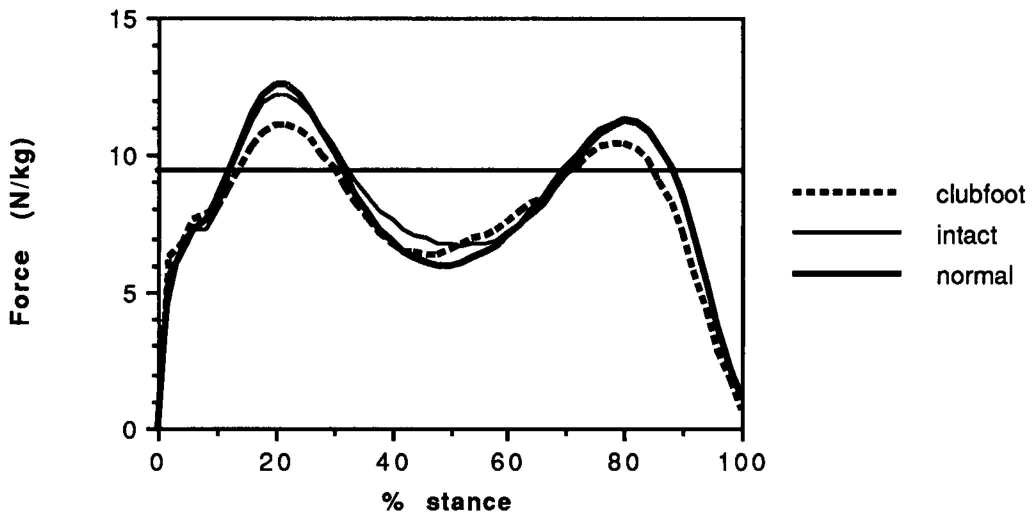

Figure 5. Averaged vertical forces

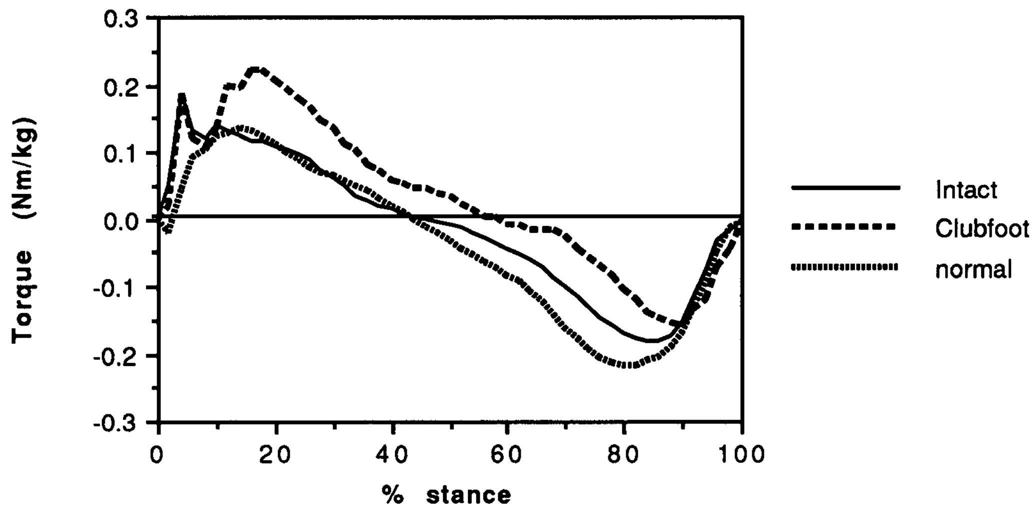

Figure 6. Average vertical moment patterns

The vertical moment (MZ) (Table 4) also showed statistically significant differences. The clubfoot has a net internal moment while the normal and intact feet have a net external moment. These differences can be observed in Figure 6.

There is a pattern noticeable on all graphs with respect to the clubfoot which is not seen in the normal leg group graphs. There is a slight peak at heel strike prior to the expected peak early in the stance phase. This is most noticeable in the vertical moment graphs but is also seen in the vertical and A-P forces.

RELATIONSHIPS BETWEEN CLINICAL AND GRF DATA

Vertical Moment

The original hypothesis of this study was that the net vertical moment as measured with a Kistler force platform would correlate significantly with the degree of valgus or varus and the total range of motion in the subtalar joint. The expectation was that a foot in valgus would have a net external moment and and varus foot would have a net internal moment. A foot with more rigidity would have greater moment peak amplitudes. The data obtained from the force plate would help differentiate between the children with a clubfoot and normal feet, and also the severity of clubfeet.

A regression analysis was performed to test the original hypothesis. This analysis was done with all subjects in one group and then examined in the individual groups. The independent variables chosen for the regression analysis were heel position, subtalar range of motion. The dependent variable was vertical moment (Mz). The correlation between the heel position and subtalar range of motion versus the net moment for all subjects in one group was .324, with an adjusted r^2=.027. The analysis done with the groups separated showed a much stronger correlation between the independent variables with Mz (Table 5) for the clubfoot and the intact group versus the normal group. All these correlations, however, are non-significant ($p<.05$).

Table 5. Correlations (and adjusted r^2) between subtalar range of motion (Sub) and heel position (Heel) with Net Moment (Mz) for the three groups.

	Sub x Mz	Heel x Mz	(Heel + Sub) x Mz
Normal (n=16)	.332 (r^2=.11)	.369 (r^2=.08)	.349 (r^2=.005)
Intact (n=5)	.178 (r^2=.03)	-.627 (r^2=.19)	.909 (r^2=.65)
Clubfoot (n=5)	.811 (r^2=.32)	-.226 (r^2=.05)	.844 (r^2=.42)

Net Anterior-Posterior Force

The clinical data demonstrated a significant difference in ankle range of motion between the clubfoot and the other two groups (Table 3). This reduction in ankle range of motion is a cummulative result of a significant restriction in dorsiflexion and plantarflexion. Propulsion during gait requires an active push off phase produced by extension at the hip and knee, and ankle plantarflexion (provided that the foot began in dorsiflexion). From the ground reaction force data, it was observed that the propulsive phase was significantly reduced in the clubfoot group (Figure 5). Considering the relationship between the ankle range of motion and the propulsive ability of a foot, a polynomial regression was performed between the two to examine the relationship between the ankle range of motion and the net anterior-posterior forces. The relationship expected was that the greater the ankle range of motion, the larger the propulsive phase would be. The analysis was performed using all subjects in one group and then dividing the groups for separate analyses. Using all subjects, the correlation between ankle range of motion and net anterior-posterior force was .46 (r^2=.21). For the clubfoot, intact and normal groups respectively the correlations were .92 (r^2=.84), .96 (r^2=.91), and .40 (r^2=.16). The correlations were higher in the clubfoot and intact groups versus the normal group.

GRF Pattern Trends

As mentioned earlier, the clubfoot and intact groups have a spike on the vertical moment ground reaction forces at heel strike (Figure 6). These are observed on the individual data plots, most noticeably in the vertical moments and the anterior-posterior forces. At heel strike, the primary force absorption is performed through the subtalar joint. This peak may reflect the limited range of motion in the clubfoot. To look at this phenomena more objectively, each mean plot for each subject was examined for presence of a spike at heel strike (see Appendix A for individual mean plots). If a spike was present on at least two of the three components of ground reaction for a given subject's side, a value of "1" was given, and if no spike was present a value of "0" was given. A 2x3 ANOVA was performed comparing the subtalar range of motion between the individual plots which received a "1" versus a "0" value for spike with respect to each group. The results are summarized in the following table.

Table 6. Differences between subtalar range of motion (degrees) between those subjects who showed spiking at heel strike ("1") and those who did not ("0").

	"1"	"0"	p-value
All Subjects	35	43.5	.02
Normal	42.6	46.3	.06
Intact	45.3	41.5	.33
Clubfoot	21.2	30	.14

As a total group of subjects, irrespective of the condition of the foot (i.e. club vs. normal), there was a significant difference in subtalar range of motion between those which presented with spiking at heel strike and those who did not. However, this significant difference did not remain after subdividing the data into their groups.

Chapter 5

DISCUSSION

VERTICAL MOMENT

Vertical moment is the rotating force the foot creates against the ground. In this study vertical moment correlated highly with a combination of the child's subtalar range of motion and the child's heel position during standing in those children who had a clubfoot. This correlation was less high in the normal group.

The heel position represents the natural position for the heel to be in during static weight-bearing. For the normal feet and the intact foot, the heel was in slight valgus between 4 and 6 degrees. For the clubfoot, the position was almost neutral (1 degree of valgus). The varus deformity in the clubfoot is a critical factor to consider when treating the clubfoot. Children with an uncorrected clubfoot have severe varus deformity and will often bear weight entirely on the lateral aspect of the foot and sometimes including the dorsum of the foot. Even though in normal children, a foot in slight valgus is the norm, surgeons treating the clubfoot will be satisfied with a heel in neutral or minimal varus.

In addition to obtaining a neutral heel, an important aspect to consider is the degree of motion the subtalar joint will still have. Compared to the normal feet, the clubfoot had 50% of the total subtalar range of motion. On average the clubfoot can obtain only one third of the eversion that the normal foot obtains including some limitation in inversion as well. Not only is the purpose of the treatment of the hindfoot deformity to obtain positional neutrality of hindfoot but also to keep it as supple as possible considering the dynamic function of the hindfoot.

The hypothesis developed for this study was based on a small pilot study including two children with clubfeet. One had a residual varus deformity while the other had a valgus or calcaneal deformity. Both had considerable rigidity in their subtalar range of motion. The ground reaction force studies on these two children resulted with a high net external vertical moment for the valgus foot and a high internal net vertical moment for the varus foot. The evidence of the subtalar joint rigidity was shown by increased magnitude of the moments.

The hypothesis was that the net vertical moment would correlate with the degree of valgus or varus and the total range of motion in the subtalar joint with the expectation being that a foot in valgus would have a net external moment and and varus foot will have a net internal moment and the subtalar joint's rigidity would exaggerate the directional trends. As a result, these relationship would help differentiate between the children with a clubfoot and normal feet, and also the severity of clubfeet.

As a group, the children with a clubfoot did show a significant difference in net vertical moment as compared to their normal peers. As expected, the direction of the net moment was internal for the clubfoot and external for the normal feet, with strong correlations for individual subjects between the heel position and subtalar range of motion with the net moment. Thus, the more inverted and rigid foot resulted in a large net internal moment, while the more flexible everted foot resulted in a smaller but external moment. This relationship was much stronger with the clubfeet and the intact feet as compared to the normal group. In spite of the high correlations in the clubfoot group, statistically the correlation was insignificant. The lack of significance may be due to the small number of subjects (n=5) in the group.

The differences found in correlations for the normal group and the clubfoot and intact groups may be due to differences in the degrees of the freedom in the clubfoot and the normal foot. For this study purposes, the clubfoot's deformity has been overly simplified. The deformity is more complex than can be expressed by simply analyzing it by its hindfoot and ankle deformities. As described in the anatomy section, the talus has the most significant and constant distortion. The neck is medially deviated (15-30 degrees greater than normal) with the neck foreshortened and the usual constriction of the neck absent. The head of the talus is usually broader and flatter, and the facet for the navicular faces medially. This medial deviation of the talus neck results in a varus and supinated forefoot. The changes in the hindfoot are reflected more proximally. The mid and forefoot in the clubfoot is often more rigid than in the normal foot. This, unfortunately, is difficult to measure quantitatively.

The subtalar joint functions in a three dimensional manner in the normal foot during gait. There is a combination of inversion and eversion along with rotation around the vertical axis. The rotation of the talus over the calcaneus is actually the key part of the torque transmitting role of the subtalar joint. However in this study, for clinical subtalar function, only a two dimensional measurement was taken to represent the three-dimensional joint. This is may not be a true assessment of the function of the subtalar joint. In addition to the degree of inversion and eversion,one could measure the angle between the longitudinal axis of the foot and the transmalleolar axis to describe the rotational capabilities of the subtalar joint. However, this measurement is difficult to obtain reliably.

The high correlations obtained in the clubfoot group is probably due to overall rigidity of the foot, both the hindfoot and forefoot, reducing the degrees of mechanical freedom in the foot. Thus, the overall rigidity allows one to isolate the significant joints (ankle and subtalar) in the clubfoot and ignore the smaller, less significant joints which may play a more significant, corporate role in the normal foot.

If the above explanation holds true for the differences seen in correlations between the clubfoot and normal foot, then this poses a problem for explanation of the high correlations found in the intact group of the children with clubfeet. The intact foot had comparatively normal range of motion and heel position for the subtalar joint. Generally, on examination, these feet are supple in the mid and forefoot as well. One possible explanation to account for this correlation would be that the dynamics of the clubfoot affect the function of the intact foot. The decreased torsion transmission capabilities of the clubfoot side may result in exaggerated torque measurements on the contralateral side. The two sides will always be interdependent to some degree and it is difficult to determine what are the most important contributing factors.

It was proposed initially in this study to include a group of subjects who had an isolated subtalar arthrodesis to act as a control group for the clubfoot subjects. Unfortunately, the pool of number of these subjects was overestimated. As mentioned above, the study has intentionally ignored the mid and forefoot deformities of the clubfoot and simply emphasized the subtalar deformity. To address the issue of mid and forefoot involvement in the clubfoot, it would be important to still control for isolated subtalar movement, if possible.

The subjective analysis of all the ground reaction force patterns, but more specifically the vertical moment force patterns, showed a spike at early heel strike in the subjects with a reduced subtalar range of motion of which this limitation is almost always in eversion (pronation). At heel strike, the foot is pronating in order to absorb the rotational forces produced by the femur and tibia over the foot. If the foot originates in a more than usual varus position at heel strike, its shock absorption ability would be initially limited, resulting in an early internal peak. The observed peak was usually followed by the expected force patterns. In addition, this peak was often more definitive in the anterior-posterior forces which may also indicate altered hindfoot mechanics at heel strike (Appendix B).

The subjective comparison of the force patterns may be a simple tool to alert one to possible hindfoot limitations in a subject, however, it does not reflect the degree of limitation. The magnitude of the peak does not correlate with the severity of hindfoot rigidity.

The lack of literature describing work using the vertical moment measurement (Mz) off the force plate raises a concern regarding the validity of the measurement and its reliability. In this study the variability of the Mz patterns was extremely high with the average coefficient of variation of 60% for the normal children and 90% for those with clubfeet. The reliability is questionable. Sutherland (Personal communication, May 12, 1991) has documented torque patterns in his work but refuses to interpret the data because of its high variability stating that the Mz measurements are totally unreliable and questions what it really measures. These cautionary comments must be seriously considered, yet it would be difficult to totally disregard the significant differences observed in the clubfeet on Mz. The validity could be addressed by performing a simulataneous kinematic analysis of the vertical rotations of the leg and ankle with ground reaction forces during gait to determine the primary joints responsible for torsion production and absorption.

HORIZONTAL PROPULSION

The clubfoot is a complex deformity involving the hindfoot, the subtalar joint, the midfoot and forefoot. However, the majority of the deformity and often recurring problems are the result of the hindfoot. This study demonstrated that the abnormality significantly restricts motion in the clubfoot as compared to the normal foot in all planes. The greatest limitations are in dorsiflexion and subtalar eversion.

On average the clubfoot barely attains a plantigrade foot . This is one of the goals of treatment of the equinus deformity. If the foot is neutral (plantigrade) on stance, treatment is considered a success. Sometimes in treatment of the equinus deformity by most commomly a tendo-achilles lengthening, over-correction may result, giving the child a calcaneal foot. The child may achieve 10 degrees of dorsiflexion, however, the ankle extensors are weakened. Therefore, the child walks with a very limited plantarflexion at toe off.

It is interesting to note the significant restriction in plantarflexion considering the original deformity involved an equinus contracture. This may be a result of the treatment given. Aronson & Puskarich (1990) studied 29 adolescent and adult patients with an idiopathic, unilateral clubfoot at a minimum of 10 years after their definitive treatment. They found that those patients who had a repeated achilles tendon lengthening had a significant decrease in plantarflexion. The time in casts (range 100-600 days) did not affect this trend.

This study showed that the ankle range of motion correlated strongly in the clubfoot and intact groups with the net anterior-posterior forces. The range of motion in the ankle correlated with the propulsive impulse. Even though there was a significant decrease in the clubfoot group in the peak propulsive force, the net impulse was not affected. These children begin the propulsion phase of gait earlier in order to compensate for the decrease in maximum power for propulsion. The early propulsive force may be due to the early heel off that would be required of those who could not dorsiflex their ankle beyond neutral (Figure. 7). If kinematic data were available, we might see greater knee and hip flexion followed by the hip and knee extending earlier to begin this propulsive force. It is difficult from the data in this study to speculate further about the effects on the proximal joints.

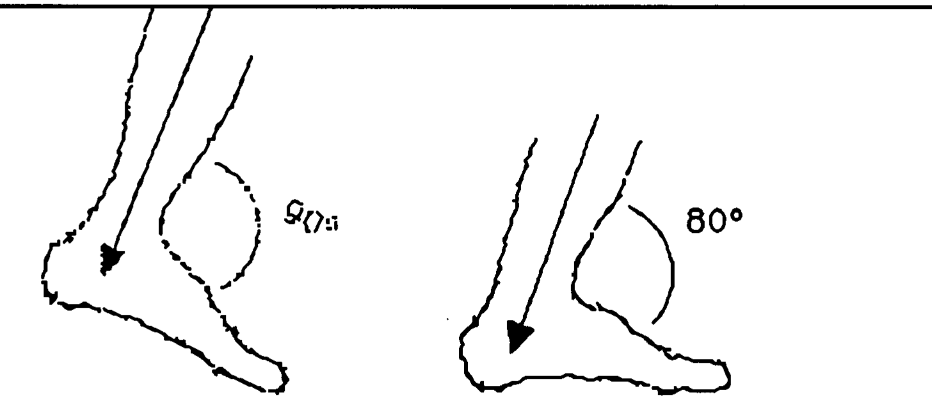

Figure 7. Early heel off phase due to decreased ankle dorsiflexion

The origin of the horizontal propulsive force has not been totally accepted as being the plantarflexors of the ankle. The function of the plantarflexors in the stance phase between heel off and toe off is not clear (Czerneicki, 1988). Simon, et al., (1978) stated that the ankle plantarflexors do not accelerate the body forward in walking. This was confirmed by Hof, et al., (1983) who correlated changes in energy of the trunk and the power output at the ankle during walking. They showed that the positive power output of the gastrocnemeuis-soleus was not correlated with an increase in trunk energy. Winter (1980) has shown that there is extensive EMG and kinetic data to suggest that the ankle plantarflexors provide significant positive power output in addition to their energy absorbing capacity in midstance phase

As mentioned earlier, several studies have used the calf girth as a measure of plantar flexor power in children with clubfeet in order to comment on the effect of the clubfoot and its treatment on the calf muscles. If propulsive force amplitude was used as a measure of plantarflexor power, the hypothesis could be tested by examining the relationship between the peak propulsive force and calf girth. This study showed the correlation was relatively low with r=.18 for both the intact and normal group and r=-.15 for the clubfoot group. The calf girth relationship to net anterior-posterior impulse resulted in similar correlations. The reduced ankle range of motion in the children with clubfeet does not limit their ability to produce an adequate propulsive force. However, from where does the power originate?

It is interesting to note that there existed a significant reduction in ankle dorsiflexion in the intact leg as compared to the normal. At birth these children are said to have one normal foot, with no evidence of rigidity in any plane of movement. Now as the children are getting older a minimal contracture has developed. If the clubfoot does alter gait patterns to some degree, this may have affect on the normal leg. An altered symmetrical gait may prove to be more efficient than trying to maintain normal gait on the better side. In the clubfoot, the dorsiflexion is restricted, thus requiring the stance phase to possibly be shortened and resulting in more time for the foot to bear weight on the forefoot or toes. Depending on how the rest of the leg responds to this alteration, the vertical displacement of the body's centre of mass may rise more than what is typically seen. In order for the child to maintain symmetry in gait, the normal foot may respond with decreasing the dorsiflexion during stance and also begin an early heel off phase. If this is a learned response, then as the foot is decreasing its time in dorsiflexion, this may result in a slight equinus contracture.

Even though the club and intact feet have restricted dorsiflexion, they still manage to maintain a fair amount of ankle range of motion, which would allow for adequate forward propulsion. Sutherland (1986), in his study of the development of mature gait analysed the kinematics in gait of 44 children aged 6 years which indicated at this stage in development, mature gait. During the stance phase the ankle flexes maximally to 10 degrees prior to heel off followed by maximal extension to 18 degrees before toe off. The total ankle range of motion during gait is only 28 degrees. All of the children in this study, except for one, could achieve at least 30 degrees of passive movement in their ankle. However, the arc of their movement was primarily in plantarflexion.

The etiology of the clubfoot has been described from two sides of the problem. The pathology of the clubfoot shows clear evidence of a deformed talus, which affects all of its articulations. The pathology of its soft tissues show shortened and often broader, contracted medial and posterior tendons. The question has never been resolved as to which came first, the tight tendons which put abnormal forces on the bone, or the abnormal bone which resulted in shorter tendons.

It is standard practice to improve the severe equinus contracture with an Achilles tendon lengthening and a prolonged stretching casting regimen, however, as others have documented, extensive lengthening produces limitations in plantarflexion strength. If the goal is to preserve the strength of the triceps surae complex while altering the arc of motion to include more dorsiflexion, then by addressing the bony deformity may be the muscles can be preserved.

Opening the ankle joint produces a considerable amount of scarring which often causes increased rigidity (R.D. Beauchamp, Personal communication, June 6, 1991). This would defeat the purpose of entering the joint. The approach might be to leave the ankle joint as is but change the arc of movement by taking a wedge, anteriorly, out of the tibia which would put the foot in greater dorsiflexion. Thus the arc of motion would be changed while preserving the calf muscles (Fig.8).

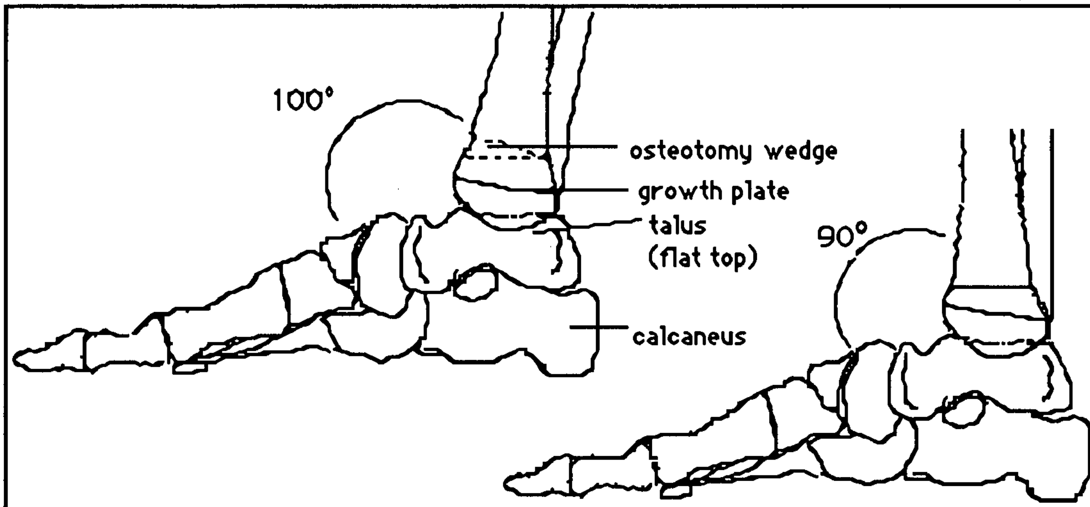

Figure 8. Change of ankle motion arc using an anterior wedge osteotomy of the tibia

SUMMARY

This study has shown differences in ground reaction forces between children with clubfeet and those with normal feet. The subtalar joint restricition and the heel position in the clubfoot does limit the absorption of the torsional forces produced by the femur and tibia over the foot. The foot with limited subtalar range of motion and a varus heel position on stance produces a net internal torque while the more flexible, valgus foot produces a net external torque. This relationship only holds for the children with clubfeet. The relationship is weak for the children with normal feet. The children with clubfeet have restricted subtalar and ankle motion and also mid and forefoot rigidity which was not addressed in this study. The ability for the forefoot to pronate adequately and supinate completely may play a greater role in torque absorption and transmission than was initially expected. Therefore, isolating the subtalar joint completely to examine torque absorption may be inappropriate for normal children. However, in children with clubfeet this relationship may be valid. More children need to be studied to make any conclusive statements.

The anterior-posterior forces obtained in this study from the children with clubfeet showed a decreased propulsive force as compared to their normal peers. There was observed a strong correlation between the child's ankle range of motion and the amount of propulsive impulse in the children with clubfeet. Interestingly, the child's unaffected foot also had restricted ankle dorsiflexion. The importance of mechanical efficiency in symmetrical gait may contribute to the children walking with less dorsiflexion on their normal foot to assimilate the gait characteristics of their clubfoot. Over a long period of gait alterations, the normal foot may lose its ability to dorsiflex. The intact foot, however, still had strong posterior muscles used for propulsion. The treatment of clubfoot includes lengthening the the achilles tendon to obtain a plantigrade foot. This has been discussed in the literature as the primary cause of the weakening of the plantarflexors. To maintain adequate plantarflexor power for propulsion, the approach towards correcting the deformity may be addressed by changing the bony relationships in the foot and ankle. Performing an anterior tibial wedge osteotomy to dorsiflex the foot would keep the plantarflexors intact allowing for stronger propulsion and a faster walking speed.

FUTURE RESEARCH

The results of this study have shown relationships between clinical and ground reaction force data. These relationships indicate that there are significant differences in gait patterns between the normal and the clubfoot. Unfortunately, the results are based on only 5 subjects with clubfeet for the torque and 7 subjects for the anterior-posterior forces. The correlations obtained were high but not statistically signficant. To ascertain whether these relationships are in fact true, a larger group of children with clubfeet must be studied. A full three dimensional kinematic and kinetic evaluation of gait of children with clubfeet would provide better description of the alterations of their gait with respect to rotational movements and joint moments in the ankle and foot as well as the proximal joints.

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bElveru, R.A., Rothstein, J.M., Lamb, R.L., & Riddle, D.L. (1988). Methods for taking subtalar joint measurements - a Clinical report. Physical Therapy, 68(5),678.

