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The Effects of Lower Extremity Boundary Conditions on Ankle and Subtalar Joint Response during Flexion Tests

Philip H. Schreiber, Jeff R. Crandall, Ehud Dekel, Gregory W. Hall, Walter D. Pilkey
Department of Mechanical, Aerospace, and Nuclear Engineering
University of Virginia

Shepard R. Hurwitz, MD
Department of Orthopedics
University of Virginia Health Sciences Center

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ABSTRACT

This paper examines the influence of anatomical boundary conditions and test apparatus degrees of freedom on the flexion response of the ankle and subtalar joints. Six lower limbs, amputated above the knee, were subjected to complete cycles of dorsiflexion and plantarflexion at non-injurious loading levels. For each lower extremity, four boundary conditions were used to determine the influence of various anatomical structures on the ankle response. Similarly, available degrees of freedom were varied such that the ankle experienced either rotation constrained to a sagittal plane or unconstrained rotation with six degrees of freedom. The results suggest that the dorsiflexion response of the ankle is highly dependent on the triceps surae muscle group, the superior tibio-fibular joint, and the relative spacing of the ankle mortise. The insensitivity of plantarflexion motion to varying anatomical boundary conditions indicates that the bony stops, ligaments, and other local anatomical structures determine the extension response. Constraining motion of the ankle to a plane resulted in increased joint stiffness relative to the unconstrained condition. These results suggest that above-knee amputations and test devices that permit biofidelic motion must be used in tests to determine the response of the ankle joint.

INTRODUCTION

The ankle and foot form a complex anatomical structure that contains 28 irregularly shaped bones, more than 70 articulating surfaces, 30 synovial joints, over 100 ligaments, and 30 muscle attachments. Owing to its complexity, the foot and ankle complex is capable of serving many functions including the ability to adapt to uneven surfaces, to assist in shock absorbency, and to limit the transfer of rotations to more proximal joints of the lower extremity.

Most motion of the foot and ankle occurs in three joints: the talocrural, the subtalar, and the midtarsal. The talocrural joint is the ankle joint proper and is formed from the talus and the distal tibia and fibula (Figure 1). The subtalar joint arises from the talus and calcaneus bones while the midtarsal joints act as the interface between the irregularly shaped tarsal bones.

Dorsiflexion and plantarflexion occur primarily in the ankle joint. These motions do not occur purely in the sagittal plane, but actually cross three planes and result in a moving, or instantaneous axis of rotation for the ankle joint (Figure 2). This triplanar motion can be attributed to both the obliquity of the ankle joint axis and the shape of the body of the talus.

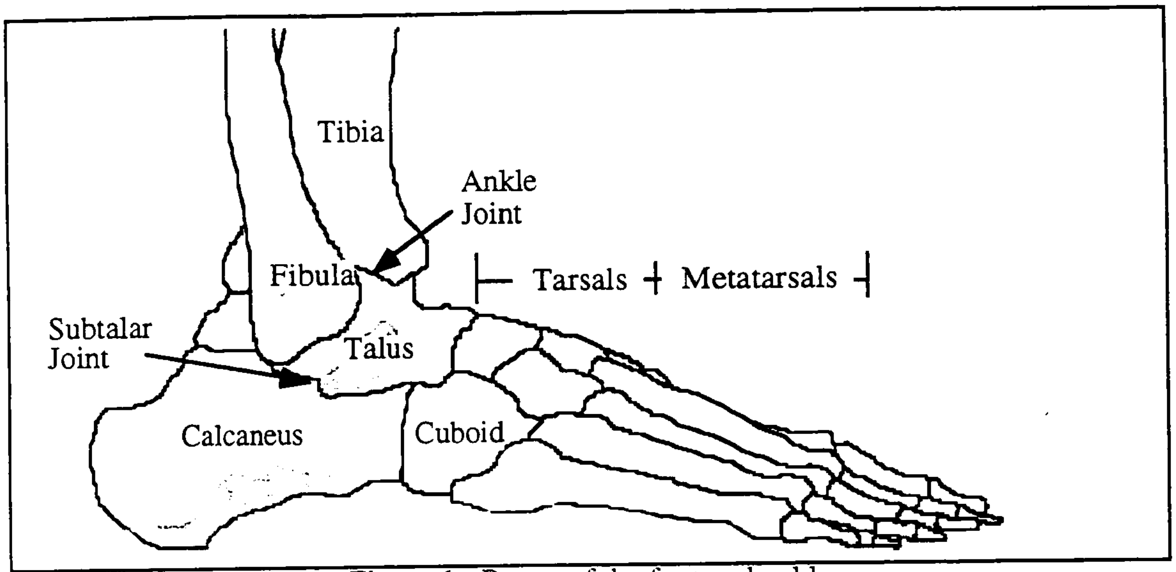

Figure 1. Bones of the foot and ankle

The conical shape of the talus results in a trochlear surface with a lateral facet that has a radius of curvature greater than that of the medial facet. Thus, the fibula moves more anterio-posteriorly than the tibia for a given rotation. Greater movement of the fibula results in medial rotation of the leg as it passes over the foot in dorsiflexion or in lateral rotation of the leg during plantarflexion. In addition to the curvature of the trochlear surface, the talus is wider anteriorly than posteriorly by approximately 0.5 mm (Stiehl, 1991). This wedge shape of the talus results in the close-packed position for the ankle joint during dorsiflexion since the talus is wedged at its widest region against the mortise formed by the tibia and fibula.

Although its contribution is significantly less than that of the ankle joint, the subtalar joint also adds to the overall range of flexion. This joint is usually modeled as a uniaxial joint capable of supination (inversion, internal rotation, plantarflexion) and pronation (eversion, external rotation, dorsiflexion). Similar to the ankle joint, the axis of rotation for the subtalar joint does not conform with the standard anatomical axes.