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APPENDIX A

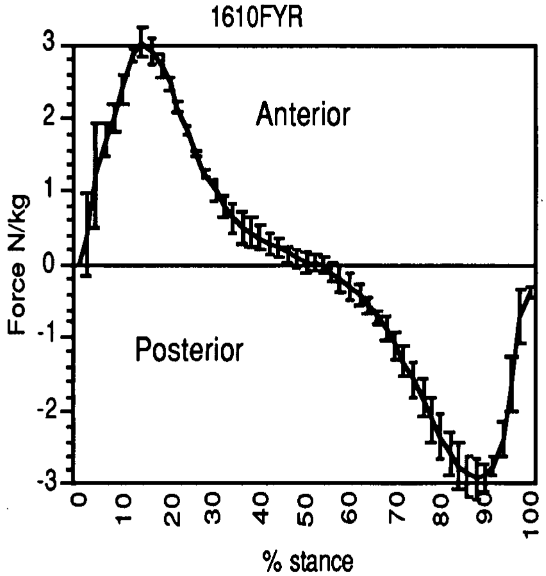
Clinical Data

	SUBJ...	GROUP	DORSI	PLA...	ANKLE	EVER	INVER	SUB	HEEL	T/F	MZ impu...	MZ1	MZ2	FZ1	FZ2	FY1	FY2	FY IMP	spike
1	17	club	-2	32	30	5	28	33	0	9	.085	.228	.12	10.5	9.9	1.3	-1.5	-7.00E-2	n
2	20	club	-1	34	32	4	11	15	0	-15	-.036	.517	-.23	10.5	9.7	2.8	-1.7	-.11	y
3	21	club	0	•	6	-5	16	11	5	-7	.021	.238	-.16	10.4	11.1	1.4	-2.2	-.21	y
4	27	club	0	31	31	7	16	23	-3	-7	.052	.415	-.27	14.8	11.0	2.9	-2.9	2.00E-2	y
5	30	club	-2	49	47	0	21	21	0	-11	.035	.120	-1.00E-2	10.7	10.6	2.4	-2.7	-9.00E-2	y
6	39	club	-6	36	30	16	11	27	0	-13	•	•	•	9.3	9.9	1.8	-2.1	-5.20E-2	n
7	40	club	6	51	57	12	24	36	6	-2	•	•	•	10.0	10.2	1.9	-2.8	-.54	y
8	17	intact	5	37	42	4	25	29	-4	10	.072	.189	-.15	9.4	10.4	1.2	-1.9	-.10	n
9	20	intact	0	68	68	16	31	47	6	14	.049	.729	-.10	11.7	11.2	2.1	-2.4	-.27	n
10	21	intact	2	36	38	12	20	32	5	-6	-.095	.170	-.40	13.1	11.0	2.2	-3.0	-.16	n
11	27	intact	8	34	42	12	27	39	7	13	-.033	.038	-.13	14.6	12.2	2.9	-3.3	-5.00E-2	y
12	30	intact	10	52	62	21	39	58	12	0	-.053	.079	-.20	12.7	11.1	2.4	-2.8	-.16	n
13	39	intact	14	51	65	34	13	47	5	11	•	•	•	10.0	11.6	1.7	-2.9	-.21	y
14	40	intact	14	65	79	19	31	50	11	11	•	•	•	9.9	10.2	2.1	-2.9	-.38	y
15	10	normL	21	43	64	13	24	47	9	11	-.049	.076	-.23	11.7	10.3	2.4	-2.8	-.16	n
16	11	normL	22	40	62	14	29	43	0	0	-.042	.028	-.11	15.3	10.7	2.7	-3.3	-.15	n
17	12	normL	22	47	69	22	29	51	0	13	-.022	.052	-.10	10.4	12.7	2.0	-2.8	-.13	y
18	13	normL	13	49	62	13	26	39	7	26	-.084	.276	-.46	14.0	12.6	3.3	-3.4	-.11	y
19	14	normL	19	47	66	17	24	41	2	12	-.098	.086	-.34	14.0	12.6	2.0	-2.7	-.15	n
20	15	normL	7	42	49	18	29	47	7	15	-.046	.146	-.28	13.9	11.2	2.6	-3.4	-7.70E-2	n
21	19	normL	16	44	60	19	30	49	12	9	8.700E-3	.292	-.19	12.9	12.4	2.7	-3.2	-.15	n
22	23	normL	15	45	60	14	29	41	0	4	3.500E-3	.209	-.18	11.6	10.8	2.0	-2.5	-.16	y
23	24	normL	21	46	67	16	28	44	13	11	1.800E-3	.148	-.15	11.5	10.6	2.1	-2.3	-.15	n
24	28	normL	15	49	64	18	29	47	5	9	-.020	.196	-.17	11.5	11.5	1.9	-2.3	-1.00E-2	n
25	29	normL	16	47	63	17	29	46	3	21	-.046	.015	-.16	11.4	11.5	2.5	-2.9	-.21	y
26	31	normL	11	44	55	21	32	53	5	12	-.103	.155	-.37	16.6	13.2	2.4	-2.7	-.12	n
27	33	normL	10	48	58	15	21	36	6	-6	-.035	.207	-.32	10.9	10.7	2.0	-2.2	-5.00E-2	y
28	34	normL	13	38	51	18	28	46	11	14	.095	.353	-.12	13.3	9.9	2.4	-2.4	5.00E-2	n
29	35	normL	12	46	58	17	32	49	3	11	-.046	.121	-.26	11.3	11.1	1.6	-2.8	-.34	n
30	36	normL	14	50	64	15	29	44	8	17	-.063	.099	-.28	12.6	10.2	2.8	-2.9	-4.20E-2	n

APPENDIX B

Norrmalized ground reaction force data for individual subjects (3 trials)

with one standard deviation error bars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Anterior
Posterior
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2
1
0
-1
-2
-3
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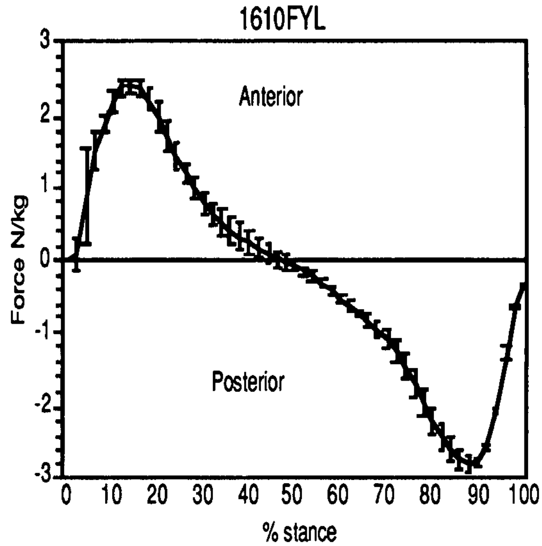
% stance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Posterior
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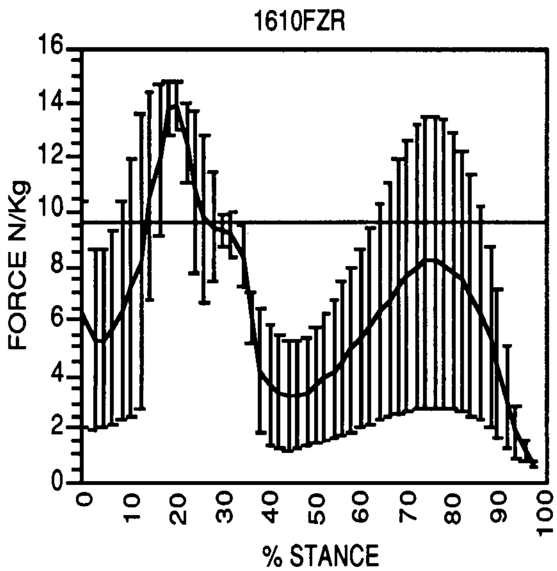
2
1
0
-1
-2
-3
0 10 20 30 40 50 60 70 80 90 100
% stance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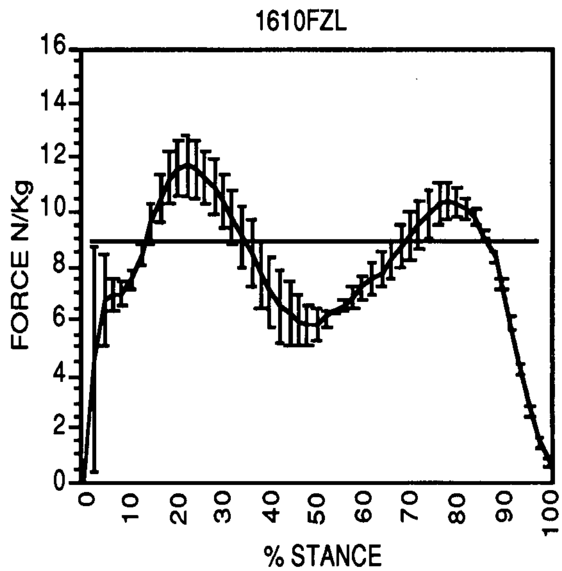
16
14
12
10
8
6
4
2
0
0 10 20 30 40 50 60 70 80 90 100
% STANCE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16
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10
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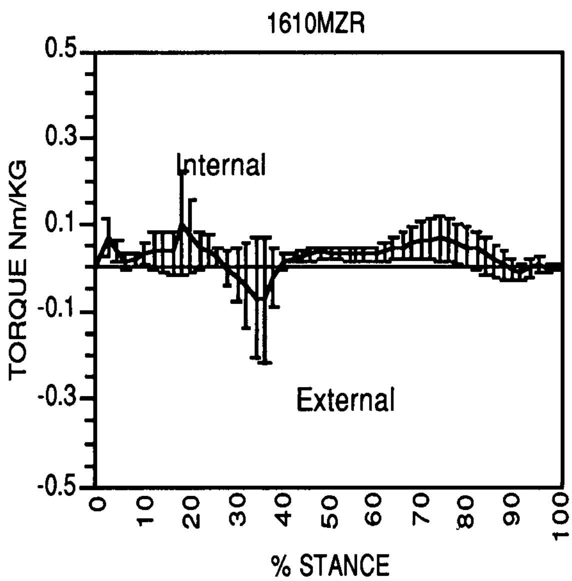
2
0
0 10 20 30 40 50 60 70 80 90 100
% STANCE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Internal
External
TORQUE Nm/KG
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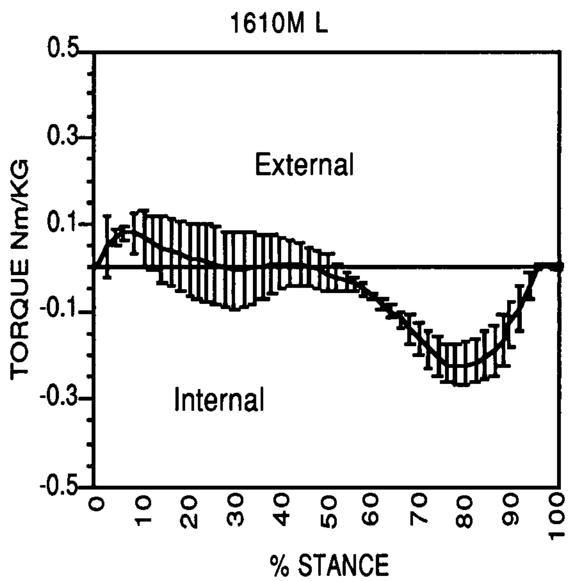
0.3
0.1
-0.1
-0.3
-0.5
0 10 20 30 40 50 60 70 80 90 100
% STANCE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External
Internal
TORQUE Nm/KG
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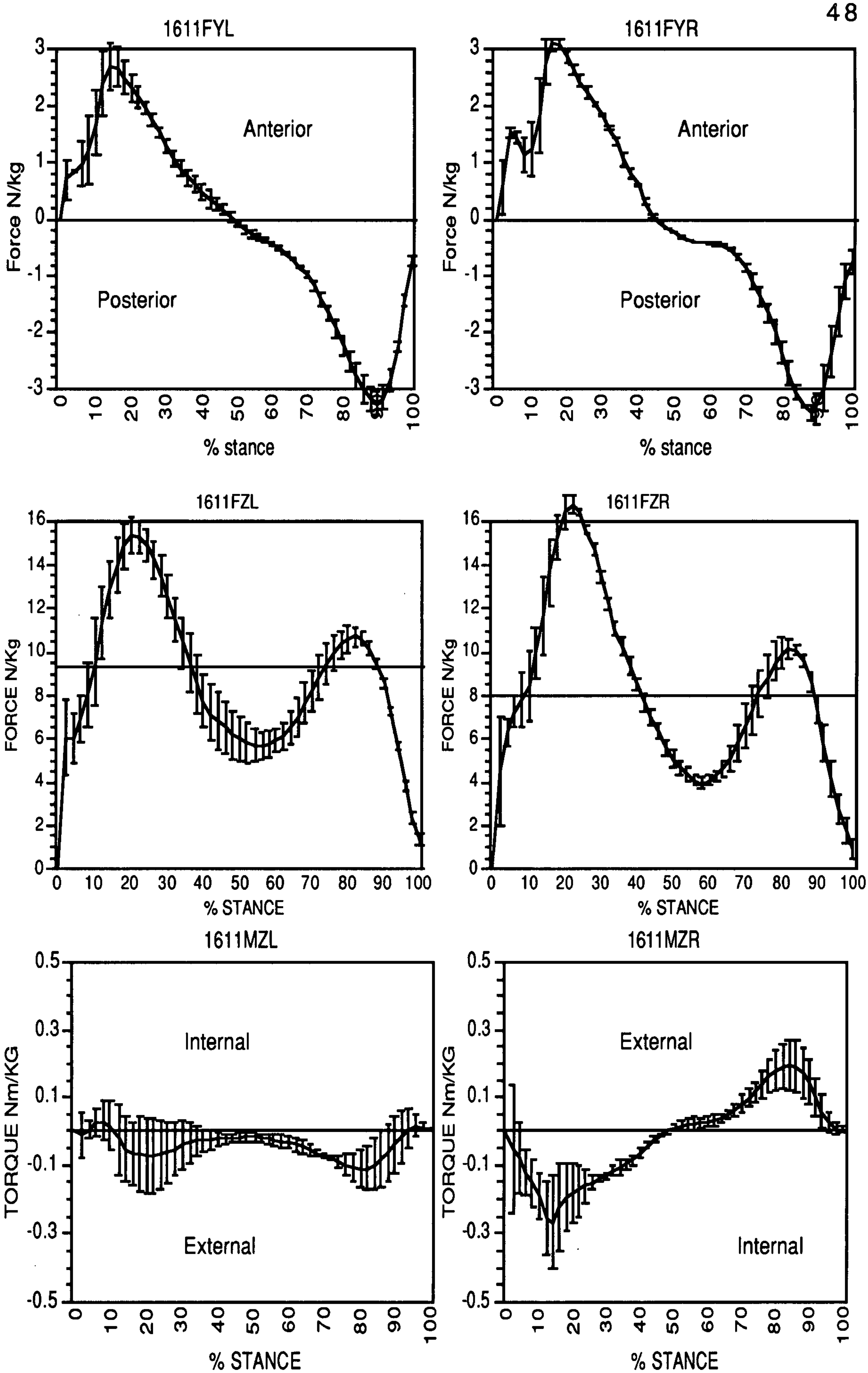
-0.3
-0.5
0 10 20 30 40 50 60 70 80 90 100
% STANCE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Force N/Kg
Anterior
Posterior
% stance
1611FYR
Force N/Kg
Anterior
Posterior
% stance
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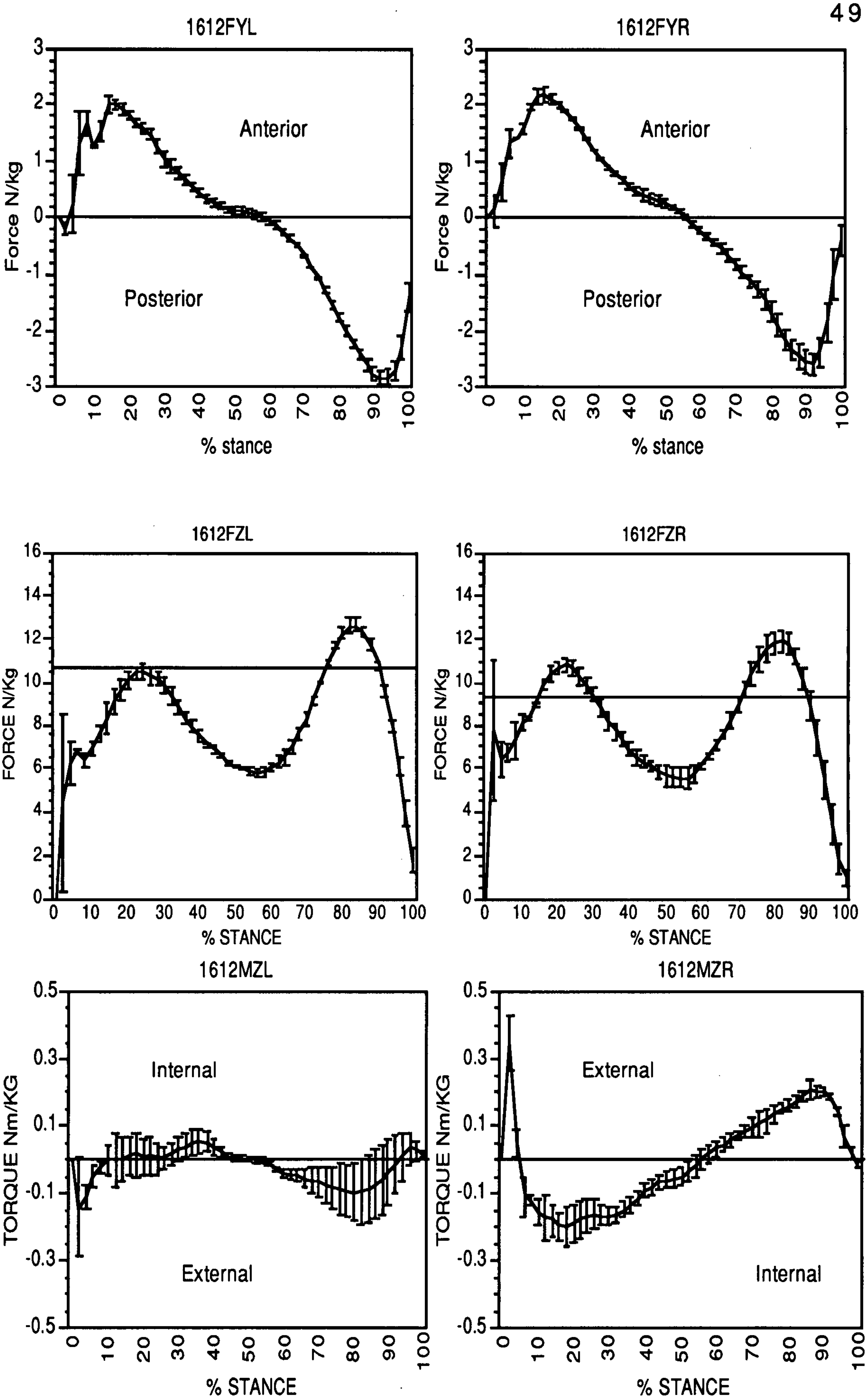
% STANCE
1611FZR
FORCE N/Kg
% STANCE
1611MZL
TORQUE Nm/KG
Internal
External
% STANCE
1611MZR
TORQUE Nm/KG
External
Internal
% STANCE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Force N/kg
Anterior
Posterior
% stance
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Force N/kg
Anterior
Posterior
% stance
1612FZL
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1612FZR
FORCE N/Kg
% STANCE
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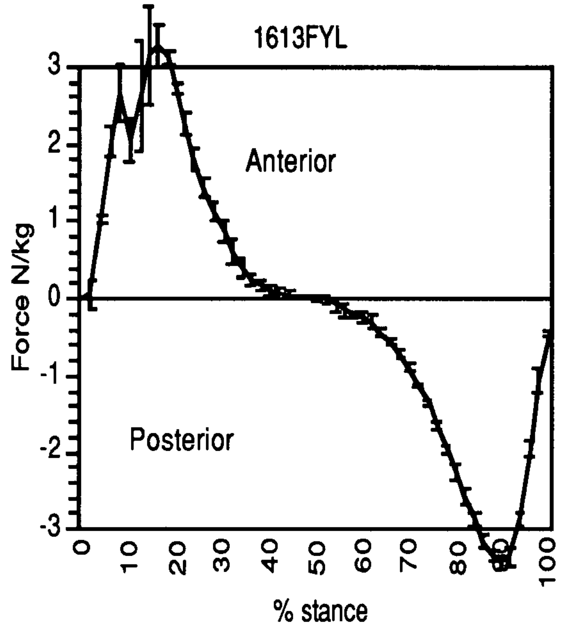
TORQUE Nm/KG
Internal
External
% STANCE
1612MZR
TORQUE Nm/KG
External
Internal
% STANCE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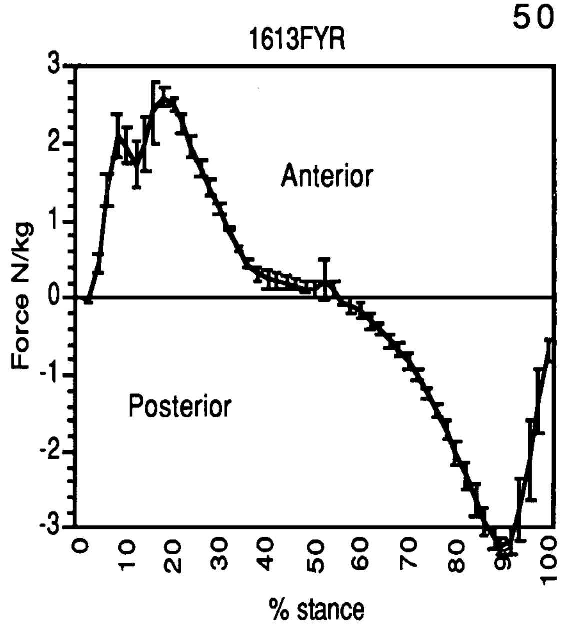
Anterior
Posterior
% stance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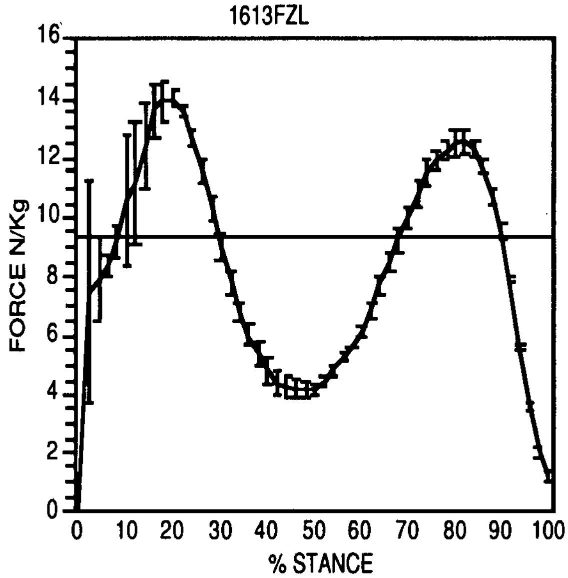
Anterior
Posterior
% stance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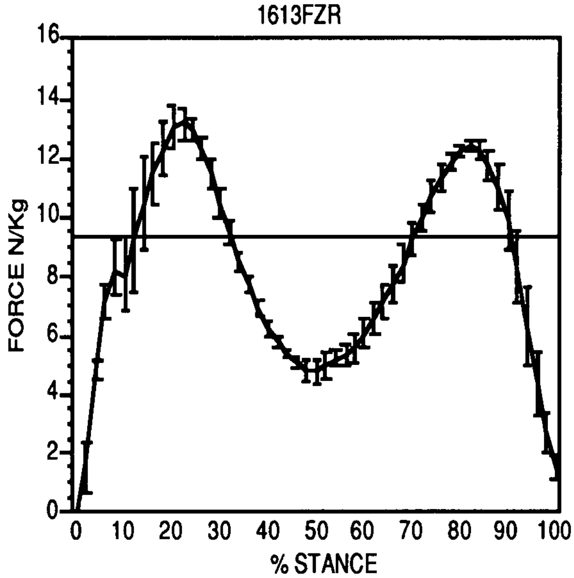
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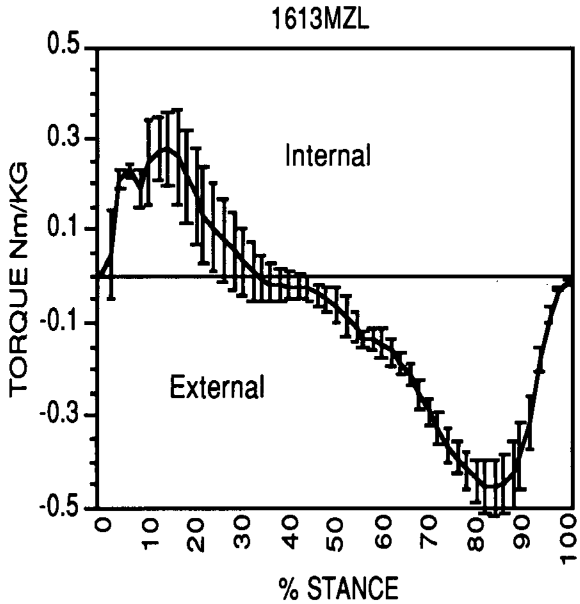
% STANCE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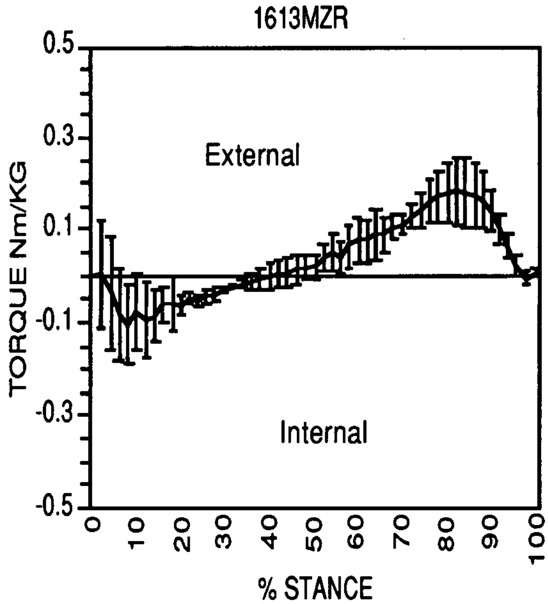
Internal
External
% STANCE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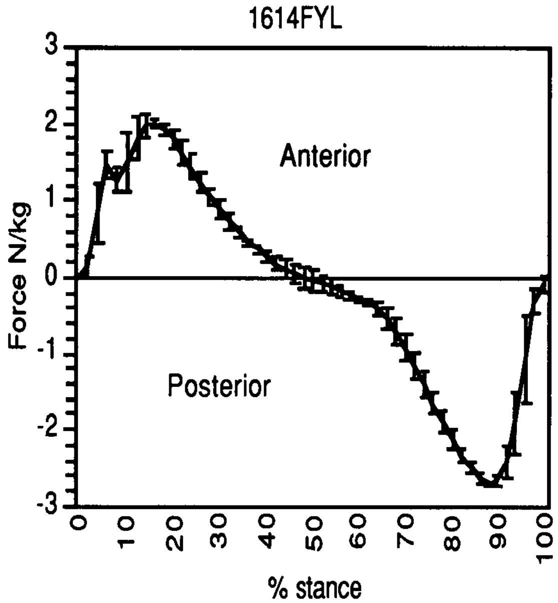
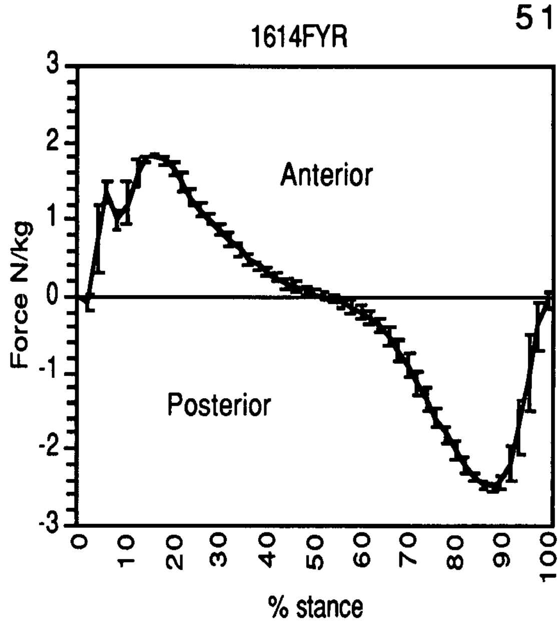
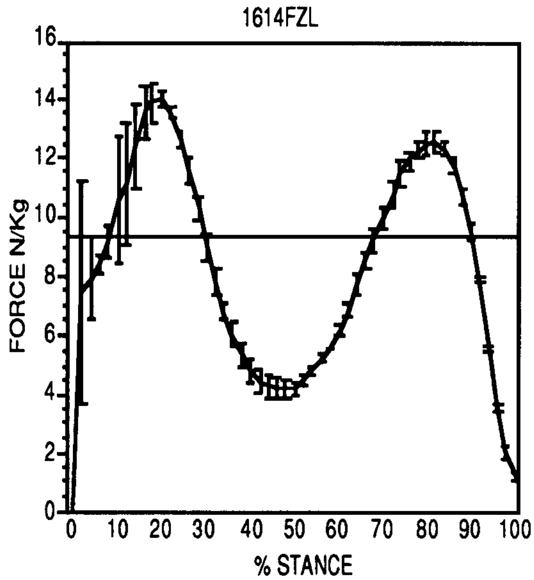
TORQUE Nm/KG
External
Internal
% STANCE


1614FYL
Force N/kg
Anterior
Posterior
% stance


1614FYR
Force N/kg
Anterior
Posterior
% stance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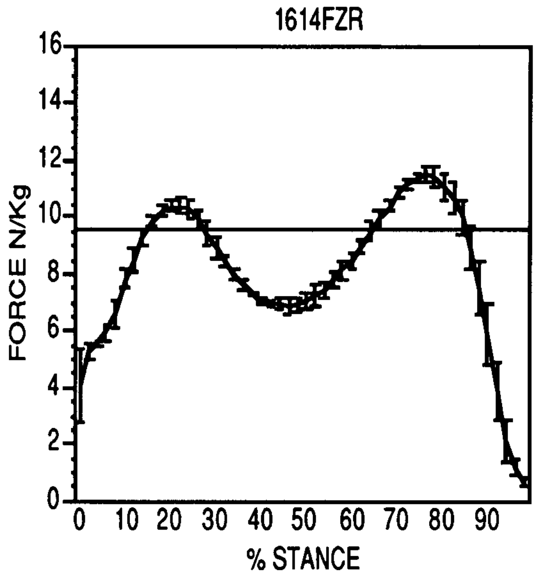
FORCE N/Kg
% STANCE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FORCE N/Kg
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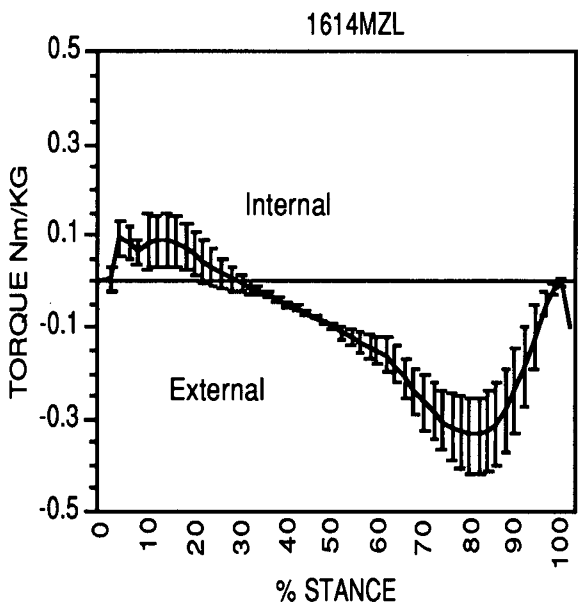
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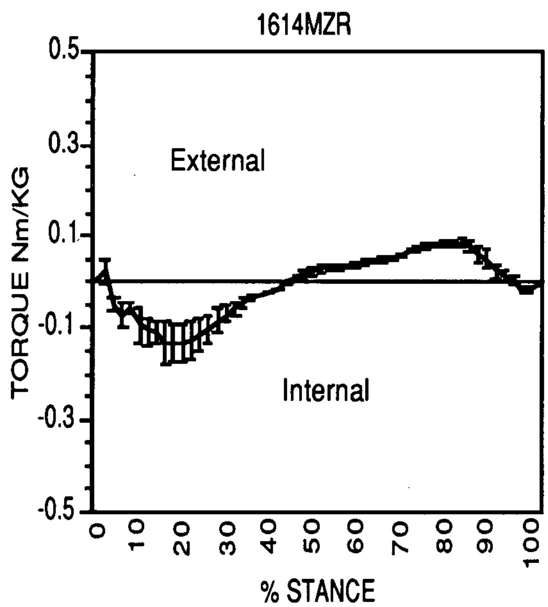
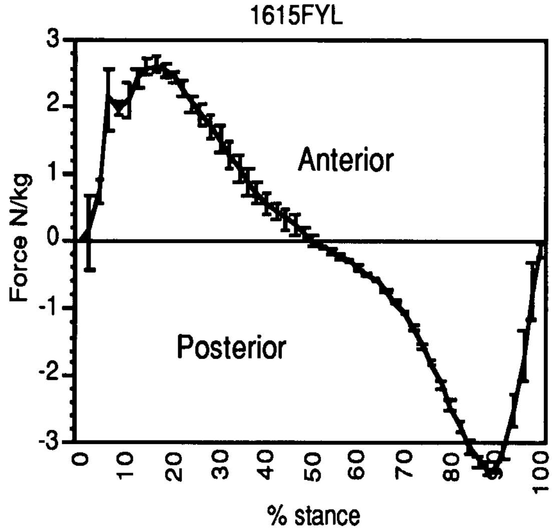
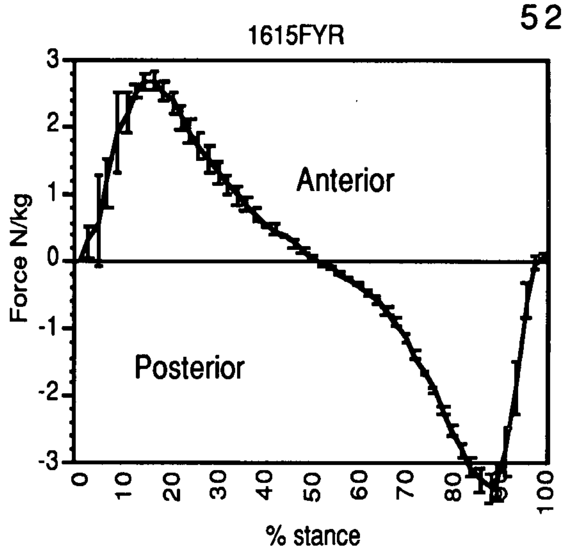
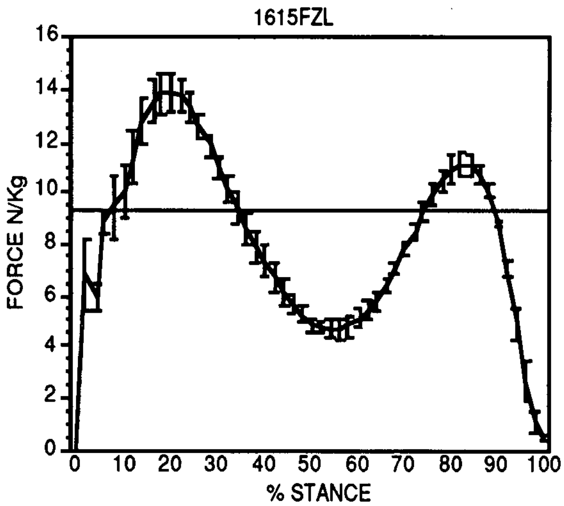
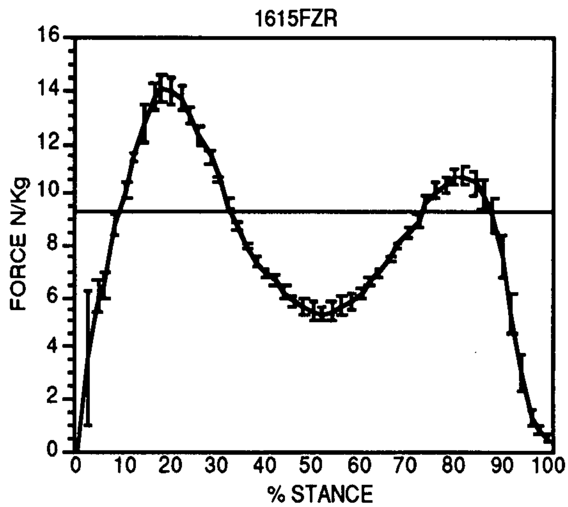
TORQUE Nm/KG
Internal
External
% STANCE

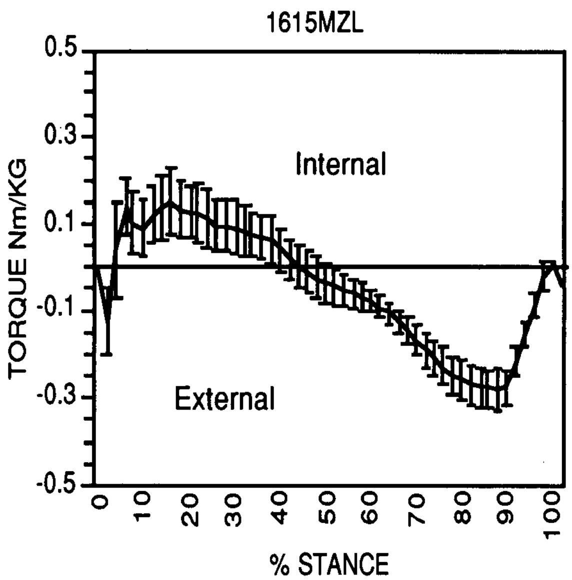

1614MZR
TORQUE Nm/KG
External
Internal
% STANCE

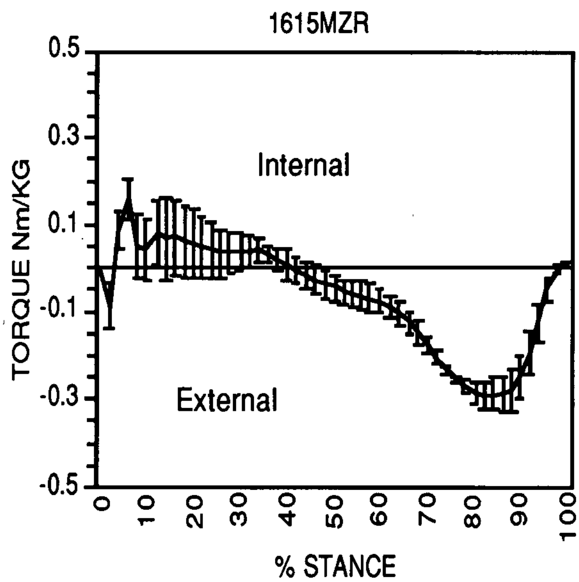

1615FYL
Force N/kg
Anterior
Posterior
% stance


1615FYR
Force N/kg
Anterior
Posterior
% stance

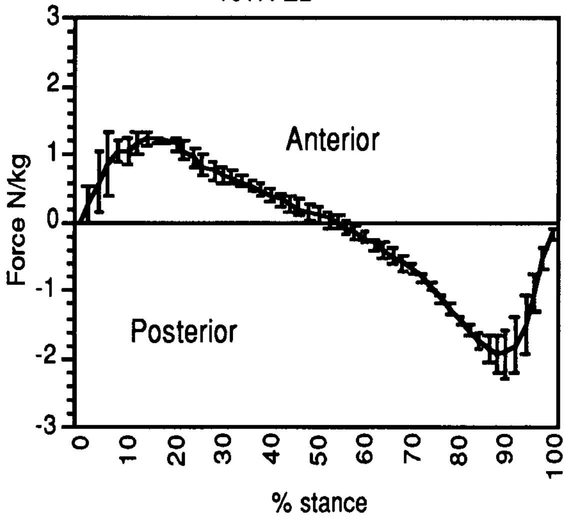

1615FZL
FORCE N/Kg
% STANCE


1615FZR
FORCE N/Kg
% STANCE

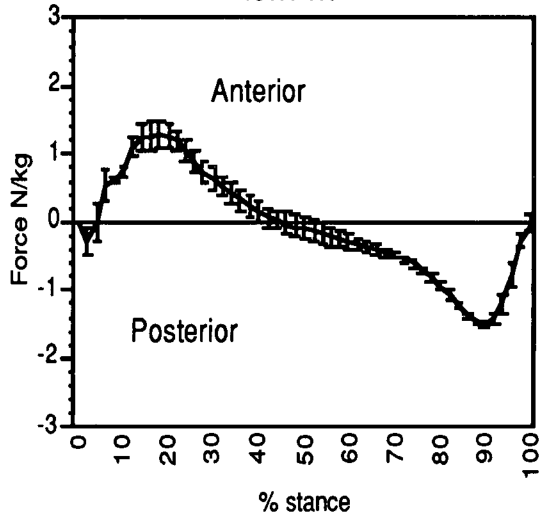

1615MZL
TORQUE Nm/KG
Internal
External
% STANCE


1615MZR
TORQUE Nm/KG
Internal
External
% STANCE

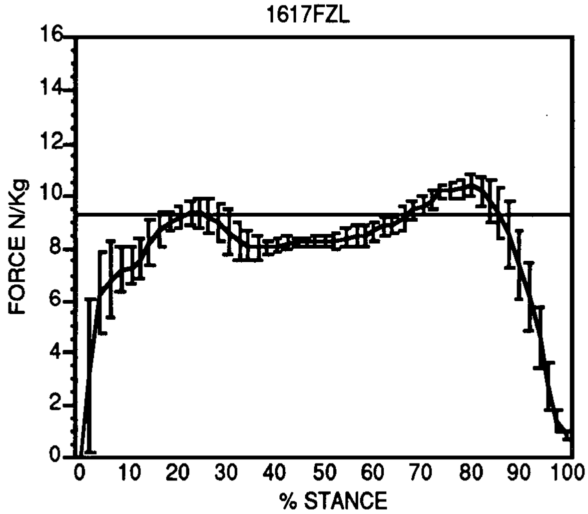
1617FZL



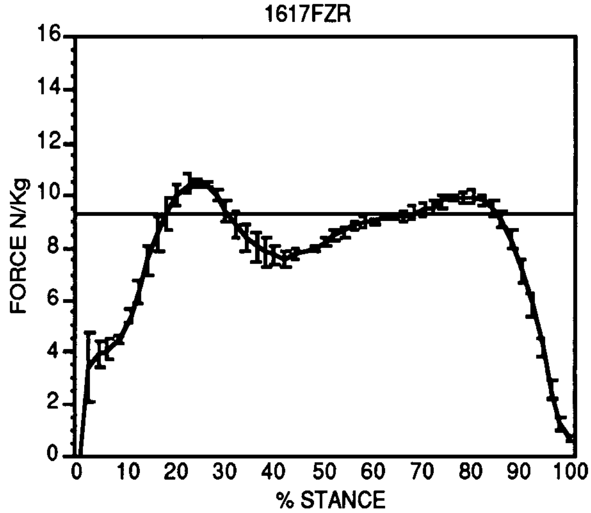
1617FYR



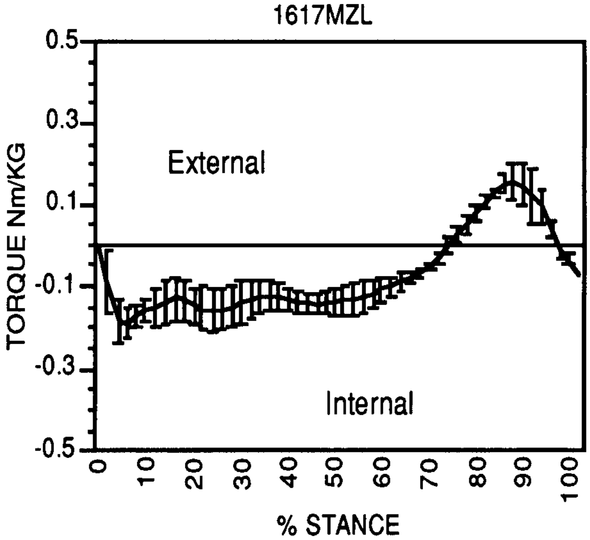
1617FZL



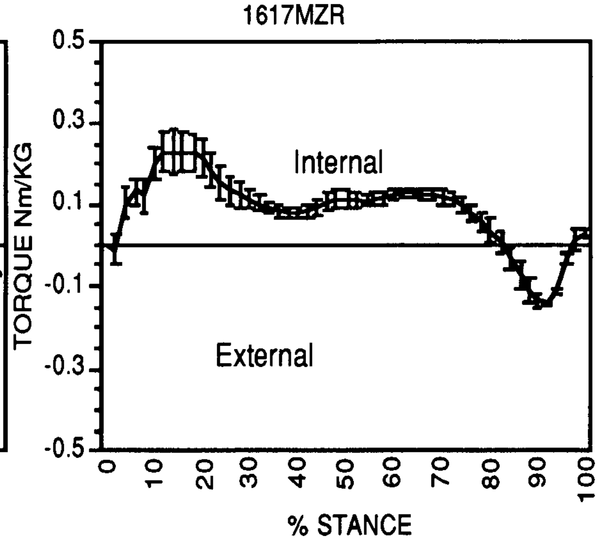
1617FZR

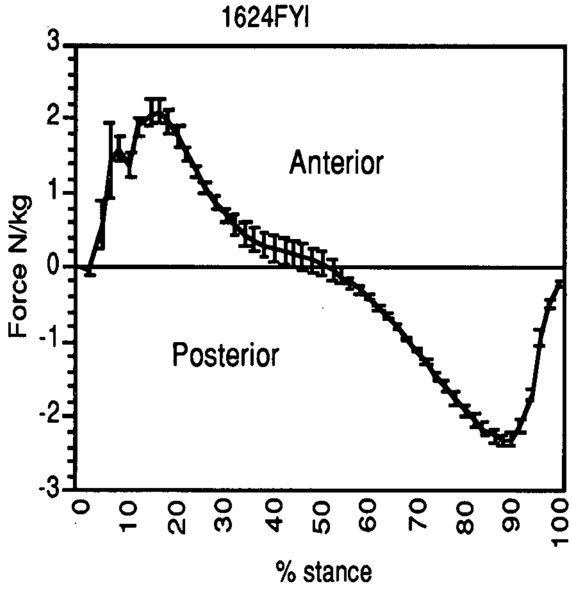


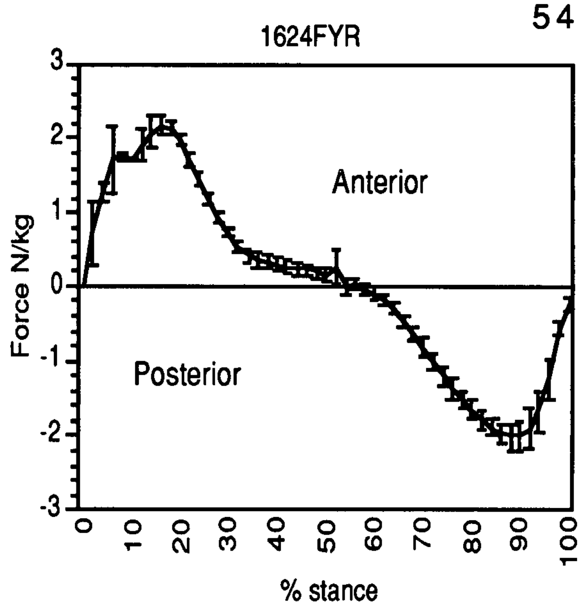
1617MZL

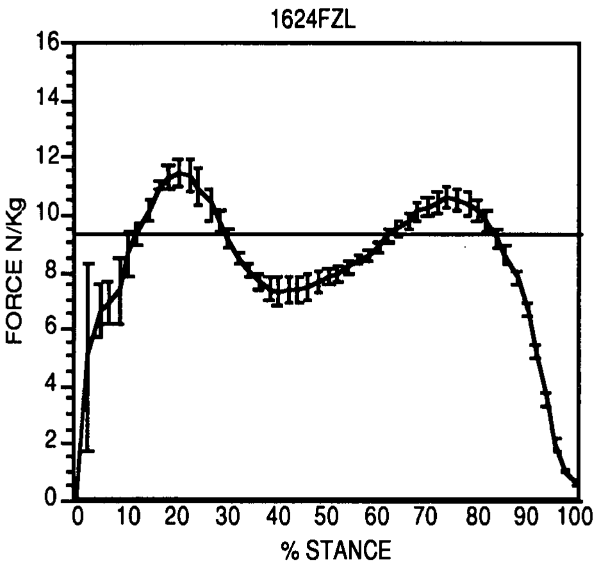


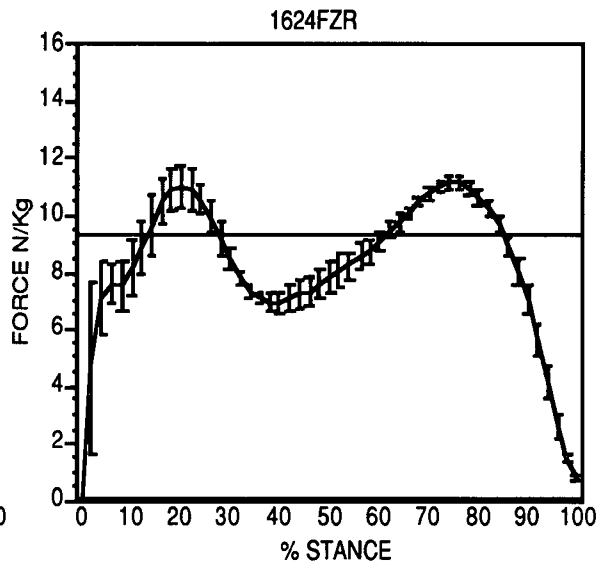
1617MZR

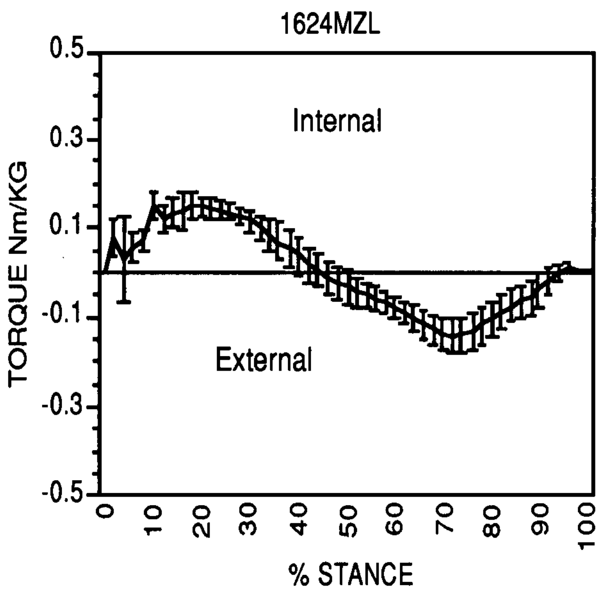


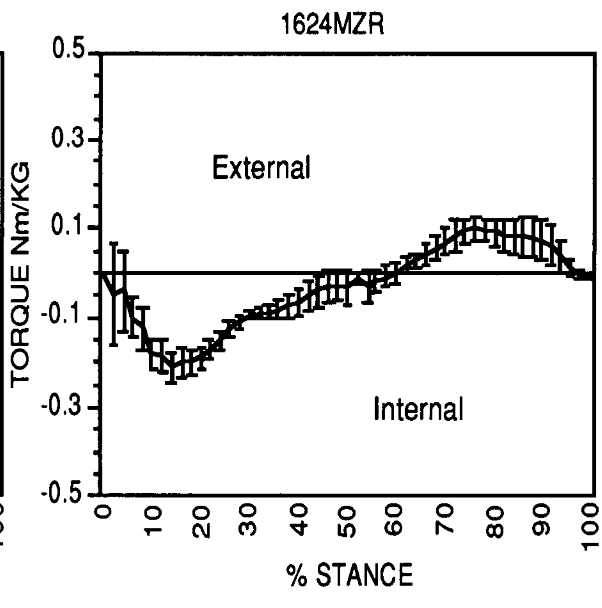

1624FYl
Anterior
Posterior
Force N/kg
3
2
1
0
-1
-2
-3
0
10
20
30
40
50
60
70
80
90
100
% stance