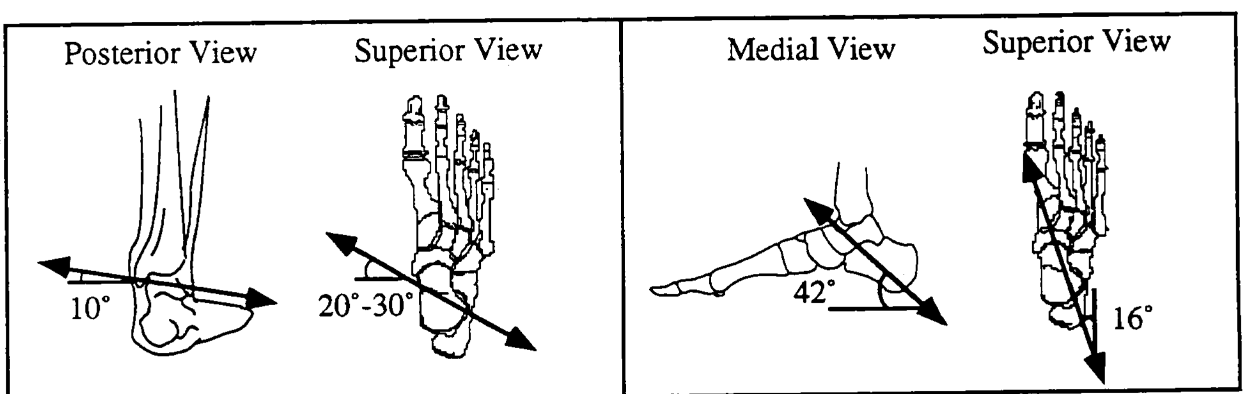

Figure 2. a) Flexion axis orientation b) Inversion/eversion axis orientation
(Adapted from Stiehl, 1991 and Norkin and Levangie, 1992)

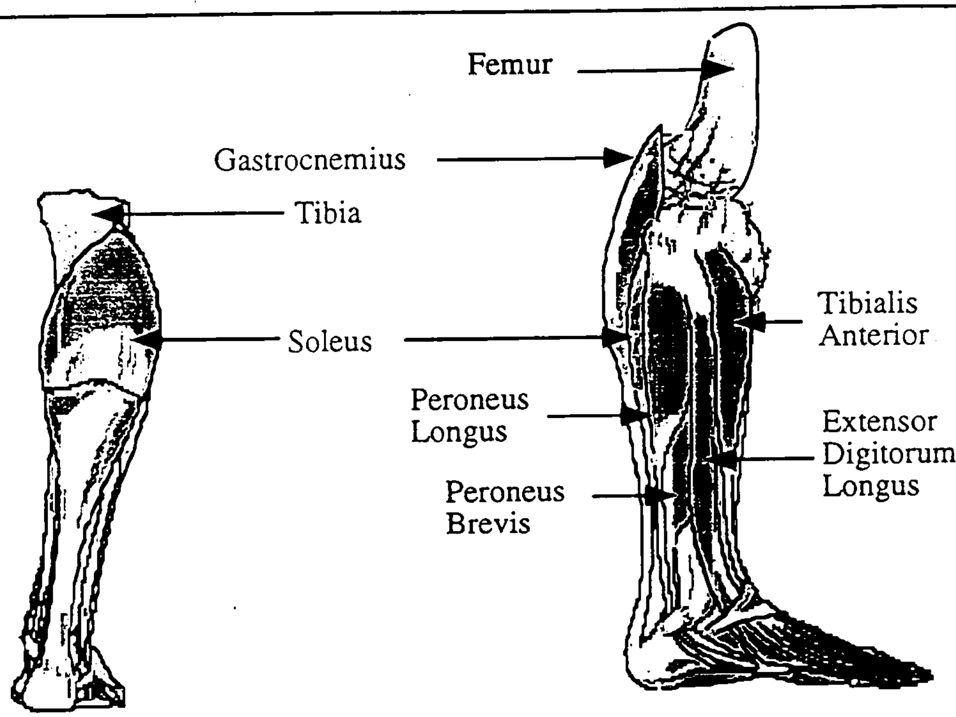

Figure 3. Muscles associated with motion of the foot and ankle

The anatomical neutral position of the ankle joint is defined with the foot at a right angle to the leg. The mechanically neutral, or "relaxed" position of the foot, corresponding to a zero torque condition about the plantarflexion/dorsiflexion axis, occurs between 15° and 20° of plantarflexion. Active dorsiflexion is produced by the extensor muscles of the leg: the tibialis anterior, extensor digitorum longus, extensor hallucis longus, and peroneus tertius muscles (Figure 3). Plantarflexion is produced by the triceps surae muscle group, which includes the gastrocnemius and soleus muscles. This muscle group also acts to oppose dorsiflexion of the ankle joint. Since the gastrocnemius muscle attaches at the distal femur, dorsiflexion is limited more when the muscle is stretched with the knee fully extended. Plantarflexion is limited by the anterior compartment muscles, which are the tibialis anterior, extensor hallucis longus, peroneus tertius, and extensor digitorum longus. These muscles also assist ligaments to minimize side-to-side movement or rotation of the mortise on the talus.

In addition to muscular constraints, ankle flexion is limited by bony factors, ligaments, and the joint capsule. During dorsiflexion, the surface of the talus comes in contact with the anterior margin of the tibial surface. During plantarflexion, bony factors such as the posterior tuberosities of the talus and the anterior and posterior margin of the tibial surface, limit extension of the ankle.

LITERATURE REVIEW

The response of the ankle joint has been extensively researched in cadaveric and volunteer studies. Many of these studies, however, have used test boundary conditions that may compromise the ankle joint response. Studies to define flexion response of the cadaver ankle have primarily used below-knee amputations. Typically the tibia and fibula were potted at mid diaphysis, with the removal of all proximal soft tissue. Amputating and potting at the mid-shaft removes essential musculature and limits relative motion between the tibia and fibula.

The attachment sites of the soleus and gastrocnemius are distributed along the proximal tibia and distal femur. Sectioning at the mid-diaphysis of the tibia ignores the influence of these muscles, resulting in an apparent increase in the ankle range of motion (ROM) and a decrease in ankle stiffness. Loading of the remaining anatomical structures can increase when the passive muscle resistance is eliminated. Removal of musculature proximal to mid-diaphysis of the tibia can alter both mechanisms of injury and injury thresholds.

Study	Boundary Conditions	Test D.O.F.	Loading Components	Loading Rate	Destructive/ Nondestructive
Rastegar (1980)	Pot tibia & fibula mid-shaft	Θz X, Y	Mz (Int/Ext Rot)	Quasi-static	Nondestructive
Rasmussen (1983)	(Not specified)	Θy	My (Dorsiflexion)	Quasi-static	Destructive
Sieger (1987)	Pot mid-tibia, Fibula free	Θx, Θy, Θz X, Y, Z	My (Dorsi/Plant)	Quasi-static	Nondestructive
Markolf (1989)	Pot tibia & fibula mid-shaft	Θz	Mz (Ext Rot)	Quasi-static	Destructive
Lundberg (1989)	In-vivo, knee straight	Θx, Θy, Θz X, Y, Z	Prescribed angle	Static	Nondestructive
Begeman/ Prasad (1990)	Pot proximal tibia, fibula intact	Θy Z	My & Fz (Dorsiflexion & axial load)	Dynamic	Destructive
Cawley (1991)	Pot mid-tibia Fibula free	Θy Z	My (Dorsi/Plant)	Quasi-static	Nondestructive, Prescribed angle
Allinger (1992)	In-vivo, knee bent	Θx, Θy, Θz X, Y, Z	My (Self generated by volunteer)	Quasi-static	Nondestructive
Begeman (1992)	Pot tibia & fibula mid-shaft	Θy Z	My & Fz (Dorsiflexion & axial load)	Dynamic	Destructive
Begeman (1993)	Pot tibia & fibula mid-shaft	Θx Z	Mx & Fz (Invers/Evers & axial load)	Dynamic	Destructive
Begeman (1994)	Pot tibia & fibula mid-shaft	Θz Z	Mz & Fz (Int/ext Rot & axial load)	Quasi-static and Dynamic	Destructive
Parenteau (1995)	Pot tibia & fibula mid-shaft	Θy Y, Z	My (Dorsiflexion)	Quasi-static	Destructive
Portier (1995)	Pot tibia & fibula mid-shaft	Θy Y, Z	My (Dorsiflexion)	Quasi-static	Destructive
	Whole cadaver, Knee flexed	Θx, Θy, Θz X, Y, Z	My & Fz (Dorsiflexion & axial load)	Dynamic	Destructive

Table 1. Literature review of previous foot and ankle motion studies

The scheme of potting the tibia and fibula together ignores the influence of the proximal tibio-fibular joint and the interosseus membrane in adjusting the grip of the ankle mortise on the talus. Rigidly fixing the fibula relative to the tibia also prohibits the natural rotation and translation of the fibula relative to the tibia during flexion. Conversely, potting the tibia at mid-diaphysis and leaving the fibula free has the opposite effect, allowing too much freedom of the mortise and excessive torsion of the fibula about its longitudinal axis.

Previous cadaver studies have also eliminated degrees of freedom associated with the natural motion of dorsiflexion/plantarflexion. Often the ankle was constrained to rotate in the sagittal plane in an attempt to produce flexion that conforms to the standard anatomical axes (Figure 4a). This motion is unnatural for the ankle, since its natural axis of rotation is skewed with respect to the anatomical frame. Constraining rotation to the sagittal plane also eliminates external/internal rotation and eversion/inversion, motions that are directly coupled with dorsiflexion/plantarflexion due to the talar geometry and oblique axes of the ankle and subtalar joints. Eliminating any of the six degrees of freedom associated with ankle flexion can cause premature binding of the joint and limited range of motion. Such artificial loading modes will likely induce failure not representative of real-world injury scenarios.

A summary of previous ankle flexion tests is shown in Table 1. This table lists respective fixation boundary conditions, permitted degrees of freedom, and loading modes used in each test.

OBJECTIVE

The study presented in this paper was intended to evaluate the effects of various lower limb boundary conditions and test degrees of freedom on the moment-angle response of the ankle joint during flexion. In order to simulate boundary conditions found in the literature, four potting fixation schemes were developed. The first scheme involved sectioning a lower extremity at mid-diaphysis of the femur, securing the knee joint in the extended position, and fixing the tibia to a stationary frame. This scheme was considered to be most biofidelic because it preserved the attachment sites of the soleus and gastrocnemius muscles and permitted natural motion of the fibula with respect to the tibia. The second scheme involved severing the lower extremity at the knee joint. This approach maintained all anatomical structures with the exception of the gastrocnemius muscle. Therefore, the influence of the gastrocnemius on ankle flexion was evaluated by comparing schemes one and two. A third scheme involved potting the tibia and fibula together at mid diaphysis. Although this eliminated the tricep surae muscle group and the superior tibio-fibular joint, it has been the most common fixation technique for cadaveric ankle flexion studies. A fourth scheme simulated tests in which the tibia was potted and the fibula left free. This scenario was intended to demonstrate the influence of the fibula on the ankle mortise.

This study also evaluated the effect of confining ankle flexion to a fixed sagittal plane. A quasi-static moment was applied about the axis of dorsiflexion. One set of tests permitted six degrees of freedom (three translational and three rotational) for a prescribed flexion moment (Figure 4b). This recommended loading mode allowed the ankle to flex in a natural manner, and permitted translation of the instantaneous center of rotation in three dimensions. A second set of tests confined ankle flexion to a fixed sagittal plane, which prevented inversion/eversion, internal/external rotation, and translation in the medial-lateral direction (Figure 4a).

TEST APPARATUS

In order to characterize fully the response of the ankle joint, the ankle was allowed to rotate about its natural axis. This was achieved using a test apparatus that permitted the foot to invert/evert, internally/externally rotate, and translate in three directions while subjecting the ankle to dorsiflexion/plantarflexion.

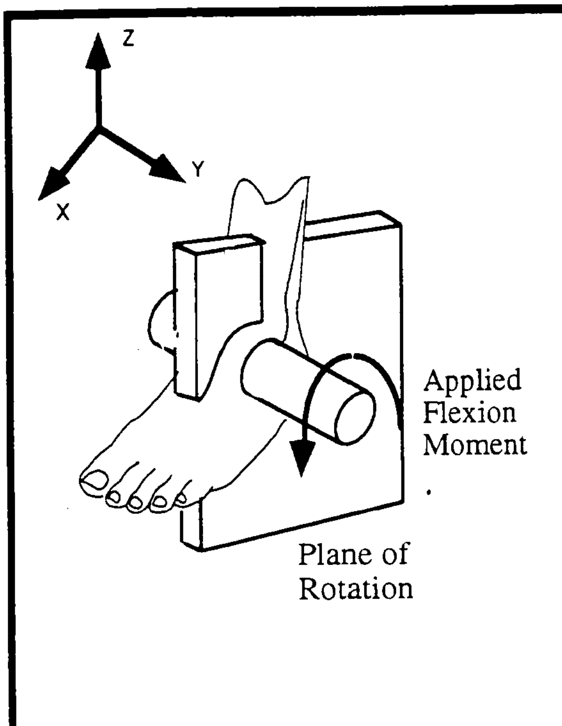

Figure 4. a) Ankle flexion confining rotation to a fixed sagittal plane.