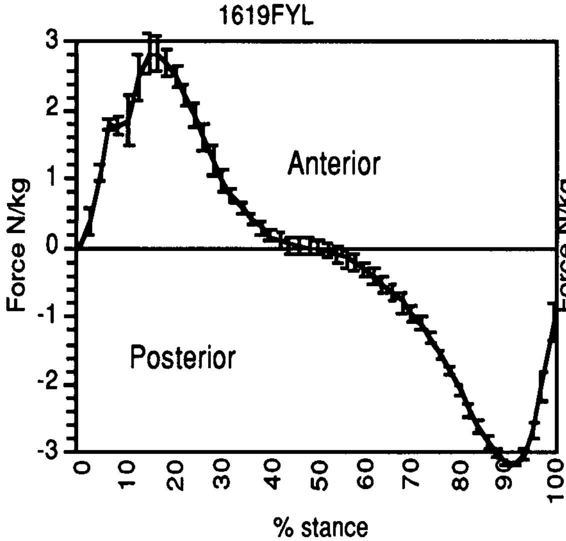

1624FYR
Anterior
Posterior
Force N/kg
3
2
1
0
-1
-2
-3
0
10
20
30
40
50
60
70
80
90
100
% stance

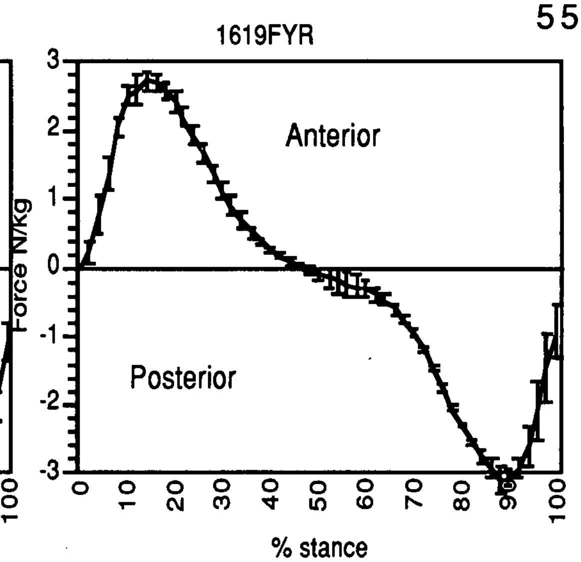

1624FZL
FORCE N/Kg
16
14
12
10
8
6
4
2
0
0
10
20
30
40
50
60
70
80
90
100
% STANCE

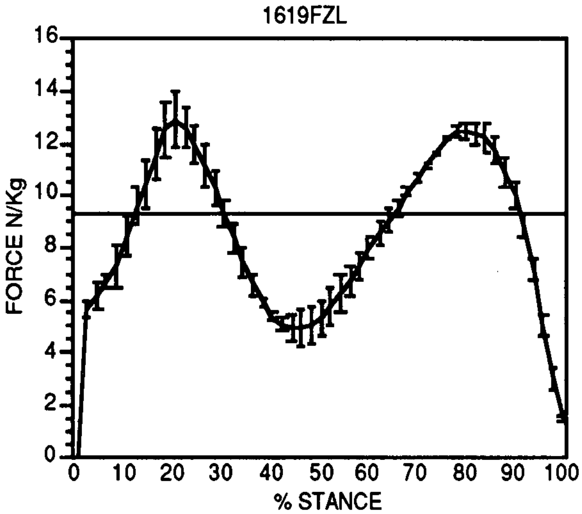

1624FZR
FORCE N/Kg
16
14
12
10
8
6
4
2
0
0
10
20
30
40
50
60
70
80
90
100
% STANCE

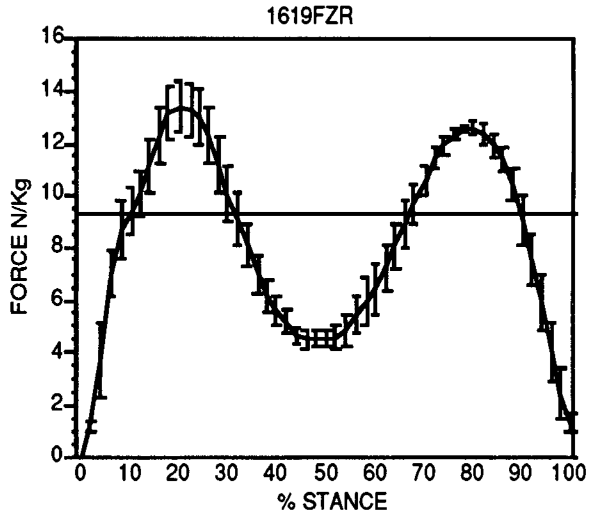

1624MZL
Internal
External
TORQUE Nm/KG
0.5
0.3
0.1
-0.1
-0.3
-0.5
0
10
20
30
40
50
60
70
80
90
100
% STANCE

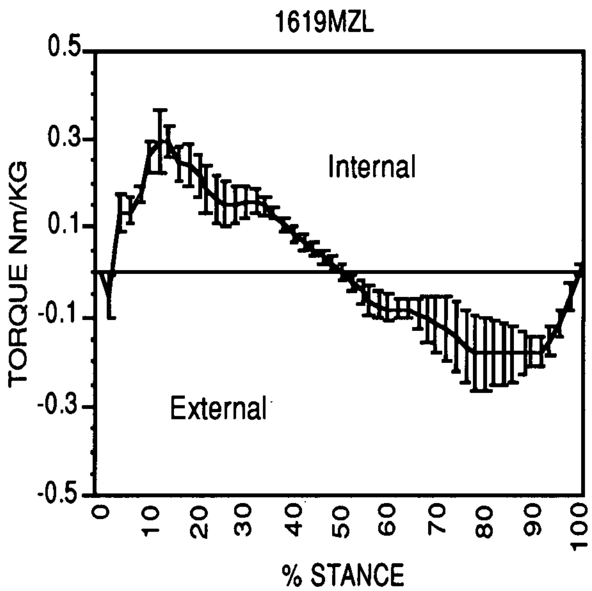

1624MZR
External
Internal
TORQUE Nm/KG
0.5
0.3
0.1
-0.1
-0.3
-0.5
0
10
20
30
40
50
60
70
80
90
100
% STANCE

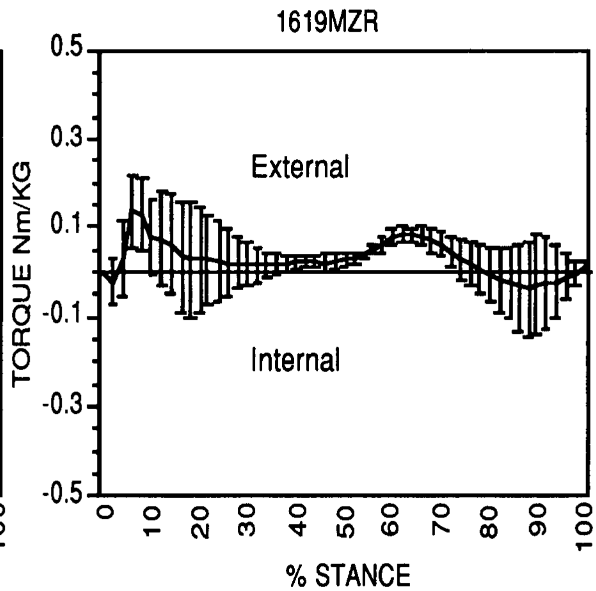

1619FYL
Anterior
Posterior
Force N/Kg
% stance

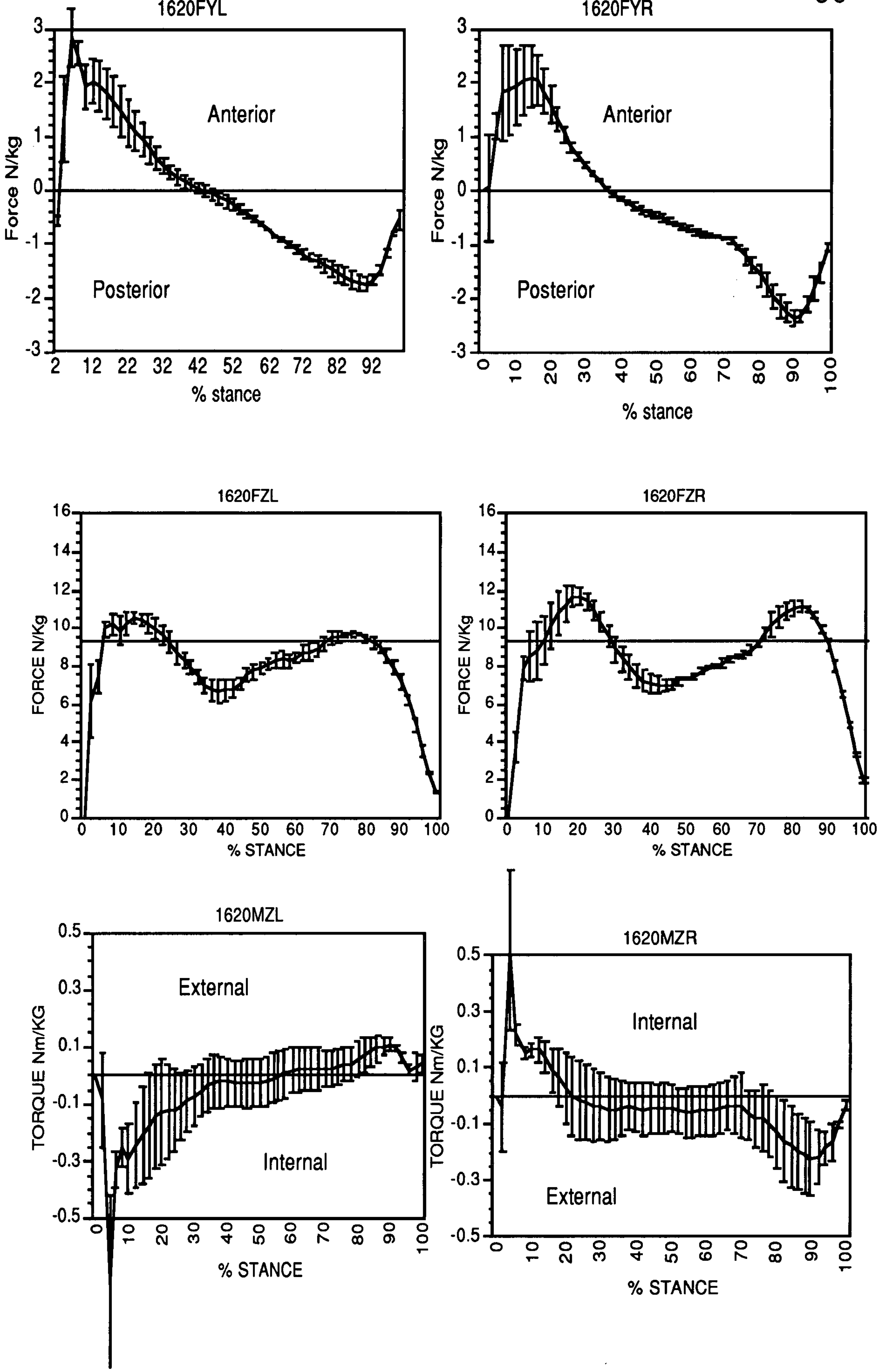

1619FYR
Anterior
Posterior
Force N/Kg
% stance

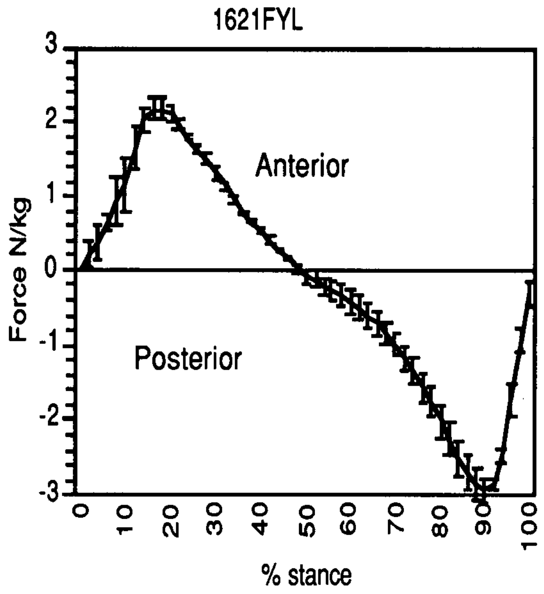

1619FZL
FORCE N/Kg
% STANCE

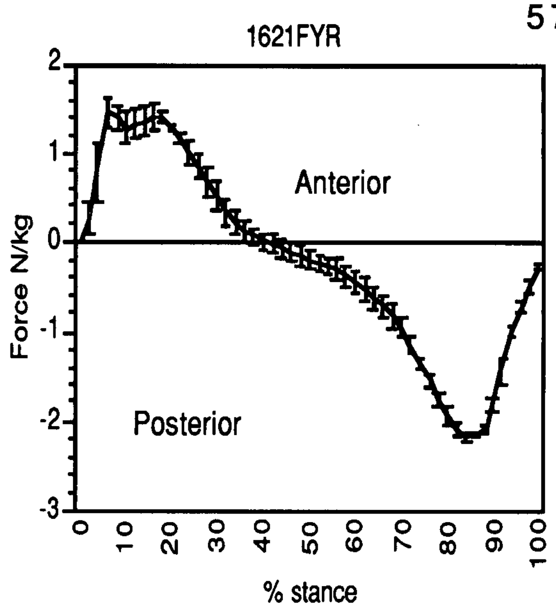

1619FZR
FORCE N/Kg
% STANCE

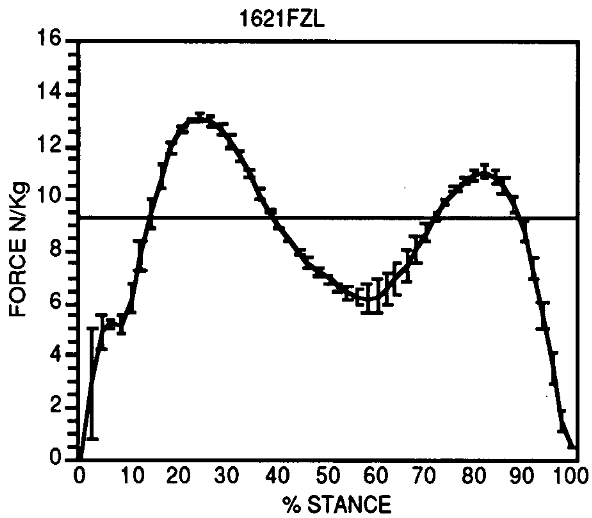

1619MZL
Internal
External
TORQUE Nm/KG
% STANCE

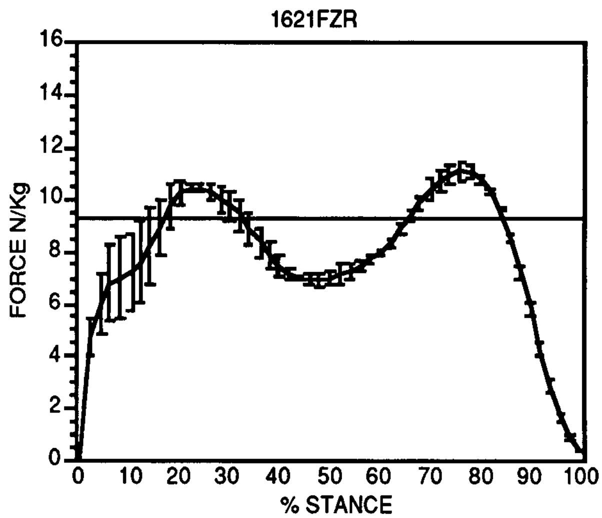

1619MZR
External
Internal
TORQUE Nm/KG
% STANCE

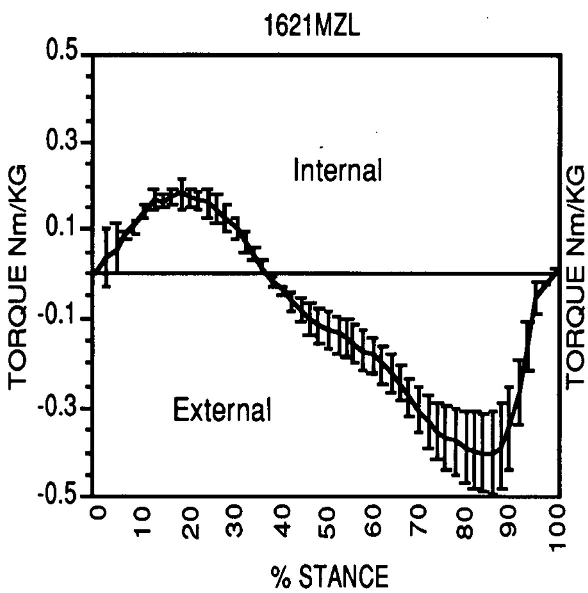

1620FYL
Anterior
Posterior
Force N/kg
% stance
1620FYR
Anterior
Posterior
Force N/kg
% stance
1620FZL
FORCE N/Kg
% STANCE
1620FZR
FORCE N/Kg
% STANCE
1620MZL
External
Internal
TORQUE Nm/KG
% STANCE
1620MZR
Internal
External
TORQUE Nm/KG
% STANCE