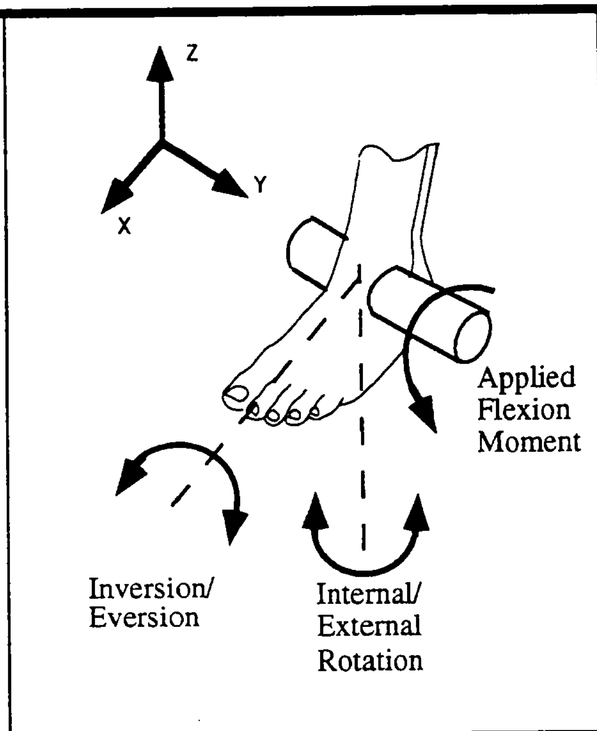

Figure 4. b) Ankle motion allowing internal/external rotation and inversion/eversion during flexion.

The ankle test apparatus consists of a gimbal assembly, with two links centered about the ankle's theoretical center of rotation (Figure 5). A sprocket, driven by a hydraulic piston at a constant rate, produces a moment in the outermost gimbal link (fork), that is aligned with the axis of dorsiflexion/plantarflexion (Y axis). As the ankle is forced in flexion, the inner link (U-beam) provides rotational freedom about the axis of internal/external rotation (Z axis) and inversion/eversion (X axis). The gimbal assembly can be likened to a gyroscope having the ankle joint at its center. A moment is transmitted through the outermost link of the gyroscope, while the inner link is free to rotate about the remaining two orthogonal axes.

The cadaver tibia is mounted rigidly to a fixed frame, and the foot is mounted to a foot plate fixed to the inner gimbal link. A universal joint connecting the sprocket to the outermost gimbal link allows the assembly to translate in the sagittal (X-Z) plane in order to compensate for motion of the ankle's instantaneous center of rotation and to accommodate for initial misalignment of the ankle center. Translation in the medial/lateral (X-axis) direction is accommodated by roller bearings in the inner gimbal link. In all, six degrees of freedom, three rotational and three translational, are permitted in the ankle's motion. The foot is forced to rotate about the Y axis (axis of dorsiflexion), while having freedom to rotate and translate in the remaining five degrees of freedom.

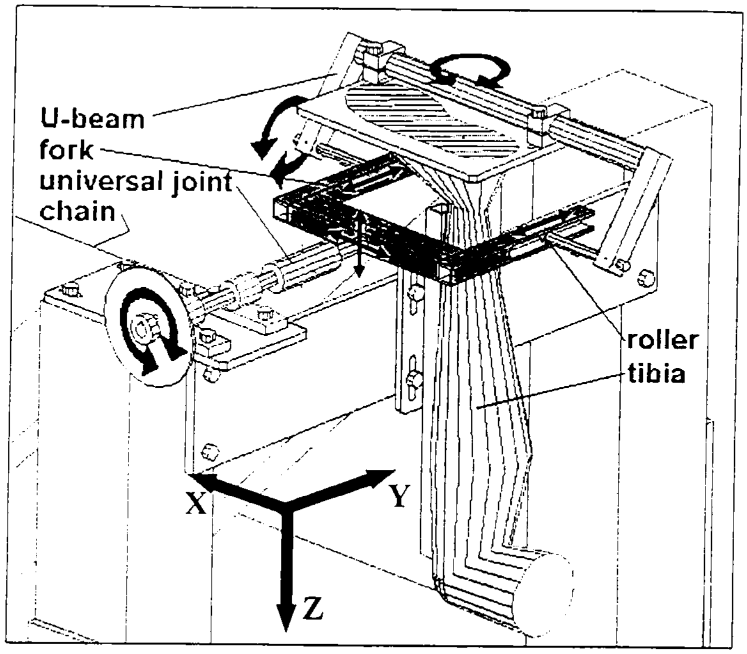

Figure 5. Test apparatus showing available degrees of freedom

With this arrangement the ankle is capable of "unconstrained rotation". The apparatus was also designed to lock one translational and two rotational degrees of freedom, confining the ankle's motion to pure dorsiflexion in a fixed sagittal (X-Z) plane (Figure 4a). In this configuration, the ankle is said to have "constrained rotation".

The moment applied about the axis of dorsiflexion was calculated from a load cell (Lebow Model #3397-300) in the piston head. The three angles of rotation (dorsiflexion, internal rotation, and eversion) were recorded by rotational potentiometers (Spectrol Model #132-0-0-103). The anatomical rotations were defined as three sequential Euler rotations; dorsiflexion/plantarflexion about the Y axis, internal/external rotation about the Z' axis, and inversion/eversion about the X'' axis. Since there were no physical shafts to measure the three Euler angles directly, the potentiometers were mounted to the foot plate, and anchored to the inertial axis system through a long rod that minimized the effect of translations on the measured angles.

TEST PROCEDURE

Six fresh frozen above-knee amputations were obtained from whole cadavers. The limbs were thawed to room temperature over a 12 hour period and kept moist with a covering of wet gauze. Ankles were x-rayed and clinically evaluated to ensure that no pre-existing trauma was present. During testing, the limb was covered with Tyvek material to prevent drying.

Ankle testing was performed in nine consecutive stages described in detail in I through IX below. Ankles were tested in both unconstrained and constrained rotation, in combination with four fixation boundary conditions; (Figure 6) 1. Femur fixed, 2. knee severed, 3. potted tibia and fibula, 4. potted tibia with fibula free. Tests began with the leg sectioned at mid-diaphysis of the femur. By imposing these four fixation boundary conditions consecutively, and progressively removing hard and soft tissue at each stage, the same limb could be used throughout the entire test matrix.

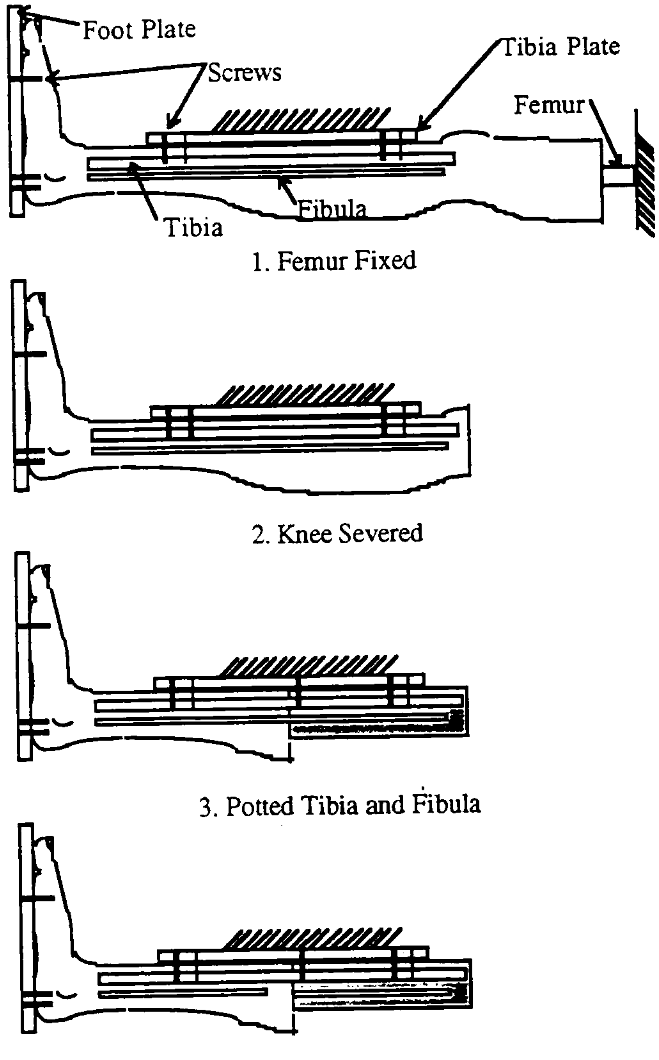

Figure 6. Four fixation boundary conditions.

A single test involved placing the ankle in the relaxed position of 15° dorsiflexion and subjecting it to a complete cycle of dorsiflexion and plantarflexion. The ankle was rotated about the flexion axis at a constant rate of 5 deg/s. Because the tests were non-destructive, the applied moment was maintained below a maximum level of 8 Nm. Based on cadaveric testing in the literature (Begeman, 1992; Parenteau, 1995), this level appeared to be a conservative estimate, well below the injury threshold. Following completion of the testing, x-rays and a detailed necropsy were performed to check for injury. None of the lower limbs sustained trauma during the experiment.

I. Mounting of the Leg

A Plexiglas plate was mounted on the anterior surface of the tibia using four 38 mm long drywall screws, two proximal and two distal. Another Plexiglas plate was secured to the inferior surface of the foot using two screws through the calcaneus and one screw through the distal first metatarsal. This mounting insured that the foot arch length remained fixed, thereby reducing rotation and translation contributions from the foot joints. The tibia plate was rigidly fixed to the frame of the test apparatus. The foot plate was mated to an aluminum plate attached to the inner gimbal link. With the ankle held in the neutral position

(0° dorsiflexion, 0° internal rotation, 0° inversion) adjustments were made so that the center of rotation of the gimbal assembly coincided with the ankle's approximate center of rotation. The approximate center of rotation was taken as the midpoint between the distal tips of the malleoli. (Stiehl, 1991). Since the apparatus allowed for three-dimensional translation, exact alignment of the assembly with the ankle center of rotation was unnecessary.

II. Preconditioning.
The ankle was preconditioned by completing 5 cycles of dorsiflexion and plantarflexion, at a constant rate of 5 deg/s. The direction of rotation was reversed when the applied moment reached approximately ± 6 Nm. The hysterisis curve remained constant after the first few cycles.

III. Unconstrained Rotation / Femur Fixed
The knee was extended and the mid-shaft of the femur was secured to the frame of the apparatus with nylon webbing.

III-A. Potentiometers were zeroed with the ankle in the neutral position. The ankle was then rotated to the "relaxed" position. For unconstrained tests the ankle was allowed to externally rotate and evert as it was brought to this position. While in the relaxed position, the applied moment was prescribed as zero. Data was acquired as the ankle underwent a complete cycle of dorsiflexion to plantarflexion to relaxed position, reversing the direction of rotation at approximately ± 6 Nm of torque.

IV. Constrained Rotation / Femur Fixed
With the femur still intact and secured, the test apparatus was configured for constrained motion in the sagittal plane. The procedure of part III-A was then repeated.

IV. Unconstrained Rotation / Knee Severed.
The lower extremity was severed at the knee by making a clean transverse cut at the knee joint. The femur and all soft tissue proximal to the severed knee joint capsule were removed. The apparatus was configured for unconstrained rotation and the procedure of part III-A was repeated.

V. Constrained Rotation / Knee Severed.
The test apparatus was configured for constrained rotation and the procedure of part III-A was repeated with the leg severed at the knee.

VI. Unconstrained Rotation / Potted Tibia and Fibula.
The leg was removed form the test apparatus. Screws securing the proximal end of the tibia to the Plexiglas plate were removed, leaving the plate attached by the two remaining distal screws. All soft tissue was removed from the proximal end of the leg to the mid-diaphysis. The exposed tibia and fibula were potted in an epoxy/sand composite (epoxy: Buehler #20-8130-128) and left to harden for 12 hours. Once hardened, the potted portion was fixed to the Plexiglas tibia plate using three screws.

The leg was re-mounted on the test apparatus as described above, and the apparatus was configured for unconstrained rotation. The procedures of parts I and III-A were repeated.

VII. Constrained Rotation / Potted Tibia and Fibula.
With the tibia and fibula potted at mid-diaphysis, the test apparatus was configured for constrained rotation. The procedure of part III-A was repeated.

VIII. Unconstrained Rotation / Severed Fibula.
A three centimeter segment of the fibula was removed just inferior to the potted tibia-fibula. The apparatus was configured for unconstrained rotation and the procedure of part III-A was repeated.

IX. Constrained Rotation / Severed Fibula.
The test apparatus was configured for constrained rotation and the procedure of part III-A was repeated with the fibula cut at the mid-diaphysis.

DISCUSSION AND RESULTS

Hysterisis plots were created by graphing the flexion angle as a function of applied moment. Figures 7 and 8 show the typical effects of the various fixation boundary conditions and permitted degrees of freedom on the ankle ROM for one of the lower extremities. Figures 9 and 10, obtained from the same limb, show the amount of inversion/eversion and internal external rotation accompanying dorsiflexion/plantarflexion for the four fixation boundary conditions.

Effect of Boundary Conditions

It is evident from Figures 7 and 8 that dorsiflexion ROM for both the unconstrained and constrained cases is significantly affected by the fixation boundary conditions. Progressive removal of the proximal anatomical structure during the fixation process produces successive increases in the available dorsiflexion ROM. The fixed femur boundary condition demonstrated the smallest ROM in dorsiflexion (4.7° constrained, 4.6° unconstrained), for an applied moment of 6 Nm. This response was followed by the severed knee fixation (17.5° constrained, 21.9° unconstrained), the potted tibia/fibula fixation (22.7° constrained, 30.4° unconstrained), and the severed fibula fixation (24.5° constrained, 30.0° unconstrained).