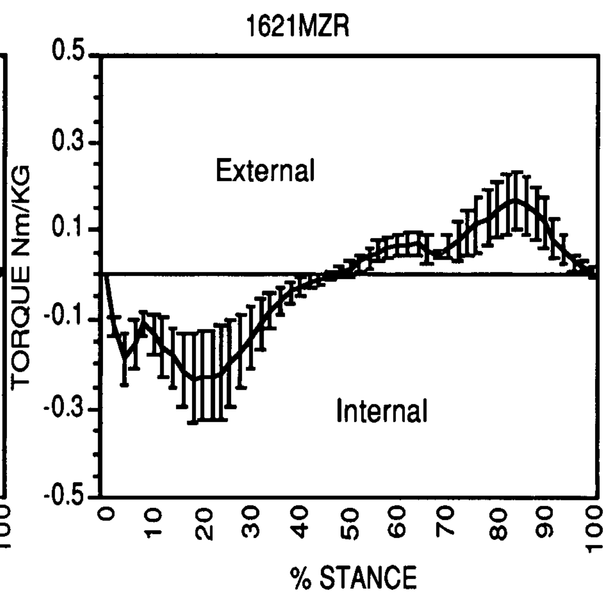

1621FYL
Force N/Kg
Anterior
Posterior
% stance

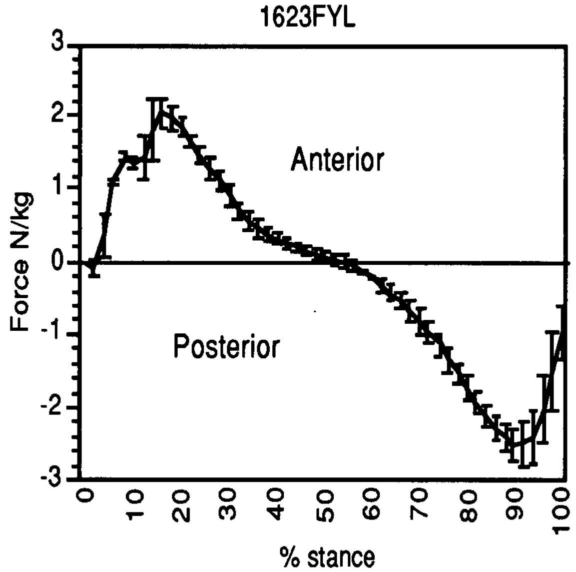

1621FYR
Force N/Kg
Anterior
Posterior
% stance

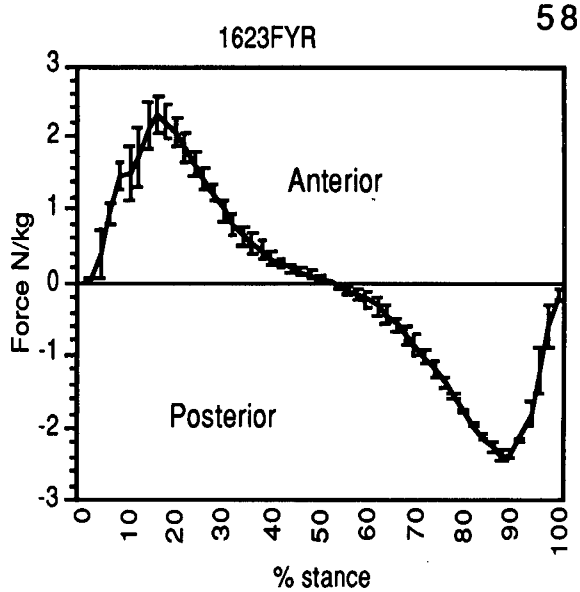

1621FZL
FORCE N/Kg
% STANCE

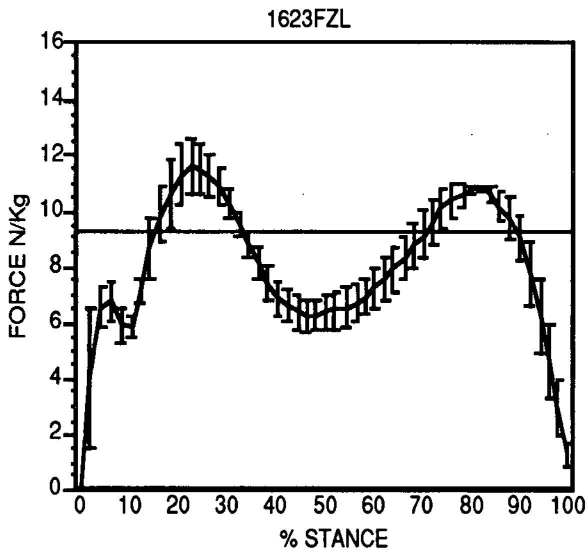

1621FZR
FORCE N/Kg
% STANCE

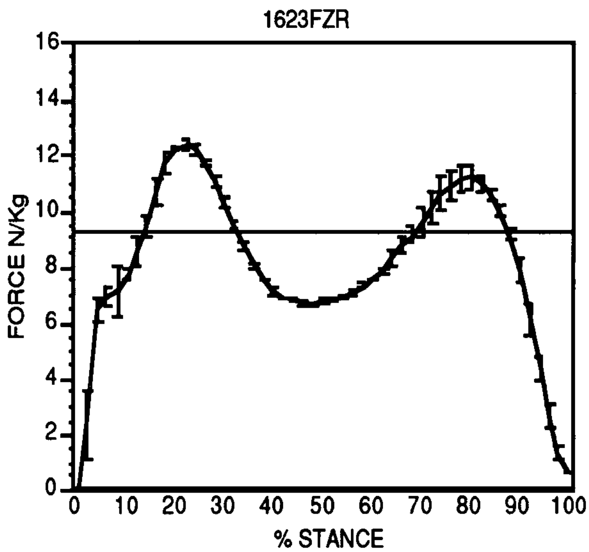

1621MZL
TORQUE Nm/KG
Internal
External
% STANCE

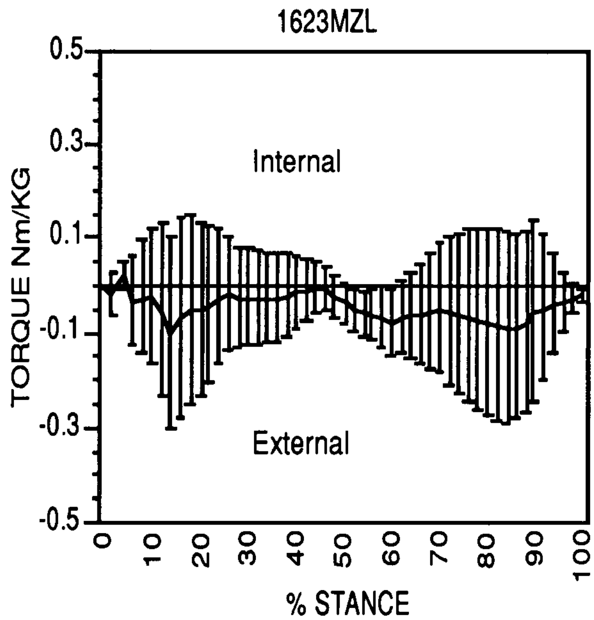

1621MZR
TORQUE Nm/KG
External
Internal
% STANCE

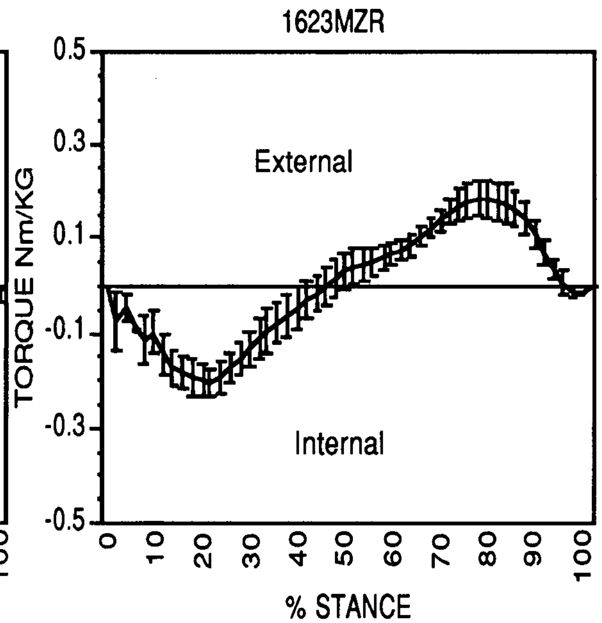

1623FYL
Force N/Kg
Anterior
Posterior
% stance

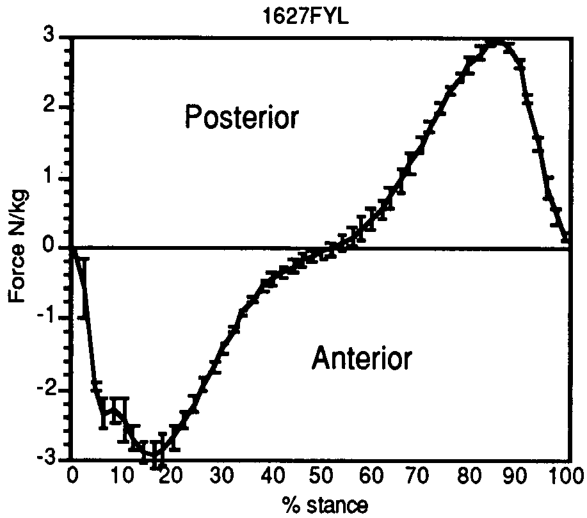

1623FYR
Force N/Kg
Anterior
Posterior
% stance

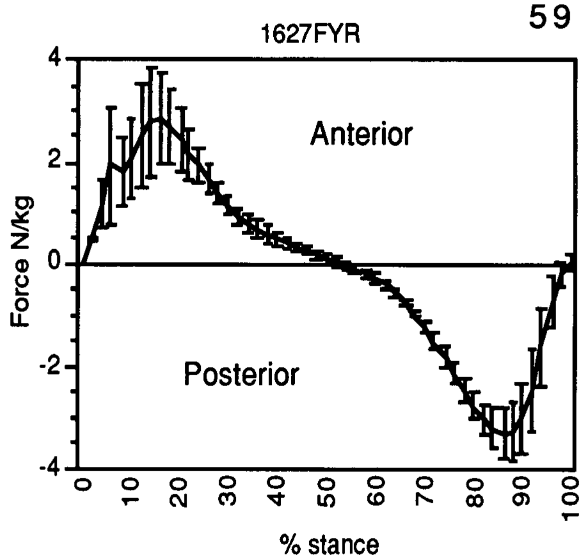

1623FZL
FORCE N/Kg
% STANCE

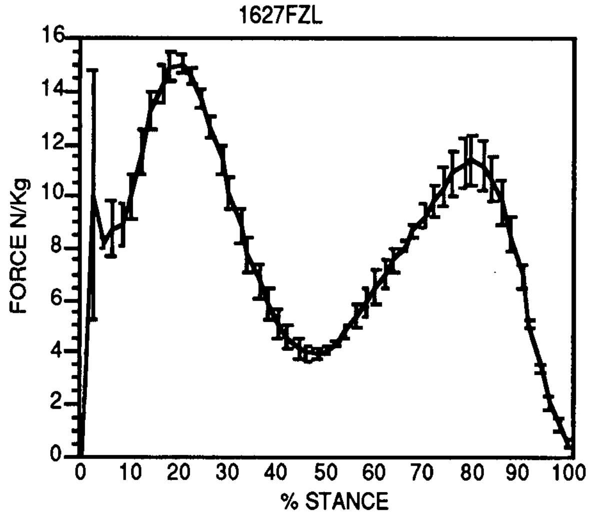

1623FZR
FORCE N/Kg
% STANCE

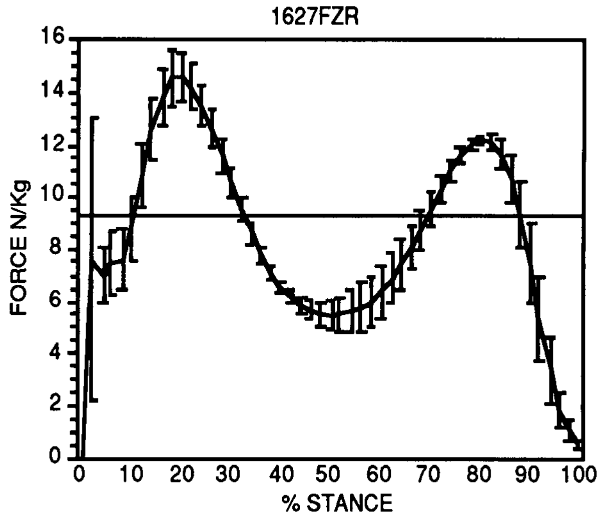

1623MZL
TORQUE Nm/KG
Internal
External
% STANCE

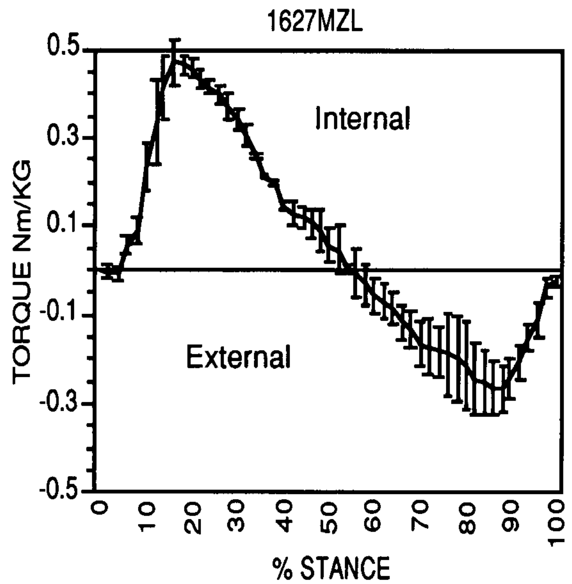

1623MZR
TORQUE Nm/KG
External
Internal
% STANCE

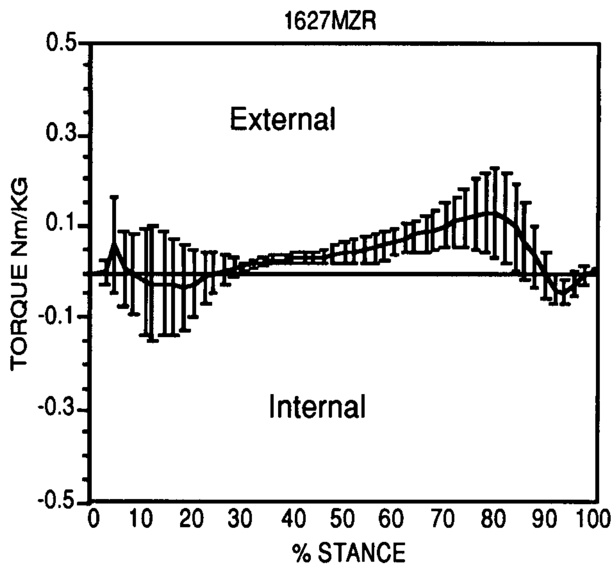

1627FYL
Posterior
Anterior
Force N/kg
% stance

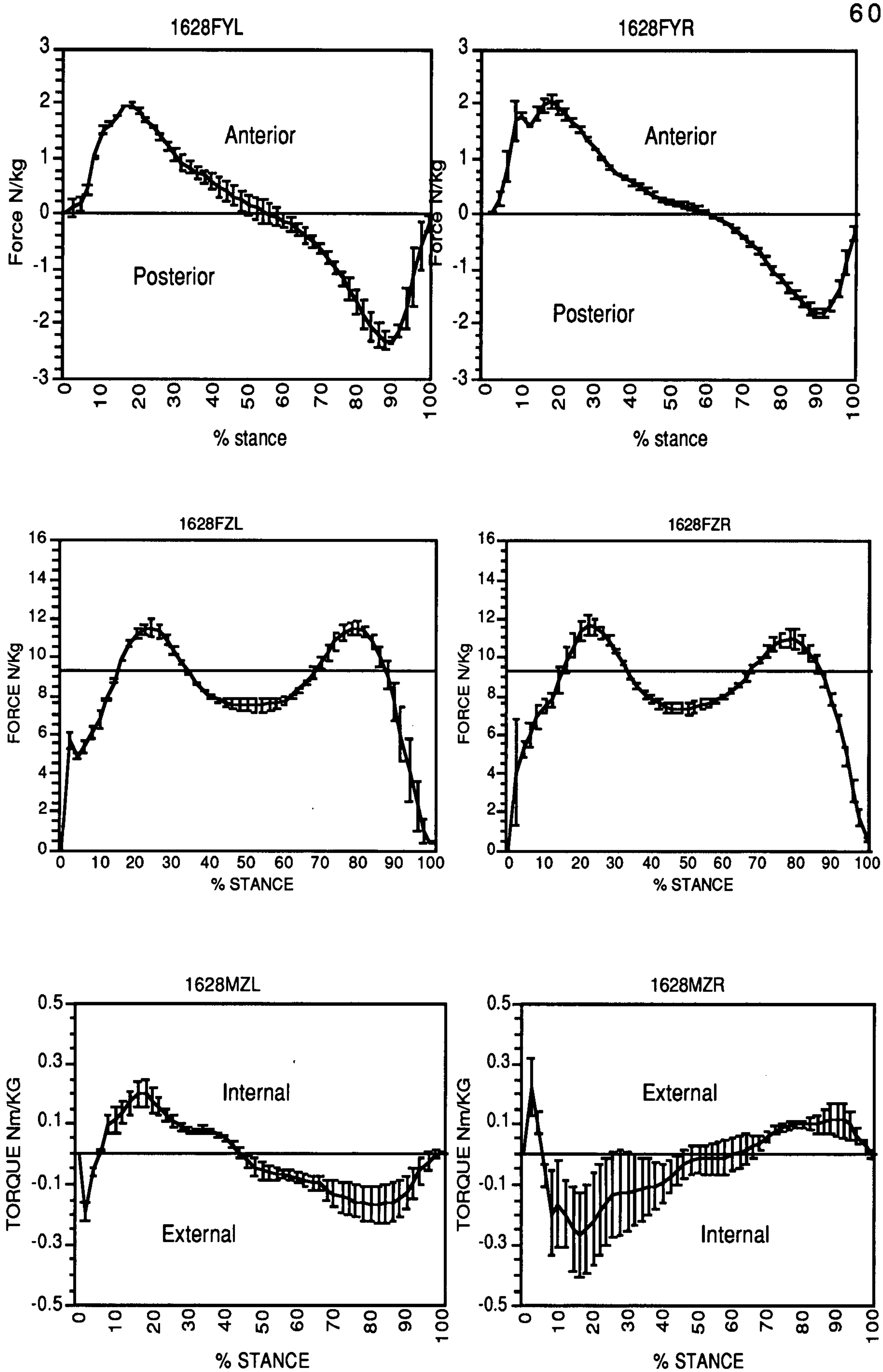

1627FYR
Anterior
Posterior
Force N/kg
% stance


1627FZL
FORCE N/Kg
% STANCE

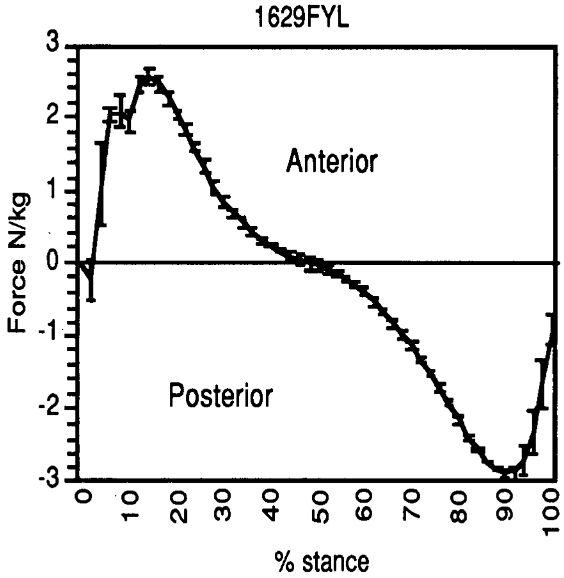

1627FZR
FORCE N/Kg
% STANCE

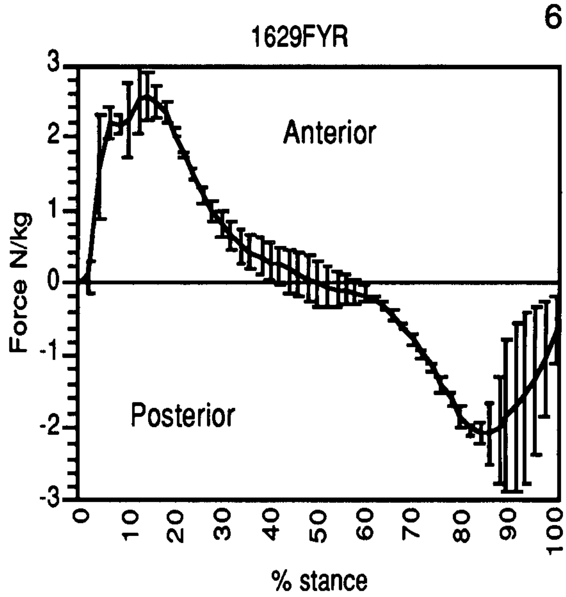

1627MZL
Internal
External
TORQUE Nm/KG
% STANCE

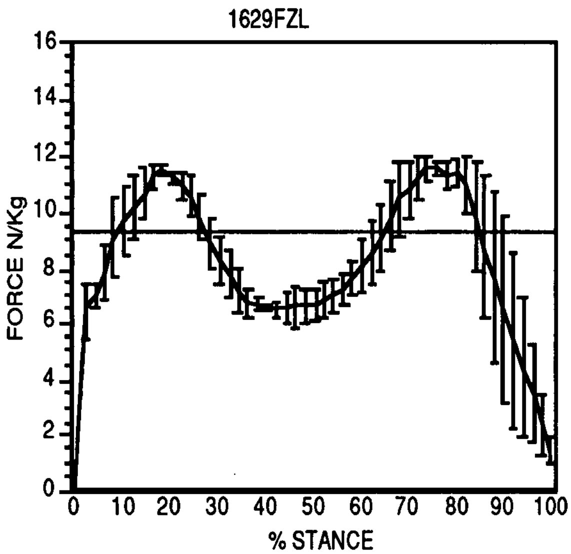

1627MZR
External
Internal
TORQUE Nm/KG
% STANCE

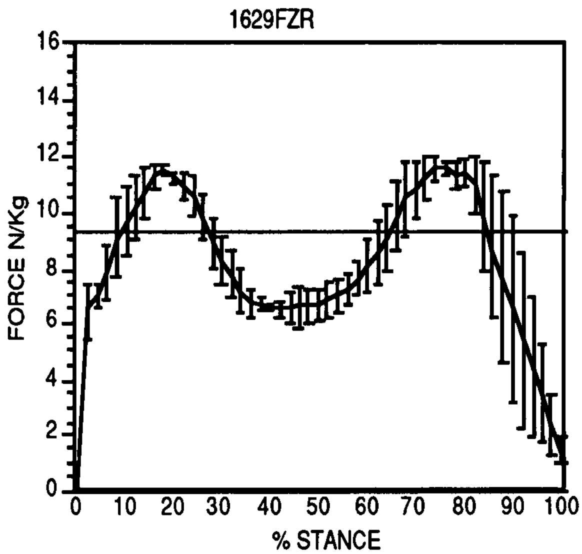


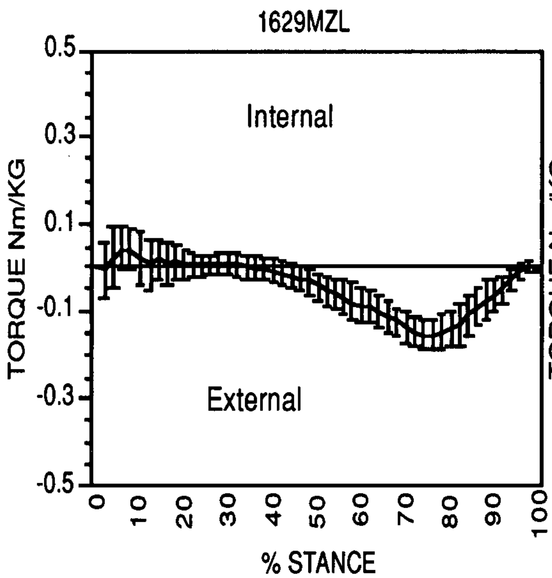
1628FYL
1628FYR
Force N/Kg
Anterior
Posterior
% stance
1628FZL
1628FZR
FORCE N/Kg
% STANCE
1628MZL
1628MZR
TORQUE Nm/KG
Internal
External

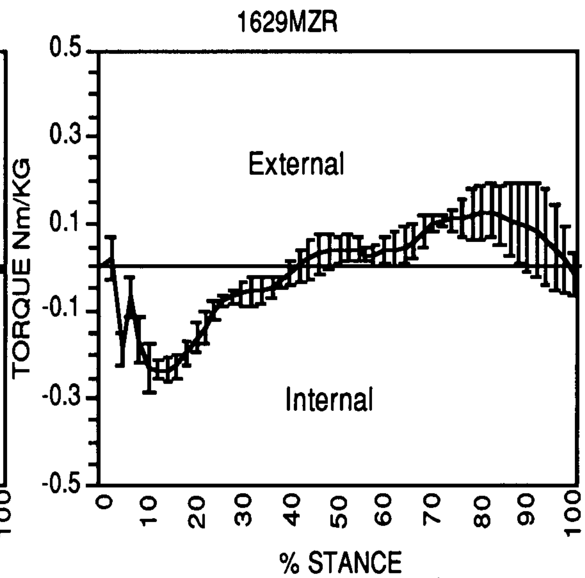

1629FYL
Force N/kg
Anterior
Posterior
% stance

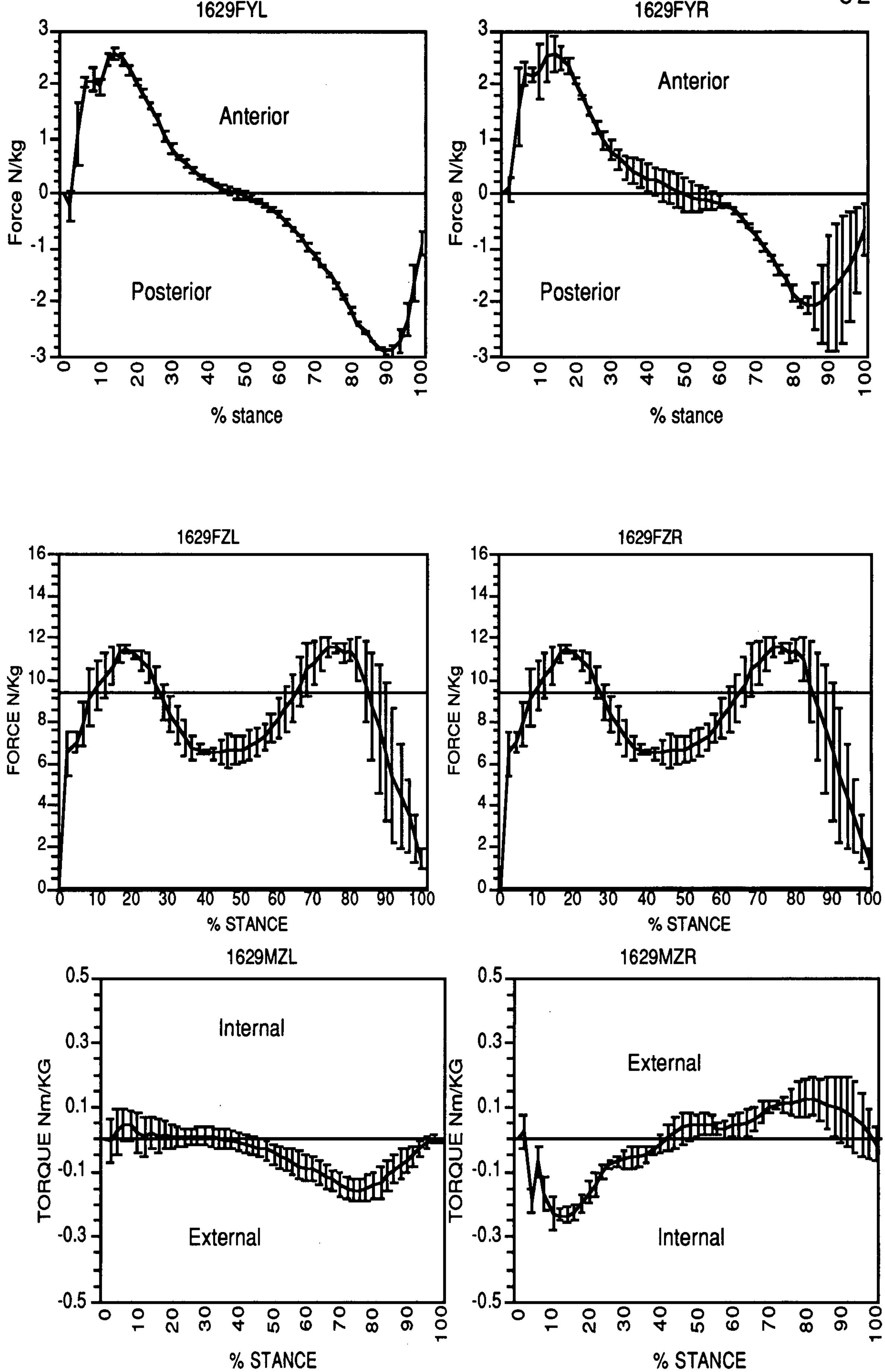

1629FYR
Force N/kg
Anterior
Posterior
% stance

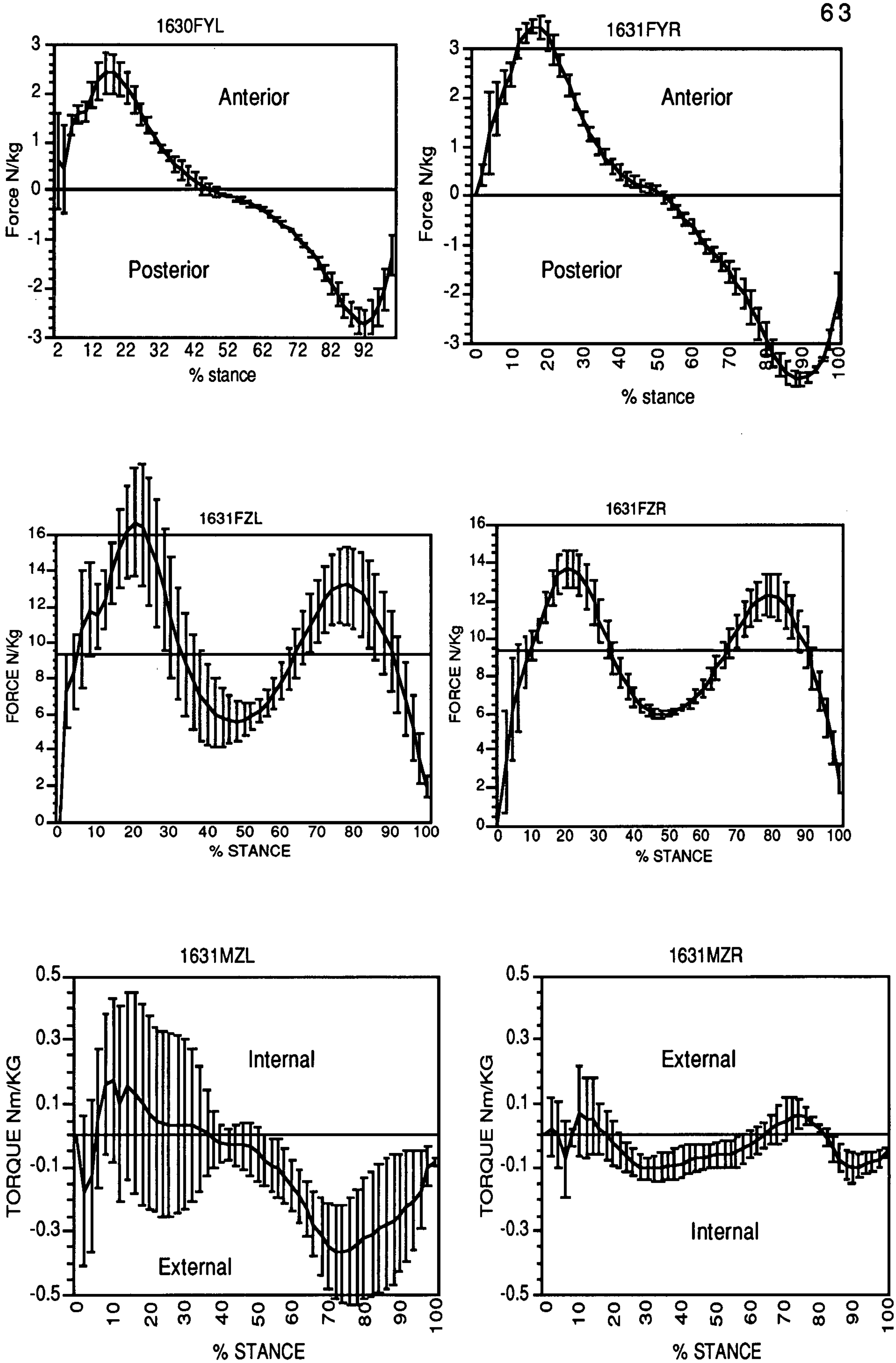

1629FZL
FORCE N/Kg
% STANCE


1629FZR
FORCE N/Kg
% STANCE

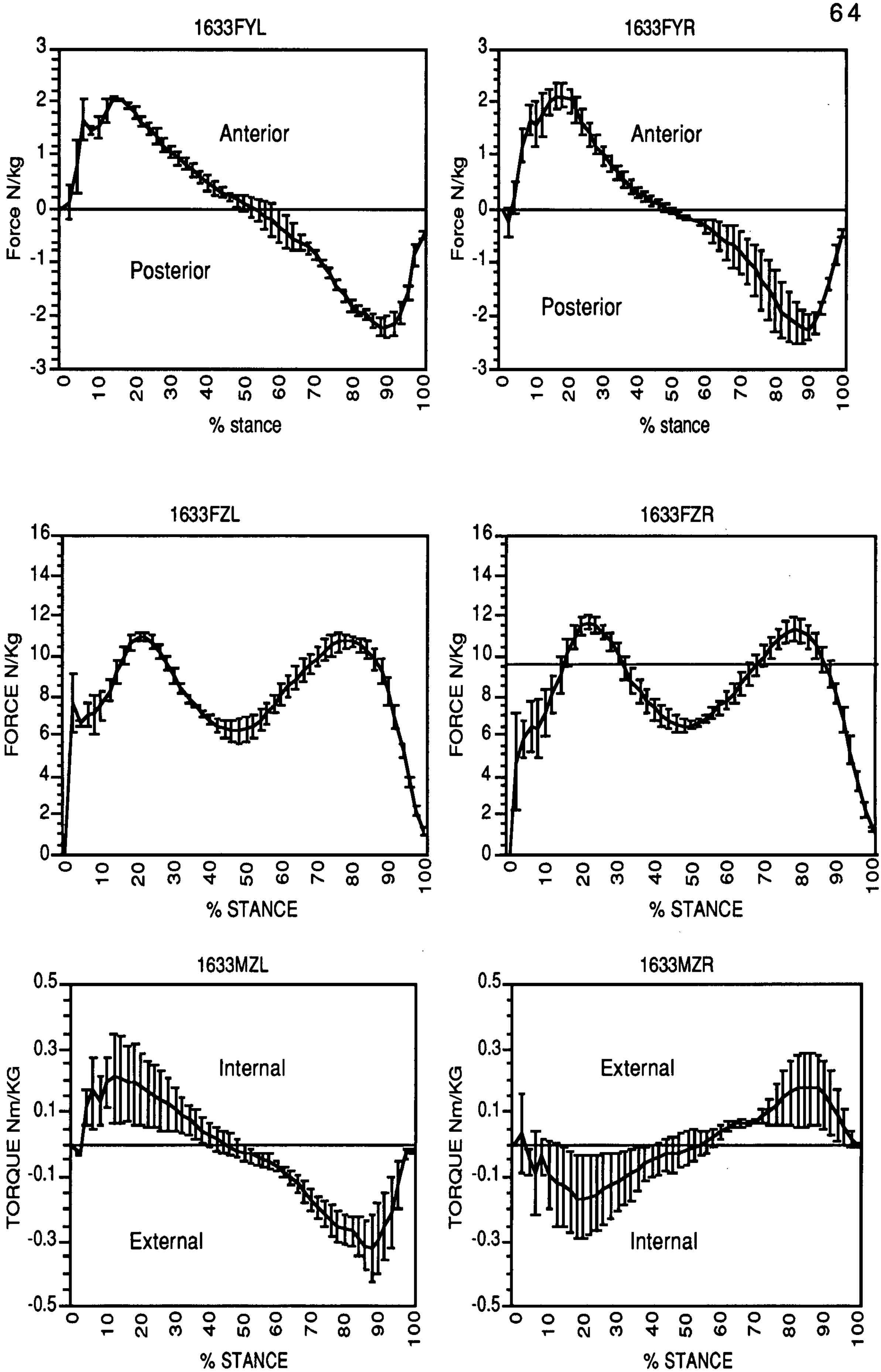

1629MZL
TORQUE Nm/KG
Internal
External
% STANCE

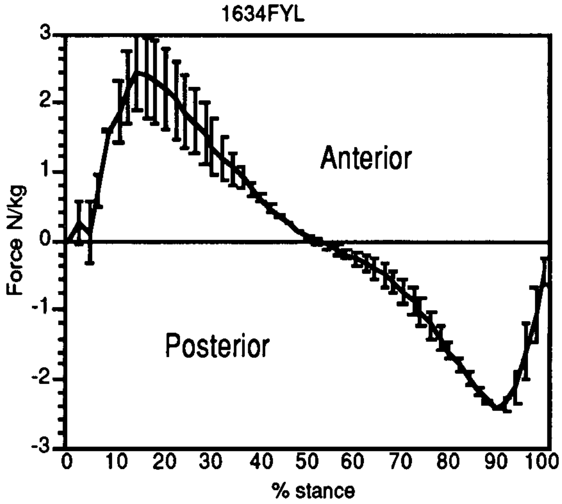

1629MZR
TORQUE Nm/KG
External
Internal
% STANCE

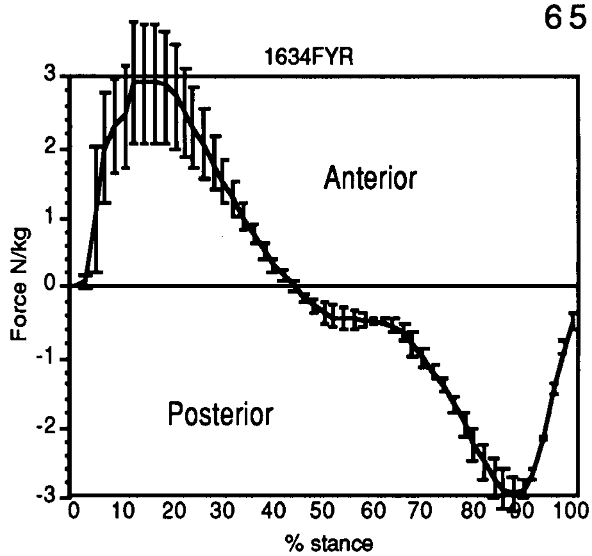

1629FYL
Force N/kg
Anterior
Posterior
% stance
1629FYR
Force N/kg
Anterior
Posterior
% stance
1629FZL
FORCE N/Kg
% STANCE
1629FZR
FORCE N/Kg
% STANCE
1629MZL
TORQUE Nm/KG
Internal
External
% STANCE
1629MZR
TORQUE Nm/KG
External
Internal
% STANCE