Results indicate that dorsiflexion ROM is highly dependent upon the gastrocnemius muscle that attaches above the knee. To a lesser extent, the tests also demonstrate the dependence of dorsiflexion on the superior tibio-fibular joint and the soleus muscle. The testing suggests that previous ankle studies that have severed the leg at or below the tibial plateau have overestimated ankle compliance. Average results for the six lower extremities are summarized in Table 2 and Figures 11 and 12.

		Fixed Femur	Severed Knee	Potted Tib-Fib	Severed Fibula
Constrained	Dorsiflexion	4.7 ± 2.4	17.5 ± 4.4	22.7 ± 1.7	24.5 ± 1.4
	Plantar flexion	28.3 ± 4.0	29.4 ± 4.5	29.3 ± 5.0	31.8 ± 5.6
Unconstrained	Dorsiflexion	4.6 ± 2.5	21.9 ± 7.1	30.4 ± 6.9	30.0 ± 6.4
	Plantar flexion	32.6 ± 7.3	32.7 ± 5.5	33.5 ± 6.5	34.9 ± 6.1

Table 2. Resulting ROM for applied ±6 Nm applied moment.

It is evident from Figures 7 and 8 that plantarflexion ROM is virtually unaffected by the fixation boundary conditions. This indicates that plantarflexion ROM is controlled more by local architecture of the ankle joint complex than the extensor muscles.

The amount of inversion/eversion accompanying ankle flexion during unconstrained rotation remains unaffected by changing boundary conditions. This is evident in Figure 9, where eversion angle is shown as a function of dorsiflexion/plantarflexion angle. Eversion accompanying dorsiflexion appears to depend

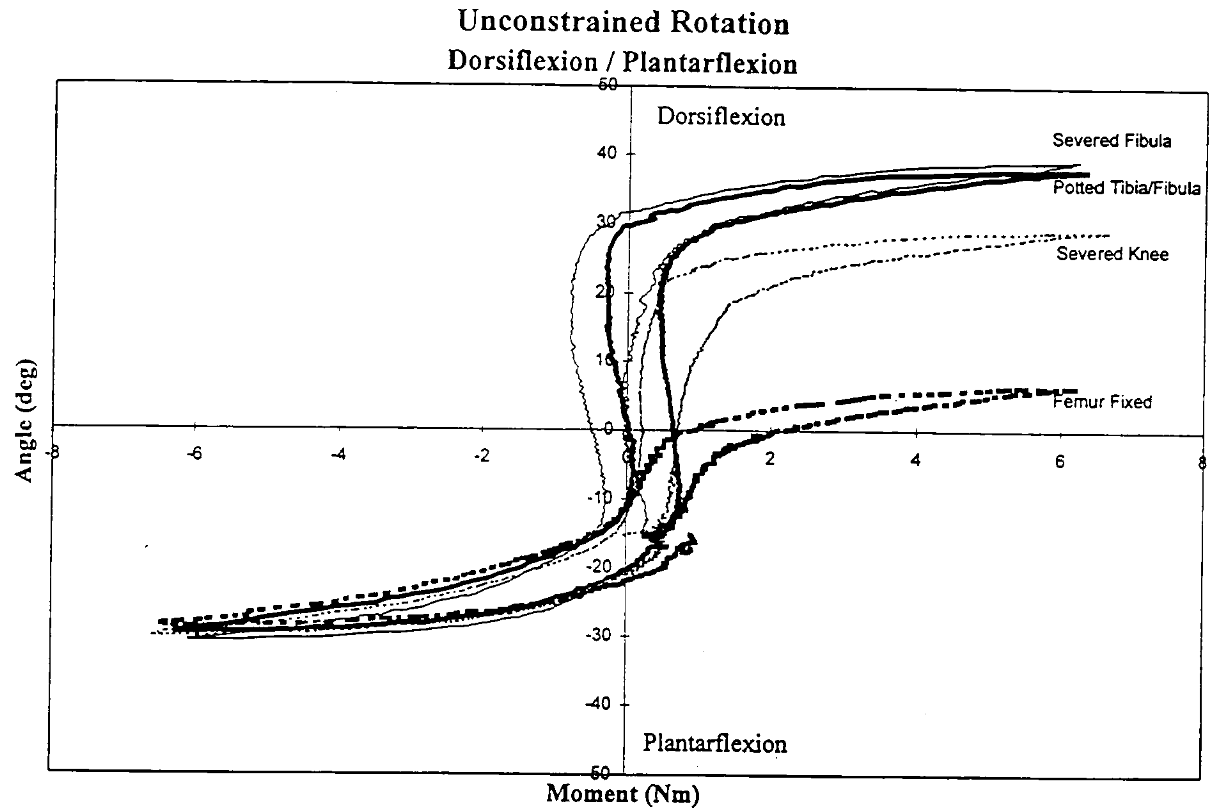

Figure 7. Unconstrained rotation. Dorsiflexion plantarflexion angle versus applied moment.

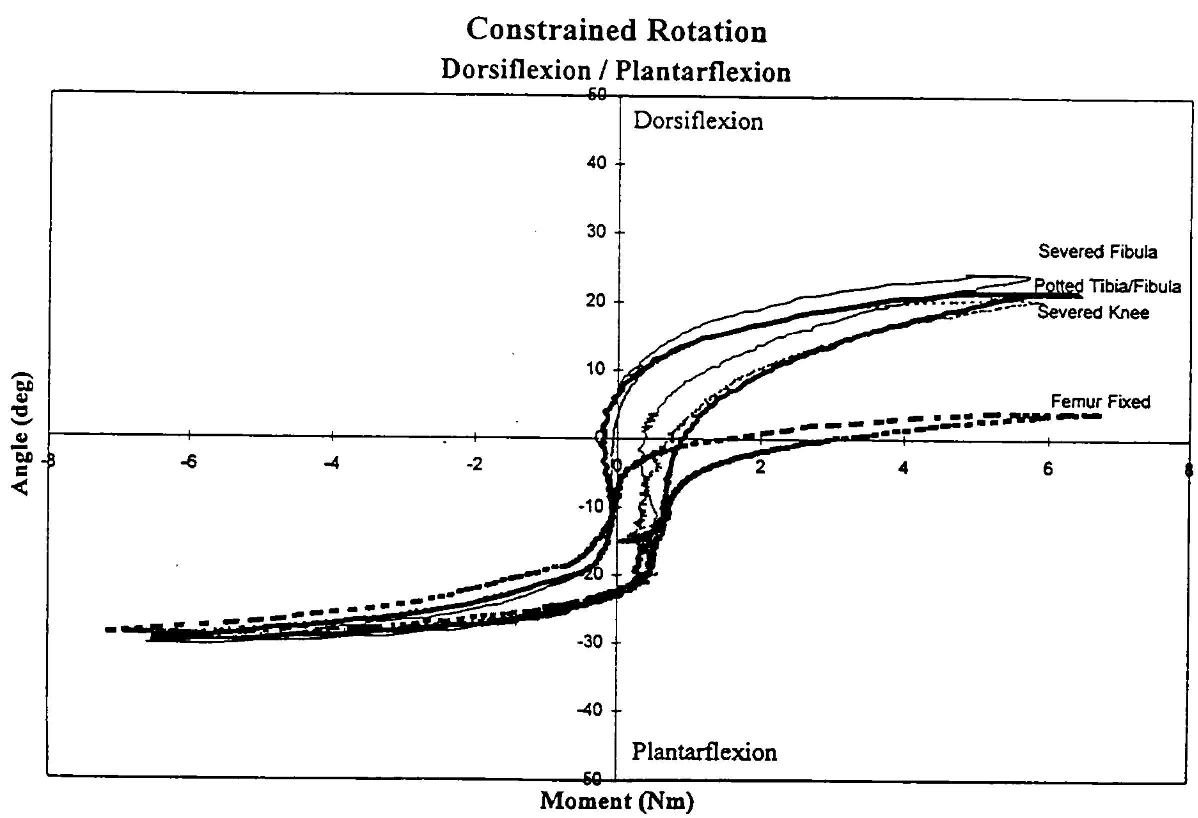

Figure 8. Constrained rotation. Dorsiflexion/plantarflexion angle versus applied moment.

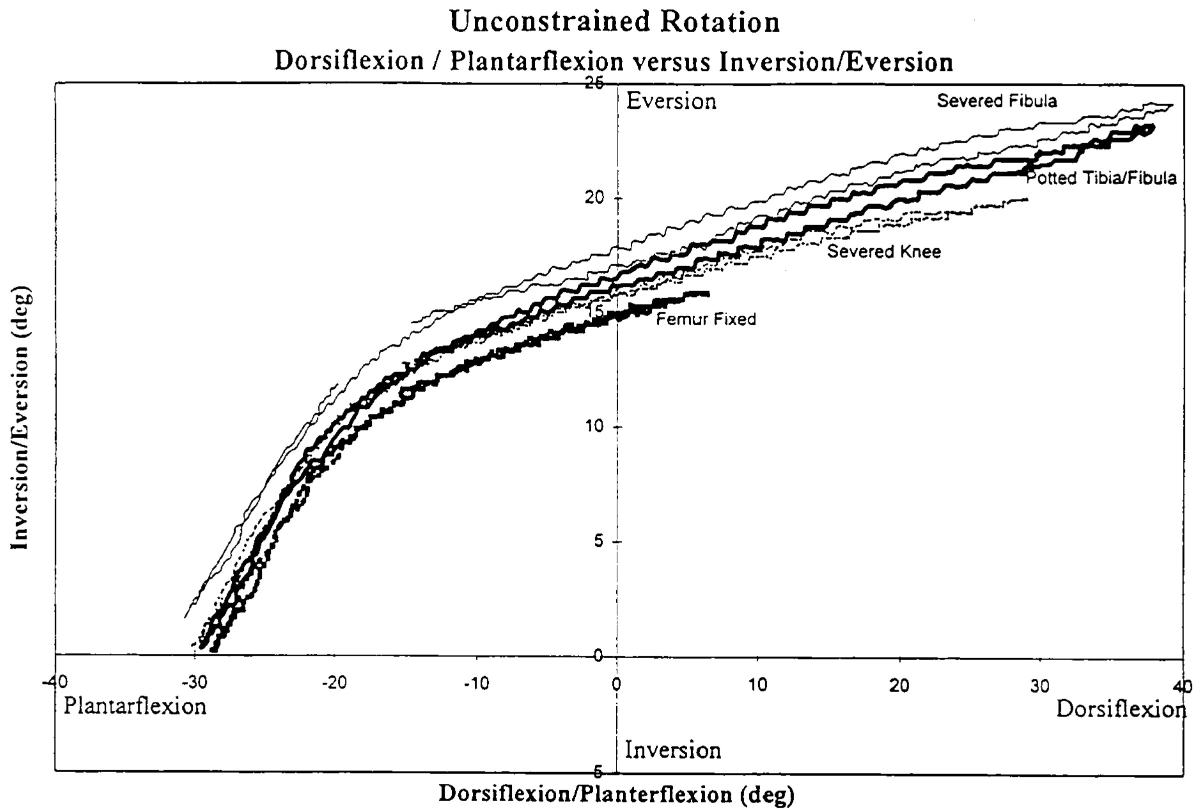

Figure 9. Inversion/eversion accompanying dorsiflexion/plantarflexion during unconstrained rotation