1630FYL
Anterior
Posterior
Force N/kg
% stance
1631FYR
Anterior
Posterior
Force N/kg
% stance
1631FZL
FORCE N/Kg
% STANCE
1631FZR
FORCE N/Kg
% STANCE
1631MZL
Internal
External
TORQUE Nm/KG
% STANCE
1631MZR
External
Internal
TORQUE Nm/KG
% STANCE


1633FYL
Force N/Kg
3
2
1
0
-1
-2
-3
Anterior
Posterior
0 10 20 30 40 50 60 70 80 90 100
% stance
1633FYR
Force N/Kg
3
2
1
0
-1
-2
-3
Anterior
Posterior
0 10 20 30 40 50 60 70 80 90 100
% stance
1633FZL
FORCE N/Kg
16
14
12
10
8
6
4
2
0
0 10 20 30 40 50 60 70 80 90 100
% STANCE
1633FZR
FORCE N/Kg
16
14
12
10
8
6
4
2
0
0 10 20 30 40 50 60 70 80 90 100
% STANCE
1633MZL
TORQUE Nm/KG
0.5
0.3
0.1
-0.1
-0.3
-0.5
Internal
External
0 10 20 30 40 50 60 70 80 90 100
% STANCE
1633MZR
TORQUE Nm/KG
0.5
0.3
0.1
-0.1
-0.3
-0.5
External
Internal
0 10 20 30 40 50 60 70 80 90 100
% STANCE


1634FYL
Force N/kg
% stance
Anterior
Posterior
3
2
1
0
-1
-2
-3
0 10 20 30 40 50 60 70 80 90 100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-1
-2
-3
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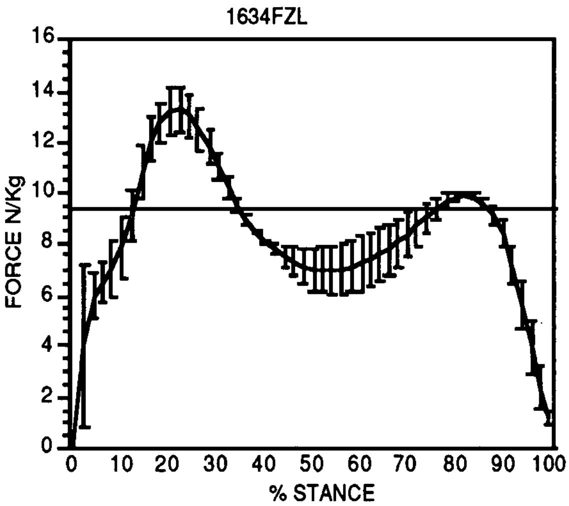
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FORCE N/Kg
% STANCE
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6
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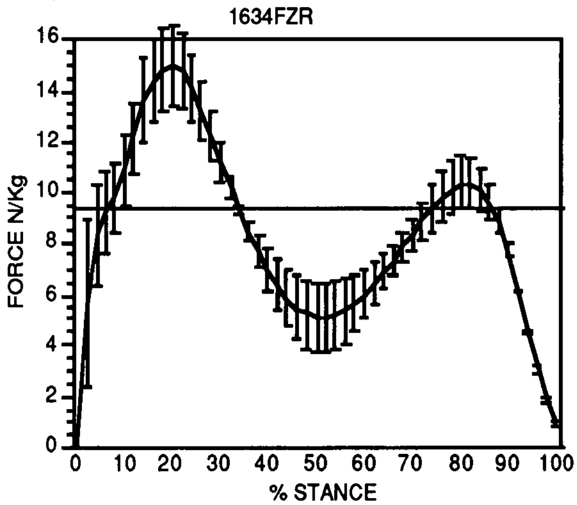
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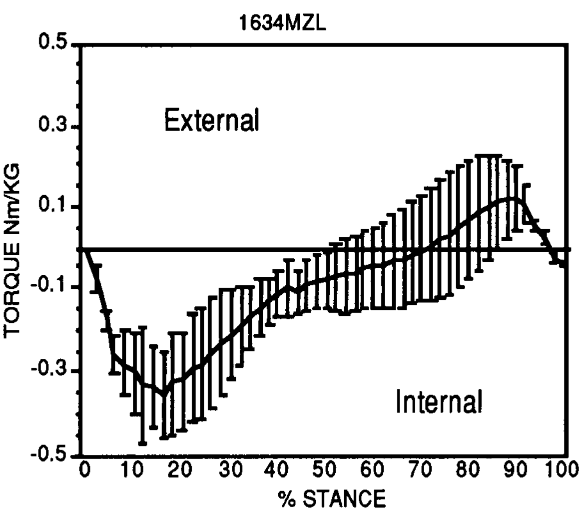
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TORQUE Nm/KG
% STANCE
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Internal
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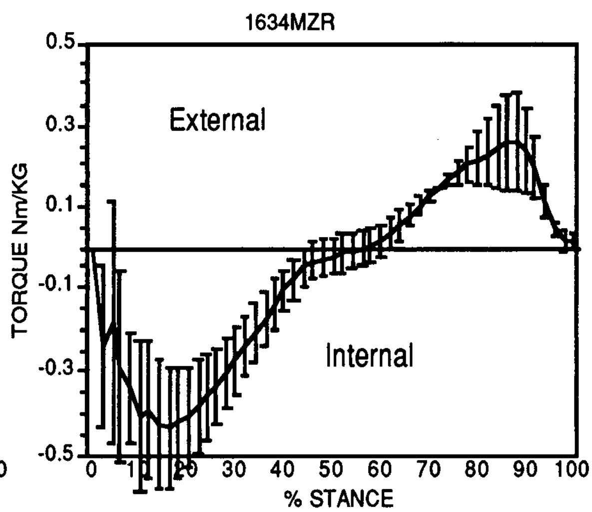
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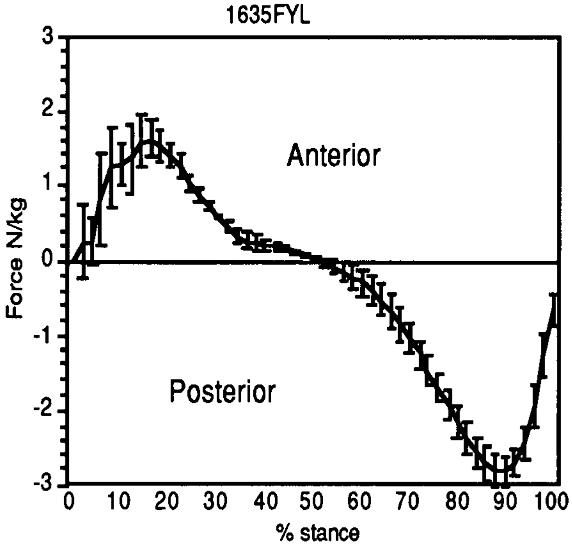
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Posterior
Force N/kg
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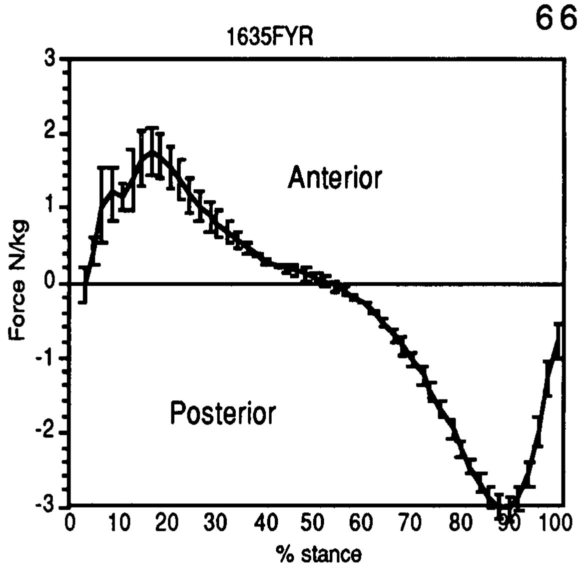
% stance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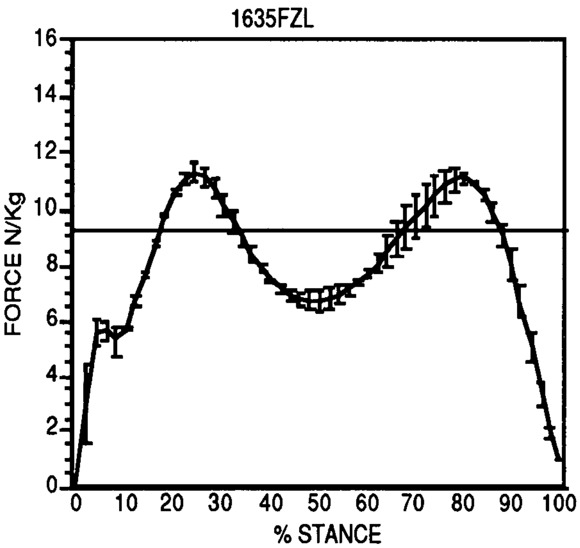
% stance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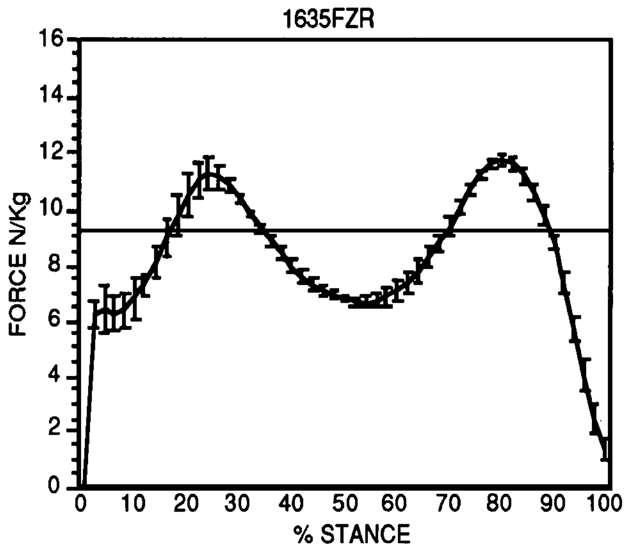
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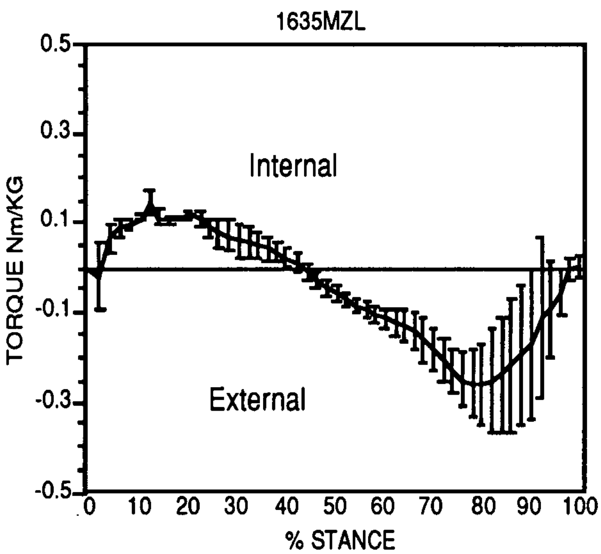
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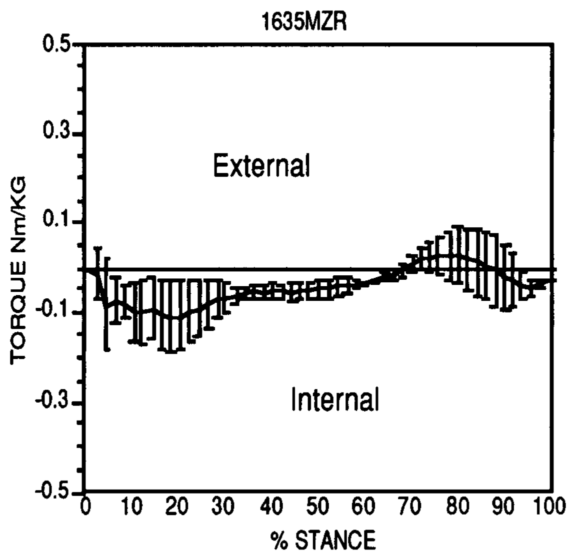
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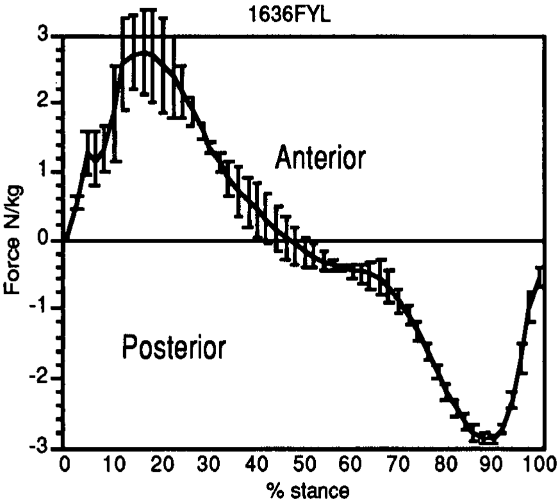
% STANCE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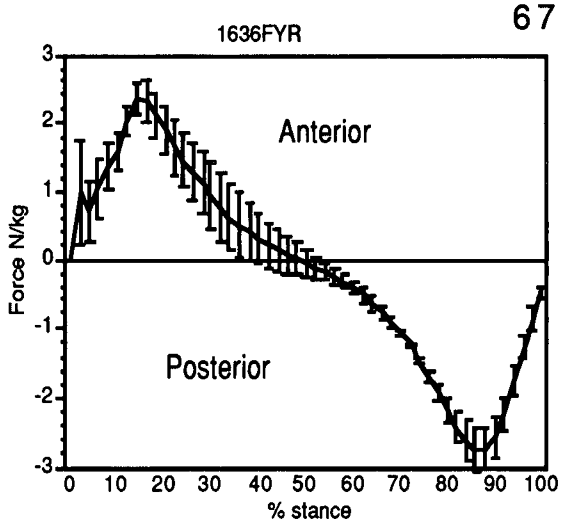
Anterior
Posterior
Force N/kg
% stance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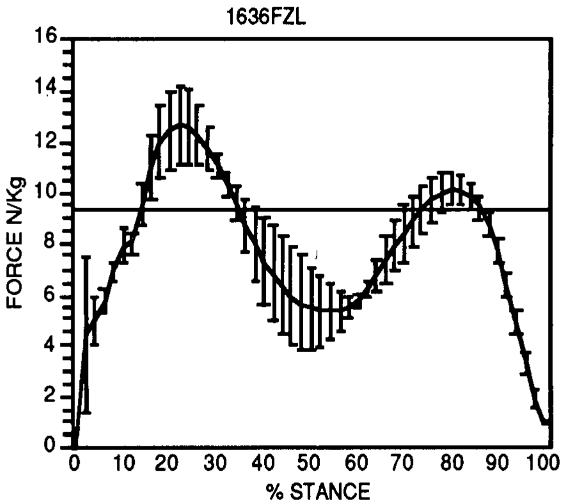
Anterior
Posterior
Force N/kg
% stance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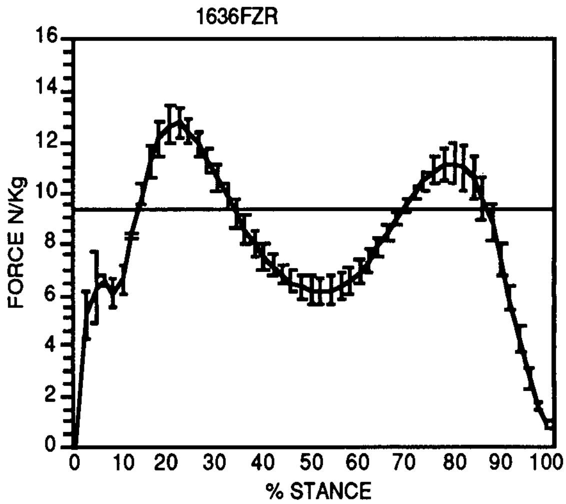
FORCE N/Kg
% STANCE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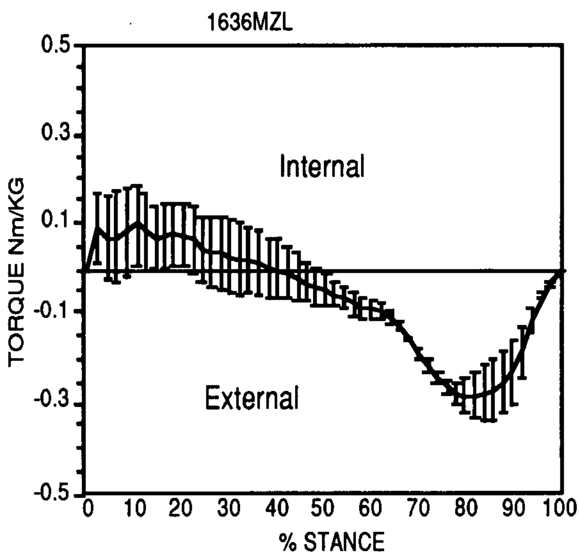
FORCE N/Kg
% STANCE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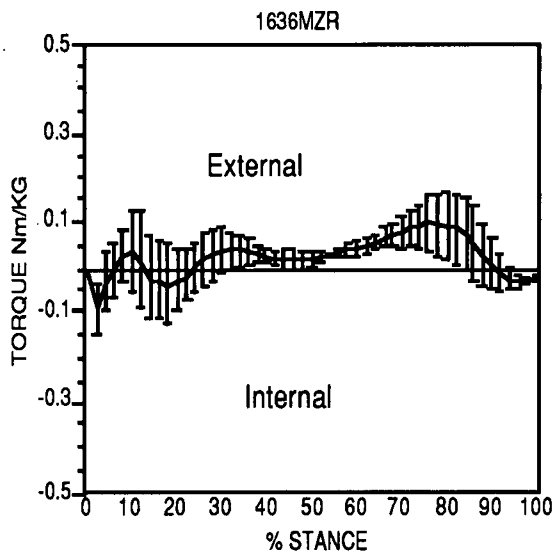
External
TORQUE Nm/KG
% STANCE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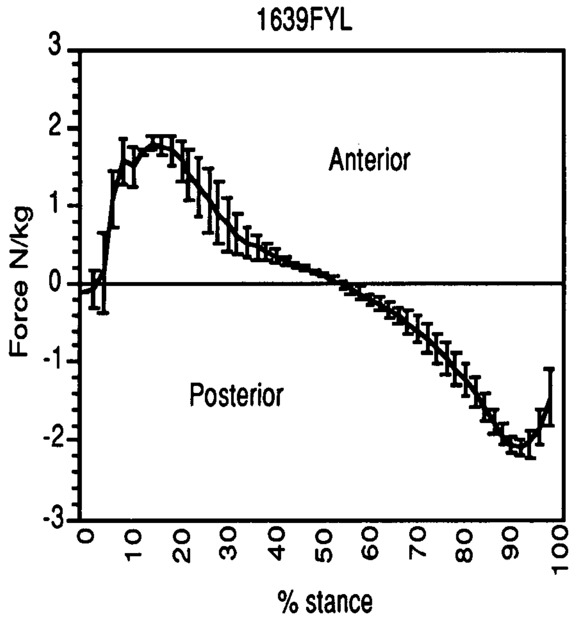
Internal
TORQUE Nm/KG
% STANCE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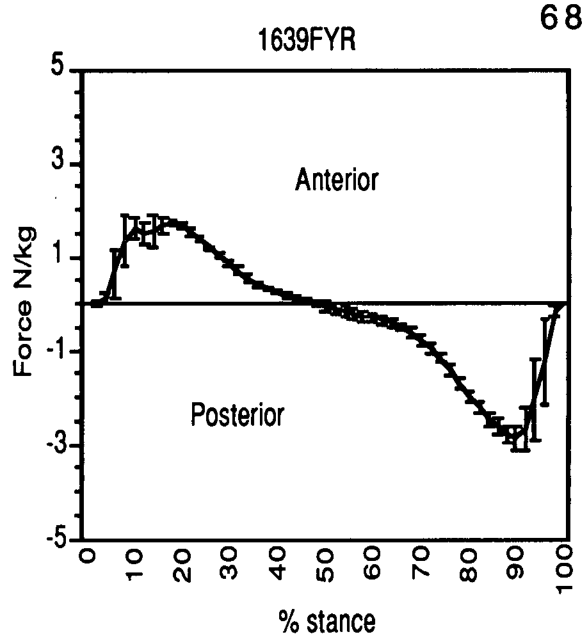
Anterior
Posterior
Force N/kg
% stance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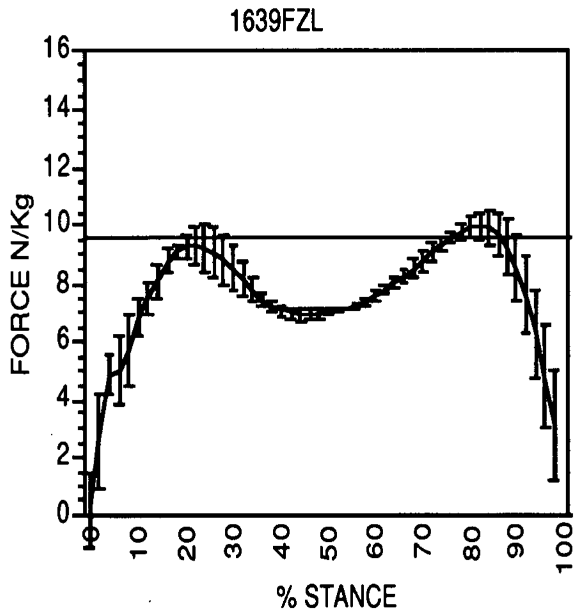
Posterior
Force N/kg
% stance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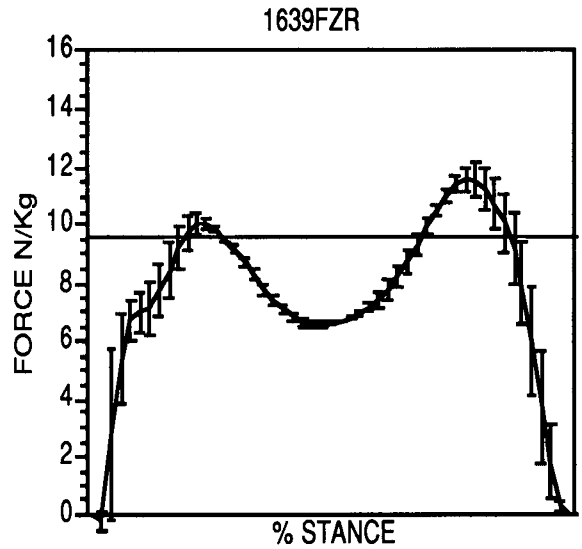
% STANCE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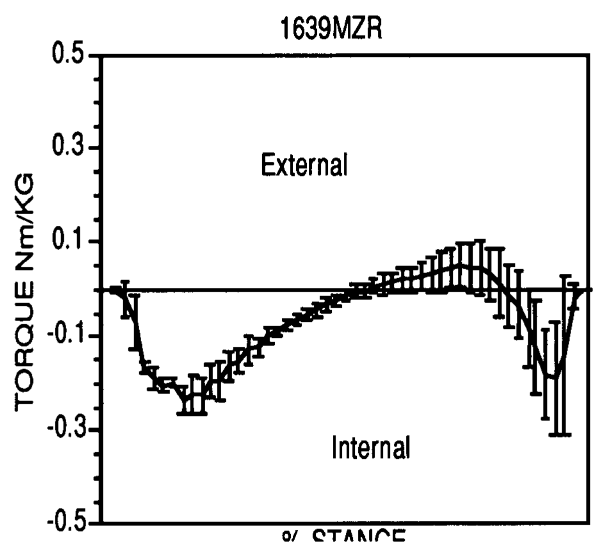
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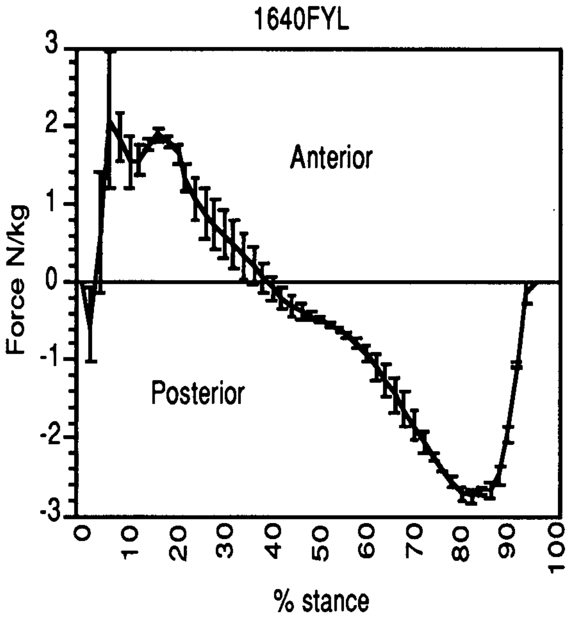
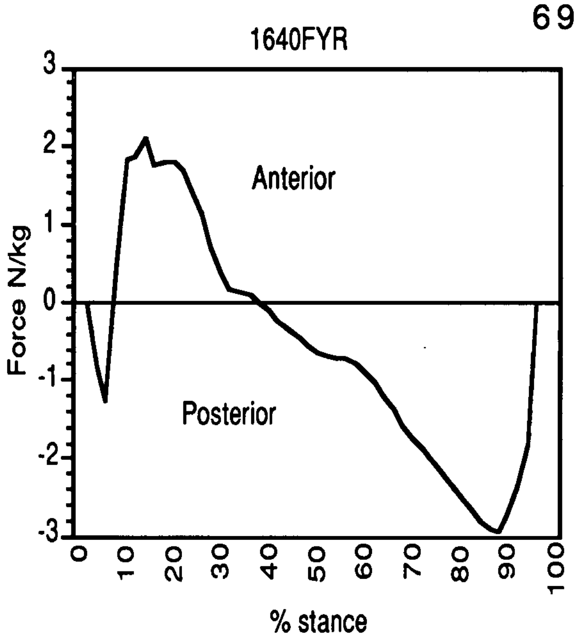
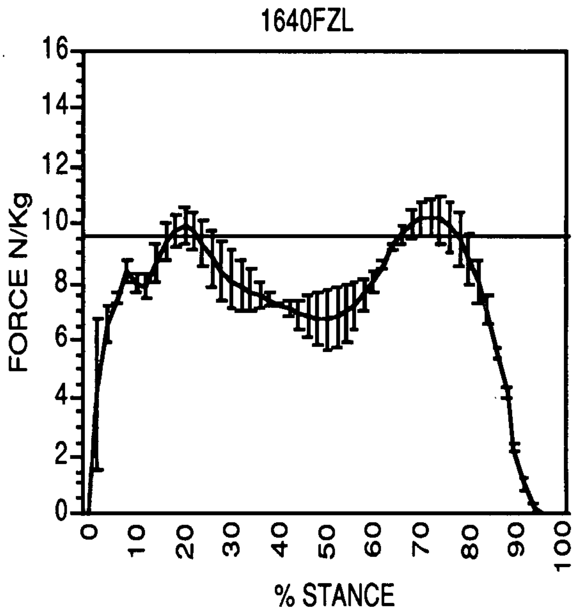
Internal
TORQUE Nm/KG


1640FYL
Anterior
Posterior
Force N/kg
% stance


1640FYR
Anterior
Posterior
Force N/kg
% stance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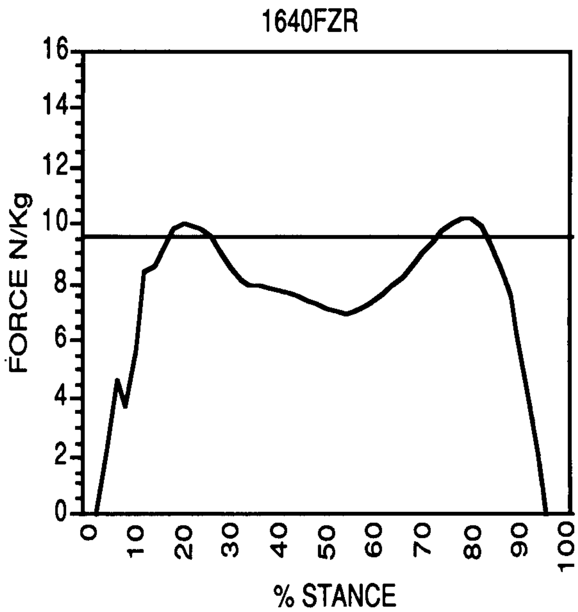
FORCE N/Kg
% STANCE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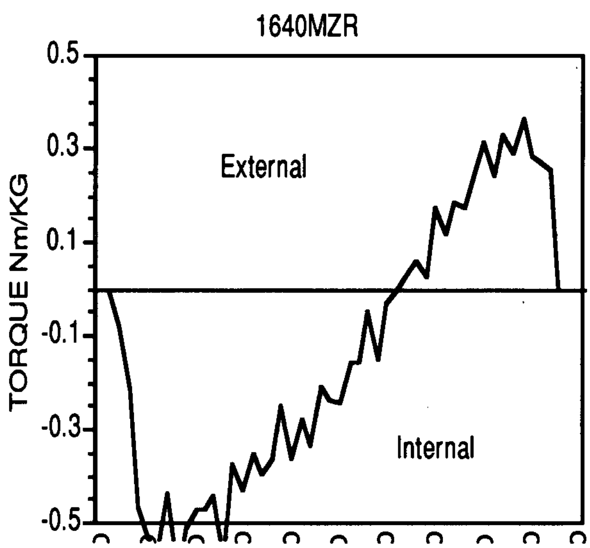
FORCE N/Kg
% STANCE


1640MZR
External
Internal
TORQUE Nm/KG

APPENDIX C

Pilot Studies

GROUND REACTION FORCES IN CLUBFEET

Clubfoot is one of the most common birth defects with the incidence being 2:1000 live births (Tachdjian, 1985). The child is born with a foot that is in equinus, has considerable forefoot adduction and a heel in varus. Without treatment, walking may be very difficult or impossible. The goal of the treatment is to have the child function as normally as possible. Unfortunately, the foot will never be normal. Assessment of the foot is made upon radiographic measures and clinical function. The gait of the child is assessed by the surgeon's visual judgement.

Objective measurements of gait of individuals with clubfeet is limited to two studies in the literature. One study only assessed the muscle action during gait using electromyography (Otis and Bohne, 1986). This study concluded that there were minor differences between the normal foot and clubfoot with respect to the medial gastrocnemius. and the tibialis anterior muscles. The unilateral clubfoot had no significant differences however, the bilateral clubfoot had increased duration of the medial gastrocnemius. Brand et al (1981), examined surgically treated clubfeet with respect to centre of path pressure. They concluded that there was no correlation between the centre of path pressure and the severity of the clinical deformity.

The purpose of this study was to examine the gait of children more closely using kinetic measures to get a clearer picture of what differences there may be between children with clubfeet and without. This study will more specifically compare children with unilateral clubfoot, bilateral clubfeet, and non-clubfeet, and to describe any differences. The objective of this study was also to determine whether adaptational changes in gait are performed by children with clubfeet which may be a concern for the child in adulthood.

METHODS:

Ground reaction forces were measured using a Kistler multi-component force platform with a 12 bit analog-to-digital converter interfaced to a Data General 20 desktop computer. The force platform output includes four components of the ground reaction force: vertical, antero-postero, medial-lateral, and vertical moment. These data were sampled through a the data is collected through a 64-channel analog-to-digital converter at a rate of 100 Hz. Walking speed was measured using photocells placed on each side of the platform at 3.15 m apart

Each subject was brought into the lab for orientation of the facilities and protocol. Sufficient practice was permitted to ensure that contact with the force platform will be made with a smooth, unbroken stride at the subjects' natural walking cadence. Trials which differed more than 5% of subject's average speed or for which targeting was evident were rejected. Data was retained from 3 successful trials from each leg at both the walking and running speeds.

RESULTS:

Clinical

Three subjects were used for this study: 1) with unilateral clubfoot; 2) with bilateral clubfeet; and 3) without clubfeet. The treatment for the both children with clubfeet was posterior medial releases. The child with unilateral clubfoot also had metatarsal osteotomies for severe forefoot adduction. Basic clinical data was taken for each child and in summarized in Table 2. The primary items to note are the differences in range of motion with respect to ankle dorsiflexion and plantarflexion, and the degree heel varus or valgus during standing. The child with bilateral clubfeet had considerable restriction in plantar flexion. She stood in an approximately 5 degrees of dorsiflexion and could not stand on her toes. In addition, she had significant heel valgus when standing, and the subtalar joint was considerably stiff with a relatively supple forefoot. The left foot was more severe than the right.

The child with unilateral clubfoot (left) had restriction in dorsiflexion, however, he did have a plantigrade foot when standing. He had significant heel varus which was rigid in addition to a rigid forefoot. He also had a 2 cm leg length difference.

Temporal Gait Characteristics:

There were considerable differences in individual natural speeds in these children. In the normal child, the child with bilateral clubfeet, and the child with unilateral clubfoot the average walking speeds were 1.35 m/s, 1.04 m/s, and 1.51 m/s, respectively (Table 1).

Medial - Lateral Forces (Fx):

The medial-lateral ground reaction forces were significantly different for each child (Tables 1 & 3, Figures 1 & 2). The normal child peaked at an average of .051 body weight (BW) with an impulse of 3.3 Ns. The child with bilateral clubfeet averaged .092 BW with an impulse of 6.9 Ns, being greater on the left. The pattern was somewhat similar to the normal child's pattern with a general increase in amplitude, however, there was some peaking at 20% and 80% of stance (heel strike and push-off). The child with unilateral clubfoot averaged peak forces of .119 BW and impulses of 6.8 Ns. The pattern for the right foot had two distinct peaks which occurred at heel strike and toe-off. In the left foot, a larger peak occurred at heel strike with a lesser peak at toe-off. Overall, it appeared that the children with clubfeet require a wider base of support during gait.

Antero - Posterior Forces (Fy)

The antero-posterior forces showed some interesting but less dramatic differences between each subject (Tables 1 & 3, Figures 3 & 4). The general patterns were consistent with the normal child, except in the bilateral child's left foot where propulsive forces begin much earlier than normal and remain gradual throughout the propulsive part of stance. This is reflected in the amplitudes where the differences are most obvious. The child with unilateral clubfoot had greater peak forces for both anterior and posterior directions, while the child with bilateral clubfeet had considerably less.

With respect to braking and propulsive forces, the greatest asymmetry occurred in the normal child. The net impulses imply a greater propulsive force in his right foot while a greater braking force in his left. The child with bilateral clubfeet had a small increase in propulsion in her left foot. For the child with unilateral clubfoot it is difficult to interpret, as it appears he is increasing his speed due to increased propulsive forces on both sides.

Vertical Forces (Fz)

The vertical forces again show the most obvious differences in amplitude while the general pattern is somewhat similar in each child (Table 1 & 3, Figures 5 & 6). The child with normal feet reaches vertical forces at heel strike at about 1.14 body weight (BW) and for toe off approximately 1.07 BW. For the right side, the child with bilateral clubfeet reaches 1.24 BW at heel strike with a considerable decrease in force at toe-off (1.12BW). On the left side, her heel strike forces average 1.06%BW while she does not reach the level of full weight bearing as expected at toe-off (.88 BW). For the child with unilateral clubfoot the heel strike amplitudes are generally increased (1.5 BW) and with greater unloading at mid-stance as often seen during faster cadences. On his left side, also, the peak vertical force at toe-off is significantly less than his right, 1.14 and 1.25, respectively. It is interesting to note that there is a small normal peak at initial heel strike in only the children with clubfeet on their clinically worse side.

Vertical Free Moment

The vertical free moment measures clearly showed the discrepancies between the two clubfeet results (Table 1, Figures 7 & 8). The free moment in the normal child follows the pattern of initial internal moment with external moment at toe off. His net resultant impulses for his right and left sides are .21 Nm/s internal, and .91 Nm/s external, respectively. There is some differences in amplitude between his two sides however, the pattern is fairly consistent. The child with unilateral clubfoot follows the same pattern with dramatic increases in amplitude, with an especially large internal moment on his affected side. His resultant impulse being internal in both feet, .52 Nm/s for his right and .80 Nm/s for his left. On her right side, the child with bilateral clubfeet follows the pattern of an internal moment followed by external moments with a net external resultant impulse of 1.02Nm/s. However, on her left side the pattern is the exact opposite. She begins with an external moment until an internal moment at toe off. The net external resultant impulse being twice that of her right (2.47 Nm/s).

DISCUSSION:

In order to understand what is happening in the gait of children with clubfeet, it is important to understand the articulations of the normal foot and the clubfoot , and the basic biomechanics in the foot.

Normal Anatomy and Articulations:

The ankle joint is an articulation between the talus, the tibia, and the fibula. The tibia articulates with the superior surface (trochlea) and the medial side of the talus, while the fibula articulates on the lateral side. The talus is wider anteriorly, thus securing the talus into the ankle mortise during dorsiflexion. The ankle joint articulates only in the sagittal plane.

The subtalar joint is the articulation between the talus and the calcaneus. There are three articulations involved in this joint. The posterior articulation is between the concave facet of the talus and the convex facet of the calcaneus. The middle articulation is between the facet on the undersurface of the talus and that on the sustentaculum tali of the calcaneus. The anterior articulation is between the convex undersurface of the head of the talus and a small concave facet on the calcaneus (Riegger, 1988). This joint is a simple single-axis joint which behaves like a mitered (oblique) hinge (Morris, 1977). As a result of the oblique rotation at this joint, the net articulation is in both the sagittal and the coronal planes.

The transverse tarsal joint consists of the talonavicular and the calcaneocubiod joints. The flexibility and angle of axes of these joint are directly related to the postion of the subtalar joints. When the hindfoot is everted the axes of the joints are parallel and motion is quite free, however, during inversion, the axes are no longer parallel and the motion is restricted . Movement of this joint is primarily in the plane of abduction/adduction (Czerniecki,1988).

The metatarsalphalangeal break refers to the oblique axis through the second to fifth metatarsalphalangeal joints. The purpose of this oblique axis is to distribute the weight to all the metatarsal heads rather than just on the longest only.

The clubfoot:

The primary differences in the clubfoot compared to the normal foot appear in the subtalar joint. Of all the bones in the clubfoot, the talus is least displaced but has the most changes. The bones surrounding talus seem to be adapting to these changes.

The neck of the talus has an increased medial deviation (15-30 deg.> normal), thus the articulation with the navicular is oriented in a more sagittal plane compared to the normal coronal plane. The medially displaced navicular may even articulate with the medial malleolus in very severe cases.

The posterior concave facet of the talus body is less well developed and more shallow and the plantar facets of the head often appear as one continuous flat surface which correlate with similar findings on the superior surface of the calcaneus. In addition the calcaneal posterior tuberosity is displaced upwards and laterally while the anterior end is displaced downward, medially, and inverted under the head of the talus. In the clubfoot, the articulations of the subtalar joint are considerably limited with increasing rigidity in the severe clubfoot (Turco, 1981).

Due to the equinus nature of the foot, only the posterior surface of the talus articulates with the ankle mortise. The anterior portion of the talus never articulates in the mortise, therefore, not developing the normal contours to articulate with the medial and lateral maleoli, thus restricting normal range of movement in the ankle.

Normal Biomechanics:
The motions foot are not independent of the rest of the lower extremity, but more importantly the foot accommodates for what is happening proximally. During walking, rotation of the pelvis causes the femur, tibia and fibula to rotate about the long axis. The magnitude of this rotation increase progressively from pelvis to tibia (6 - 18 deg).

During the swing phase and early stance the tibia internally rotates. To keep the weight distributed over the long axis of the leg and to absorbed the forces at heel strike, the foot compensates with an eversion of the calcaneus. Eversion is initiated by two mechanisms. The point of contact between the floor and heel is lateral to the center of the ankle joint, where the weight of the body is transmitted to the talus. Loading the limb created a valgus thrust on the subtalar joint (Perry, 1983; Wright, 1964). This eversion results in a pronation of the tarsalphalangeal joints which creates a supple midfoot for absorption of increased forces.

During midstance and push-off, the pelvis begins to rotate externally. Because the forefoot is now fixed on the ground, the lateral rotation is transmitted to the talus in the ankle mortise. The calcaneus in response, inverts under the talus resulting in supination of the foot. (Rodgers, 1988). The strong contractions of the triceps surae also tighten the plantar aponeurosis to create a rigid lever for push-off (Perry, 1983).

The ankle and foot act together in an oblique nature. During dorsiflexion, the hindfoot is often everted and and the midfoot pronated. During plantarflexion, the heel is inverted and the midfoot supinated. For normal kinematics during gait the ankle moves to a maximum of 9.6 deg of dorsiflexion and 19.8 deg of plantar flexion (Winter, 1987). The hindfoot moves into 10 deg of valgus during heel strike and then returns to neutral or occasionally slight varus during push-off (Perry, 1983).

The clubfoot:
The talus is an integral component to the biomechanics of the foot. Because the talus is involved in articulations on all of its sides, any changes to the shape of the talus will affect these articulations and the overall biomechanics of the foot.

In this study, two subjects with clubfeet were examined. The child with unilateral clubfoot had restricted dorsiflexion being only able to attain neutral position on his affected side, in addition to a varus heel position and rigid hindfoot and forefoot. The child with bilateral clubfeet had minimum active plantar flexion against body weight. She, too, had a rigid hindfoot held in considerable valgus, but had a supple forefoot.

The dorsiflexion limitation in the unilateral clubfoot possibly explains his relatively large vertical forces. The normal peak forces in the first 20% stance is between .8 to 1.3 body weight (Czerneicki, 1988). In this child, he reached 1.5 BW. A reason for this is increase may be that due to his restriction in dorsiflexion and his relative supinated foot. Energy that is normally absorbed during pronation and dorsiflexion is instead stored in potential kinetic energy (ie. such as in an egg rolling). If we were to look at vertical changes in center of mass, we would expect to see a greater vertical displacement. However, It is difficult to determine whether the increase is totally due to change in center of mass or because of his increased speed relative to the other two children. As walking speed increases, greater amplitude differences are seen in vertical forces (Winter, 1986). The increase in amplitudes are also seen in antero-posterior forces.

The restriction of active plantar flexion in the bilateral clubfeet is not as apparent in vertical forces. The energy is normally absorbed at heel contact, but because of her inability to supinate and plantarflex her feet, she cannot create a rigid lever for propulsion. Her second vertical peak force at push off is limited. This lack of propulsive force is clearly evident in her low posterior peak force, which is also reflected in her overall speed (1.05 m/s vs 1.40 m/s in the normal).

The subtalar joint acts as a directional torque transmitter. The axial torques about the long axis of the foot or tibia induces torques about the long axis of the other segment (Czerneicki, 1983). For example, with the internal torque produced in the tibia during the initiation of stance, the foot rapidly pronates under the load of body weight. In contrast, the external rotation torques produced in the lower extremity indued from the accelerating swing contralateral in the contralateral limb results in a supination of the foot. The foot's primary role is to absorb and transmit forces (Tiberio, 1988). The restriction of the subtalar to absorb and transmit force in both of these children is apparent in the vertical free moment.

If the role of the foot is to compensate for the torque being produced at higher segment levels, then ideal foot should produce a small resultant net torque. From Figures 7 & 8 we see that in the normal child and the child with unilateral clubfoot's normal foot, the net resultant torque is relatively small compared to the clubfeet. For bilateral clubfeet there is net residual external torque in both feet implying the foot's inabilty to compensate for the external torque created in the tibia and femur. For the more rigid subtalar joint (left), the net impulse is double. Because her feet are oriented in the valgus position, she can compensate for the internal torque but not the external torque. The opposite case is true for the unilateral clubfoot. Due to the varus nature and the rigidity of the hindfoot, the foot cannot compensate as well for the internal torque, however, not to the same degree.

Loss of subtalar motion denies the leg the use of its horizontal rotational component. The horizontal torque between the leg and the foot increases, unless another source of horizontal rotation becomes available. In many patients who have had a triple arthrodesis or subtalar arthrodesis, deformity develops in the ankle joint. The talus becomes loser in the mortise. Traumatic arthritic changes are often then found (Close et al.,1967). The growth potential in children allows joint remodelling leading to a "ball and socket joint" (Perry,1983).

SUMMARY:

Two results of treated clubfeet were examined. One child was left with a valgus deformity and limited plantar flexion while the other was left with a varus deformity and limited dorsiflexion and both having rigid subtalar joints. Both of these children are left with an alteration in their gait patterns. Because of the potential for growth remodelling, the ankle joint may become more of a ball and socket. However, because of the general poor development of the talus and the lack of understanding to the cause of the clubfoot, the possibility of good remodelling is slim. Due to the rigid hindfoot, these children will likely develop degenerative changes in the ankle joint in adulthood.

The effects of his deformity are obviously compensated for to some degree, in the child with unilateral clubfoot, by having another foot with full range of motion. Aside from his differences in free moment, he has managed to keep a relatively symmetrical and efficient gait. An inability to pronate to absorb forces can be compensated at the knee and hip, putting more strain on these joints. So far no one has looked at how much compensation may occur at other joints, nor has documented degenerative changes in other joints in individuals with clubfeet.

The child with bilateral clubfeet has greater difficulty in overcoming her deformity with respect to efficiency in gait, being her natural speed quite slow. She can, however, absorb the impact of the vertical forces better because of the foot's ability to pronate and create a supple forefoot. She may not develop secondary changes in other joints due the inability for shock absorption but due to the inability to compensate for torsional forces.

PEAK FORCES N/KG

Thu, Dec 7, 1989 17:10

	CONDITION	M-L	ANTERIOR	POSTERIO	VERTICAL	VERTICAL2
1	RT-NORMAL	-0.042	0.192	0.166	0.159	0.128
2	LT-NORMAL	-0.060	0.245	0.216	0.151	0.069
3	RT-BILATERAL	-0.064	0.201	0.154	0.105	0.001
4	LT-BILATERAL	-0.113	0.120	0.186	0.060	-0.118
5	RT-UNILATERAL	-0.108	0.300	0.343	0.494	0.252
6	LT-UNILATERAL	-0.130	0.298	0.303	0.521	0.145

CLUBFOOT-CLINICAL Thu, Dec 7, 1989 15:52

	CONDITION	AGE	HEIGHT	WEIGHT	DORSI	PLANTAR	TOTAL	CALF	LEG LENGTH	HEEL POSITON
1	RT-NORMAL	8								
2	LT-NORMAL									
3	RT-BILATERAL	8	131	28.80	10	20	30	25.0	66	VALGUS 15
4	LT-BILATERAL				20	15	35	24.0	66	VALGUS 10
5	RT-UNIATERAL	11	136	32.21	18	40	58	25.8	69	NEUTRAL
6	LT-UNILATERAL				0	30	30	21.0	67	VARUS 15

Figure 1

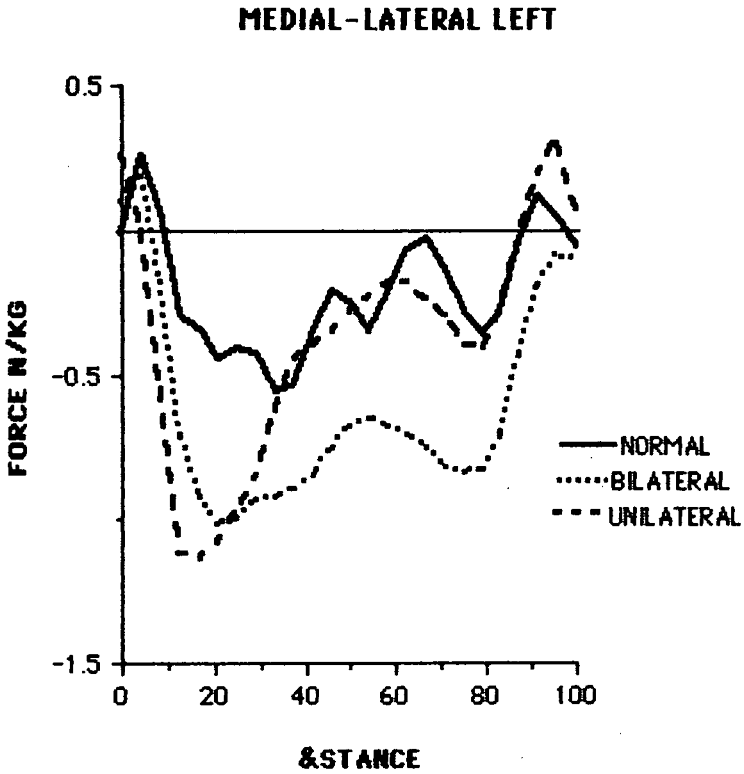


Figure 2

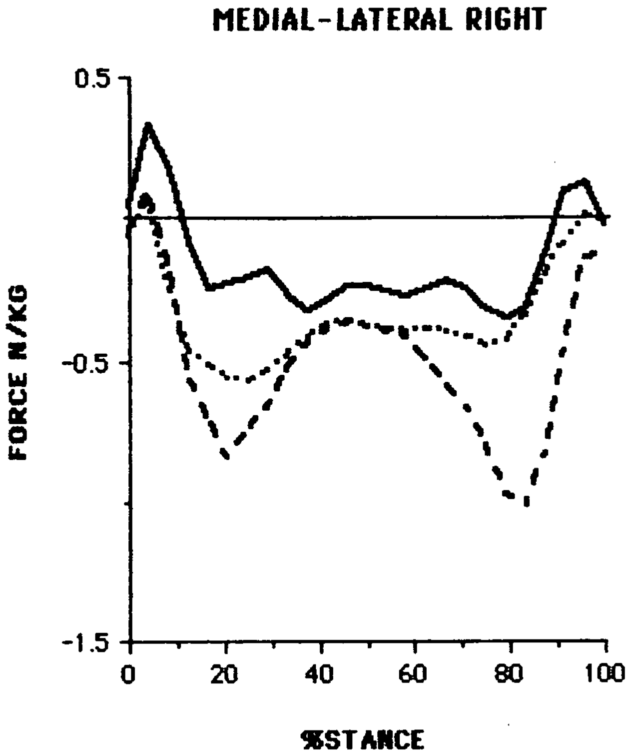
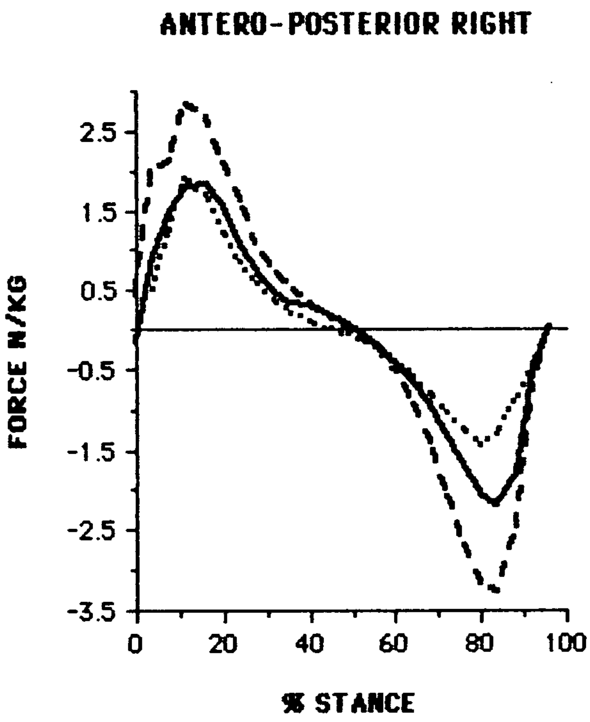


Figure 3



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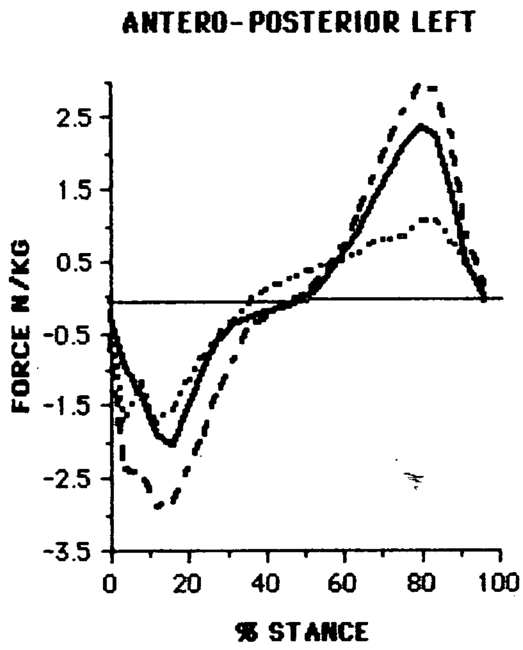

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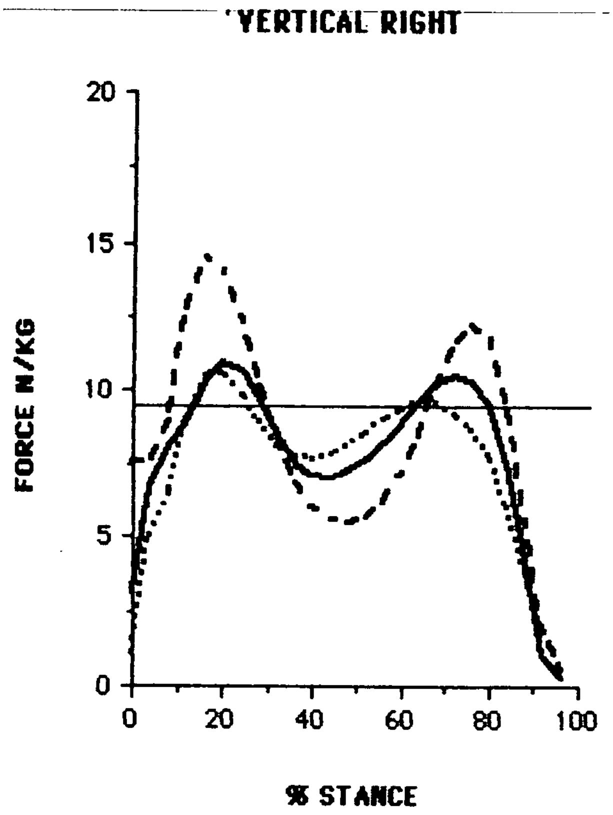

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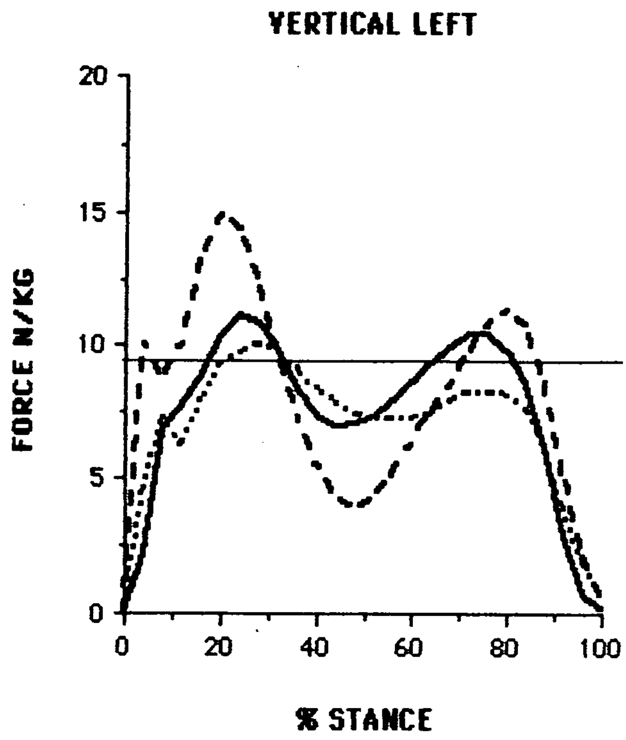

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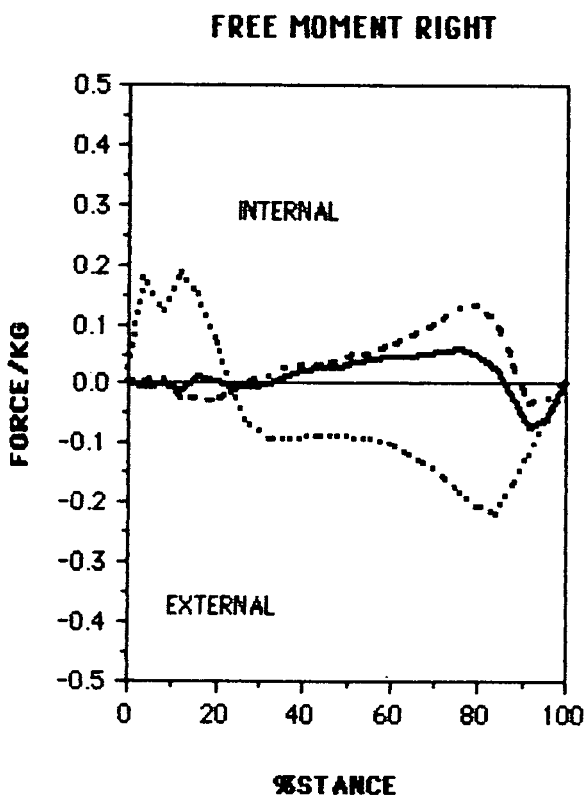
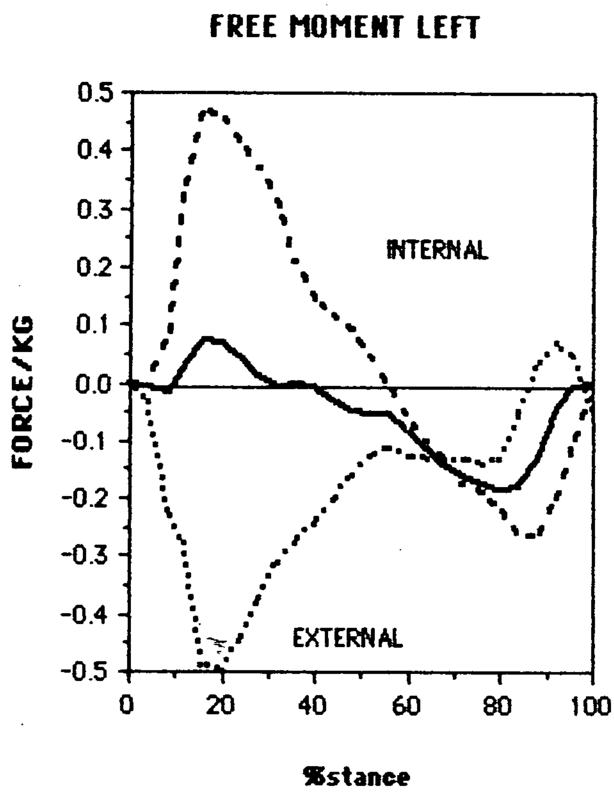


Figure 8



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THE FOOT AND VERTICAL TORQUE DURING WALKING

BONITA J SAWATZKY

PHED 573

APRIL 1990

Introduction:

Since the advent of computerized gait analysis, countless numbers of articles have evolved to show the usefulness of such analyses for clinical purposes. The force plate, in particular, has been most commonly useful for measuring ground reaction forces during walking in amputees using prosthetics. The primary purpose of the force plate is to determine how well a person's leg or prosthesis absorbs forces at heel strike and how efficient propulsion is at toe off. If force plate analyses is combined with filming, joint torques can also be calculated.

In the literature, the force plate has been used to look at vertical, antero-posterior, and lateral impulses. The Kistler force plate also measures the degree of vertical torque produced, however, only two studies in the literature have used this variable to analyze gait (Close & Inman, 1953; Schoenhaus et al, 1979). Both of these studies suggested that the degree of torque is a reflection of internal and external rotations of the leg during the stance phase in gait, however, only Scheonhaus et al (1979) tried to relate subtalar function specifically to the vertical torque (Mz) patterns obtained from the force plate. Their findings showed an initial external rotation at heel strike followed by a greater internal torque before mid stance, changing to an external torque ending with a small internal torque. The amplitudes of the torques remained relatively small which they explained to show the functional absorption of the rotational forces by the subtalar joint.

The purpose of this study was to confirm the findings in the literature, to propose clinical usefulness to this measure, as well as to discuss limitations of Mz as a measurement. The results represented in this study are from a group of normal adult subjects plus three case studies.

Methods:

A group of 14 normal adult gait data was obtained from pre-existing computer files in our biomechanics laboratory. The collection technique and the Mz raw data was obtained for analysis. In addition, three subjects with various disorders of the hindfoot were brought in for gait analysis at their natural walking speeds. One subject was 38 year old woman who had a surgical arthrodesis of her subtalar joint, post injury. Two subjects were children with clubfeet who had undergone soft tissue surgery. The young girl (8 years) had bilateral clubfeet, and the young boy (10 years) had a unilateral clubfoot. In addition to the biomechanical analysis, clinical assessments of the two children's feet were done. The measurements included ankle range of motion, subtalar range of motion, and heel position on during weightbearing.

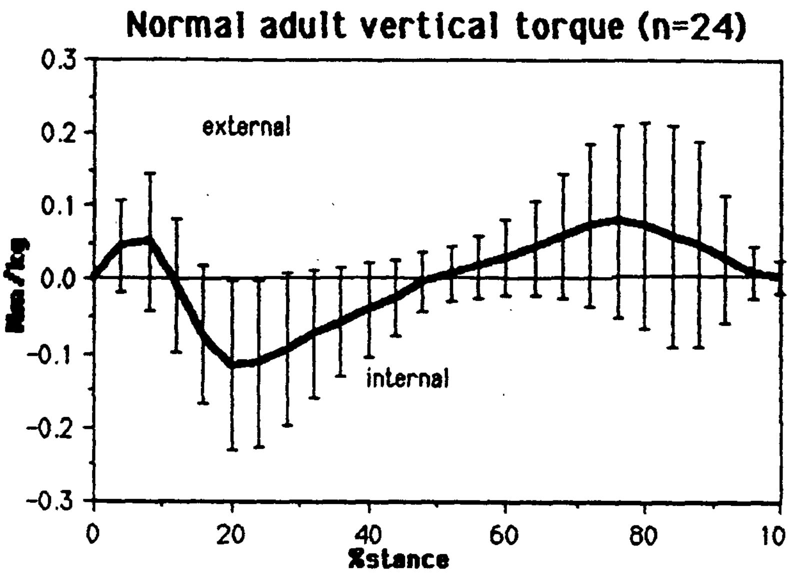
All the subjects included in this study were assessed using the following equipment and protocol. Ground reaction forces were measured using a Kistler multi-component force platform with a 12 bit analog-to-digital converter interfaced to a Data General 20 desktop computer. The force platform output includes four components of the ground reaction force: vertical, antero-postero, medial-lateral, and vertical moment. These data were sampled through a 16 channel analog-to-digital converter at a rate of 100 Hz. Walking speed was measured using photocells placed on each side of the platform.

Each subject was brought into the lab for orientation of the facilities and protocol. Sufficient practice was permitted to ensure that contact with the force platform will be made with a smooth, unbroken stride at the subjects' natural walking cadence. Trials which differed more than 5% of subject's average speed or for which targeting was evident were rejected. Data was retained from 3 successful trials at the subject's natural walking speed for both feet (except for 5 of the normal adults, where only one leg was tested).

Normal Adult Torque:

The results of 24 feet in 14 normal adult are graphical displayed in Figure 1.

Figure 1.



For the first 10% stance, there is a small external rotation, followed by a internal rotation which lasts until 50% stance. In the last 50% of the stance phase, the torque is all in the external direction. This is almost identical to what was described by Schoenhaus et al (1979).

The initial external torque is a reflection of the locking of the knee joint prior to heel strike with a small amount of external rotation of the extremity. However, as weight is loaded the limb rotates internally, causing the foot to pronate. A pronated foot creates a supple mid tarsal which can then absorb force. This internal rotation is reflected in the vertical torque. As weight is shifted to the forefoot during late stance and push off, the leg externally rotates resulting in a supinated foot which creates a rigid lever for efficient propulsion forwards.

The vertical torque created by the femur and tibia in order to create either a pronated or supinate foot is primarily transmitted through the subtalar joint. The subtalar joint is the articulation between the talus and the calcaneus. There are three articulations involved in this joint. The posterior articulation is between the concave facet of the talus and the convex facet of the calcaneus. The middle articulation is between the facet on the undersurface of the talus and that on the sustentaculum tali of the calcaneus. The anterior articulation is between the convex undersurface of the head of the talus and a small concave facet on the calcaneus (Riegger, 1988). This joint is a simple single-axis joint which behaves like a mitered (oblique) hinge (Morris, 1977). As a result of the oblique rotation at this joint, the net articulation is in both the sagittal and the coronal planes.

The subtalar joint acts as a directional torque transmitter. The axial torques about the long axis of the foot or tibia induces torques about the long axis of the other segment (Czerneicki, 1983; Perry, 1983). For example, with the internal torque produced in the tibia during the initiation of stance, the foot rapidly pronates under the load of body weight. In contrast, the external rotation torques produced in the lower extremity indued from the accelerating swing contralateral in the contralateral limb results in a supination of the foot. This allows the foot to perform it's primary role in force absorption and transmission (Tiberio, 1988).

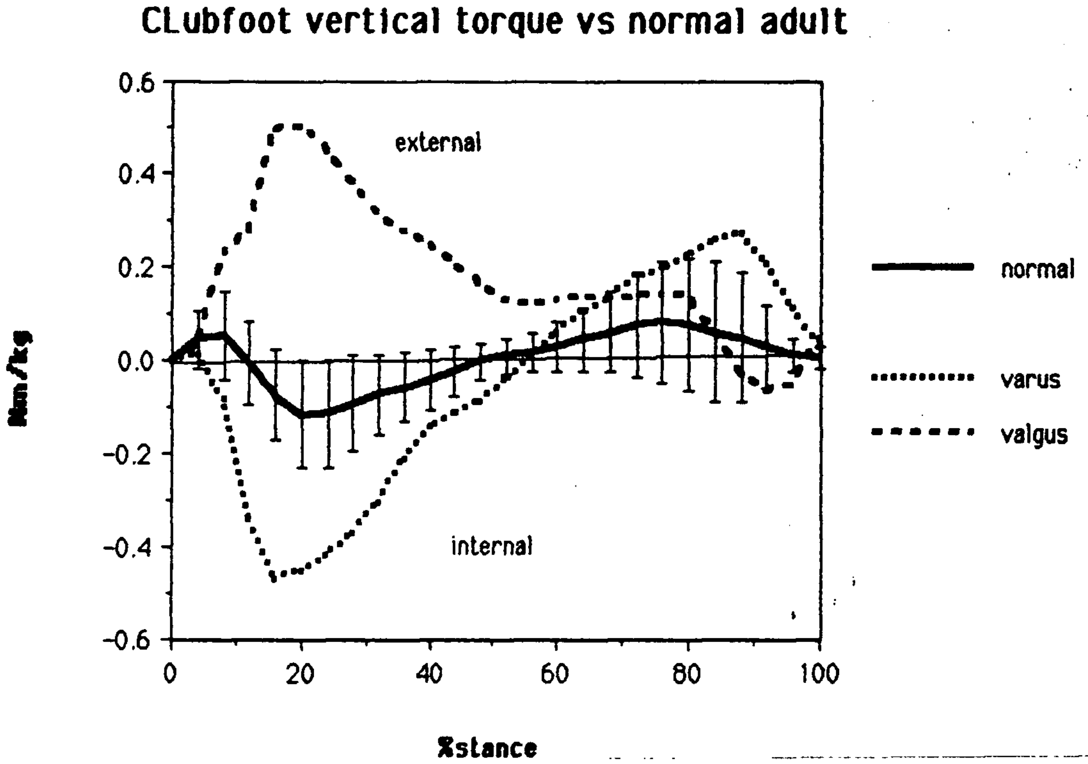
The oscillations between external and internal torque can be understood by the above explanation, however, there is considerable variability within the 24 feet tested. In the normal population, there is a range of subtalar motion as well as standing heel positions (Elveru,1988). Some people have flatter, more supple feet, while others have higher arched, and more rigid feet. The large standard deviation seen in Figure 1 may reflect the variation of individuals' feet to perform ideal pronation and supination for torque absorption.

The following two case studies examined vertical torque in extreme cases of varus and valgus deformed feet.

Clubfoot:

Clubfoot is a congenital disorder which results in a relatively rigid, inverted (or supinated), equinus foot. A larger part of the deformity stems from the considerably deformed talus with secondary changes to the adjacent articulating surfaces. The subtalar joint is often rigid and in a varus position. Treatment is necessary to bring the heel and ankle back into neutral positions. The following graph (Figure 2) are the results of the vertical torque of two children with clubfeet during walking. One child was left with still some varus deformity (10 deg) while the other child was slightly overcorrected into a valgus deformity (15 deg). On clinical exam both of the children had minimal subtalar movement.

Figure 2.



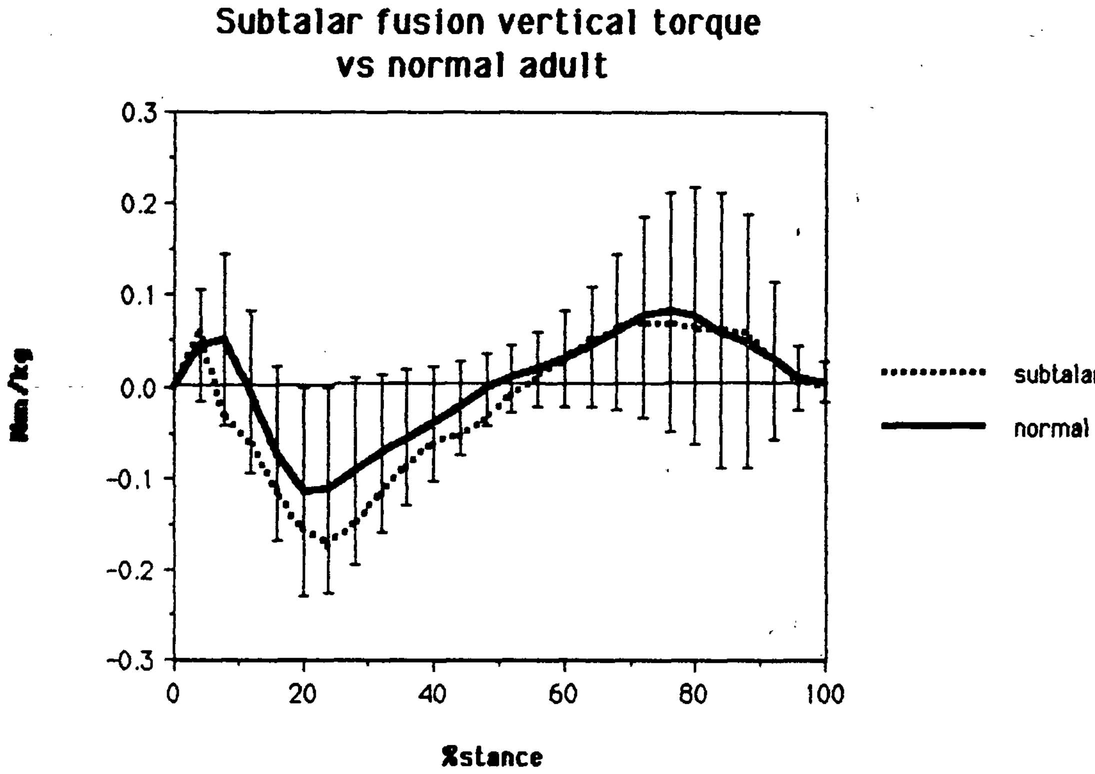
If the role of the foot is to accommodate for the torque being produced at higher segment levels, then the ideal foot should produce a small resultant net torque. In Figure 2, it is noted that in the child with a varus deformity, there is a larger amount of internal torque. This may reflect the foot's lack of ability to pronate for absorption of the internal torque created by the leg. In the child with a valgus deformity there is a large external torque which may reflect the foot's ability to supinate in order to absorb external torque and create a rigid lever for propulsion.

The above two cases show how either extreme valgus or varus deformities may affect vertical torque. If there is a range of subtalar positioning and movement, this may then explain the reason for the relatively large standard deviation in the normal adult torque. However, these children also had an additional factor that may exaggerate the magnitude of the torque found. This additional factor being a relatively rigid subtalar joint. If there is no movement in the subtalar joint would there be effective torque absorption?

Subtalar fusion:

This final subject was a woman who had undergone a surgical subtalar fusion following a traumatic injury to the supporting ligaments of the subtalar joint. Figure 3 represents the results of her vertical torque during walking.

Figure 3.



From the results and discussion so far, regarding the function of the subtalar joint and its effect on torque, it would seem reasonable to hypothesize that a restriction of the subtalar joint would decrease the foot's ability to perform these functions. As in this case, there is total loss of subtalar motion which would then deny the leg the use of its rotational component. The horizontal torque between the leg and the foot would increase, unless another source of rotation becomes available.

In Figure 3, it is clear that the woman's torque pattern is within range of normal adult torque. This slight increase in internal torque may reflect her limitation to fully pronate her foot for full absorption of internal rotatory forces of the leg, however, she probably still has enough ability within her mid tarsal bones to absorb some torsional force.

In long-term follow up cases (10-20 years) after subtalar fusions or triple arthrodesis, the ankle often adapts to the repeated torsional forces within the ankle and deformity develops in the ankle joint. The talus becomes loser in the mortise. Traumatic arthritic changes are often then found (Close et al.,1967). The remodelling potential in a joint leads to a "ball and socket joint" (Perry,1983). This explanation does not explain the reasonably good function in this woman's foot since she is only 2 years post surgery.

Discussion:

The use of force plate measurements for measuring torque around the vertical axis has not been well described in the literature. However, our findings do confirm the results of Schoenhaus et al (1979) and Close and Inman (1953). There is a consistent oscillation between external and internal torques during the various stages during stance in walking, but with relatively large variations. The torques described do correspond with the rotational movements of the leg, and anatomically, the subtalar joint is thought to be responsible for the absorption of the forces generated by these movements.

There is a range of subtalar motion in the normal population which would then reflect in a wide range of torque magnitude. From the results of the cases with severely limited subtalar motion (ie. varus and valgus deformities), gross changes in torque patterns are observed. A foot with a varus deformity is unable to absorb internal torsion and the foot in valgus is unable to absorb external torsion. Measuring vertical torque during walking may be a useful measure to determine the function of excessive pronated or supinated feet. In the literature, this has often been examined using centre pressure of path (Brand et al, 1981; Aronson and Puskarich, 1990; Rodgers, 1988; Katoh et al, 1983; Zernicke et al, 1985), with often non-conclusive results.

A limitation of this study was the use of single case subjects for comparing clinical deformities with the results found on force plate analysis. A larger study need to be done with subjects who have a large range of weightbearing heel positions need to be examined to see if there is a relationship between torque and heel position. It would also be beneficial to test several cases of isolated subtalar fusions to see if this was an isolated case of possible adaptation of the foot to restricted subtalar motion or if, in general, the magnitude of torque does increase following fusion.

The torque measured from the force plate is a total measure of all influences of rotational forces exerted. It is difficult to isolated where most of the rotational forces are being absorb or transmitted. From the anatomical structure of the subtalar joint, it is reasonable to expect it to be the primary source. However, what the force plate is measuring is not clear. Like the woman with an isolated subtalar fusion, other deformities need to be considered to control for the various segments in the chain. For example, to examine subjects who have had knee fusions, in order to rule out the knee in the role of torsion absorption.

Summary:

This study has shown that there is a consistent pattern in vertical torque during walking obtained from a force plate. In the cases with extreme positioning of the subtalar joint, their torque patterns reflected their limitations. There is hope for effective use of vertical torque obtained from the force plate for assessment of clinical function of the subtalar joint, inspite of its limited use in the past. Larger studies involving subjects who have undergone subtalar fusion, a triple arthrodesis, or knee fusion need to be considered to attempt to control for sources of rotational absorption, in order to isolate the primary contributor of the torque obtained from the force plate during walking.

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