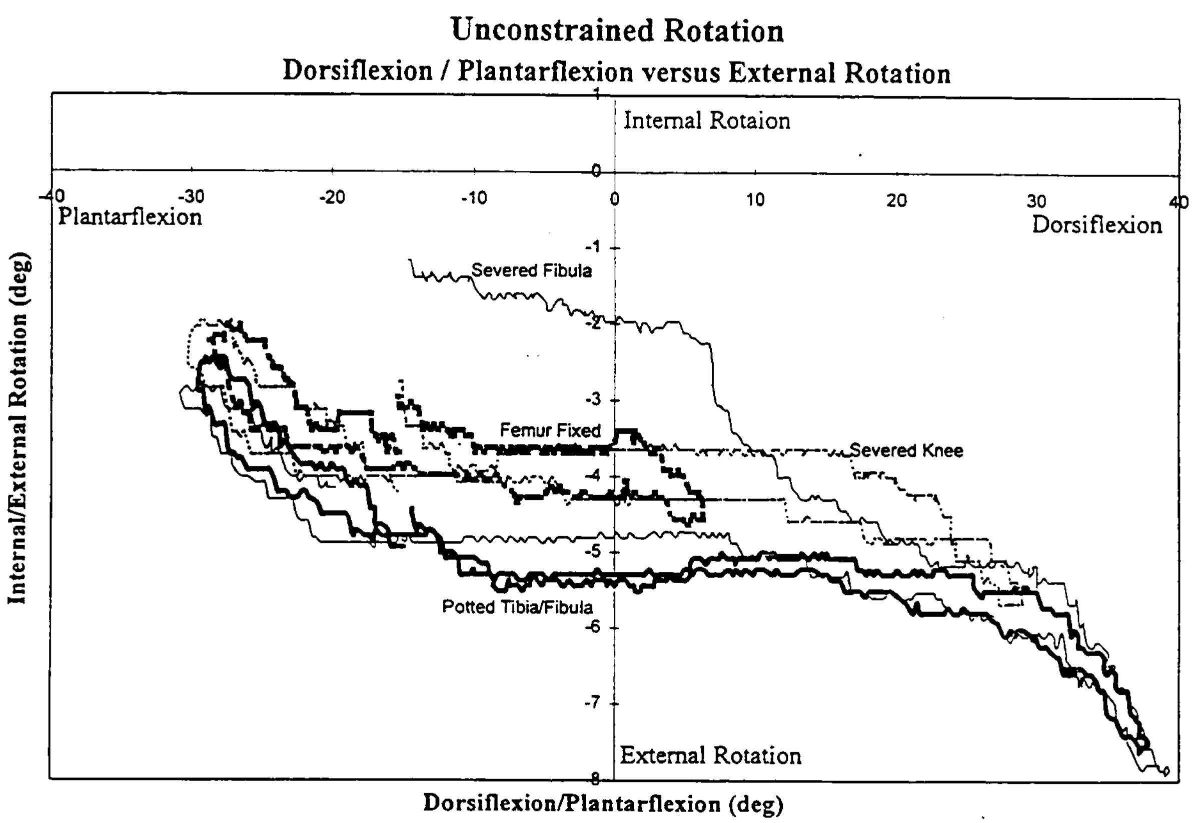

Figure 10. Internal/external rotation accompanying dorsiflexion/plantarflexion during unconstrained rotation.

primarily upon local bone, joint capsule and ligament geometry rather than muscle involvement.

The amount of internal/external rotation accompanying ankle flexion during unconstrained rotation is minimally affected by changing boundary conditions, with the exception of the case when the fibula is severed. Severing the fibula disrupts the ankle mortise structure and causes the ankle to become unstable with internal external rotation. This instability is evident in Figure 10, where inversion/eversion angle is shown as a function of flexion angle. In the test with the severed fibula boundary condition, the foot does not return to its initial position upon completing one cycle of flexion, but remains at a position of excessive internal rotation.

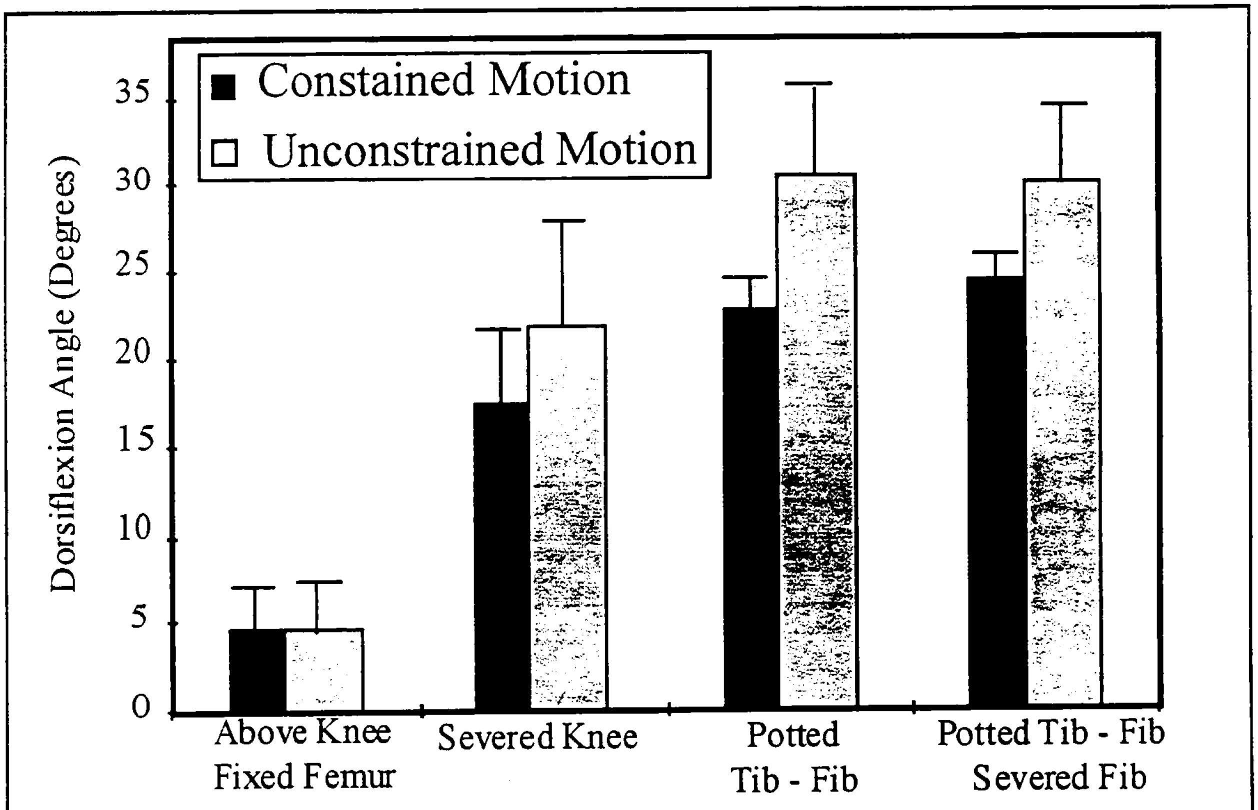

Figure 11. Dorsiflexion results with varying boundary conditions and degrees of freedom

Constrained versus Unconstrained Rotation:

Plantarflexion ROM was greater in the unconstrained case than in the constrained case for all four fixation boundary conditions (Figures 11 and 12). Plantarflexion at +6 Nm of applied moment increased an average of 4.3° (femur fixed), 3.3° (knee severed), 4.2° (potted tibia/fibula) and 3.1° (severed fibula) when additional rotational degrees of freedom were permitted about the X and Z axes and translation was allowed along the Y axis.

No significant difference in dorsiflexion ROM was observed when comparing the constrained versus unconstrained rotation for the femur fixed position. This may result from the fact that the overall range of dorsiflexion was small due to the action of the gastrocnemius muscle. Upon severing the knee, however, the dorsiflexion ROM was greater in the unconstrained case than the constrained case. Dorsiflexion at -6 Nm applied moment increased an average of 4.4° (knee severed), 7.3° (potted tibia/fibula), and 5.5° (severed fibula) during unconstrained rotation. This difference in constrained versus unconstrained ROM accompanying the removal of the gastrocnemius muscle suggests that maximum dorsiflexion for these conditions is limited by bony and ligamentous architecture.

For the unconstrained case, this local architecture produces external rotation and eversion accompanying maximum dorsiflexion. For the constrained case this local architecture acts to limit dorsiflexion. These results are summarized in Table 2.

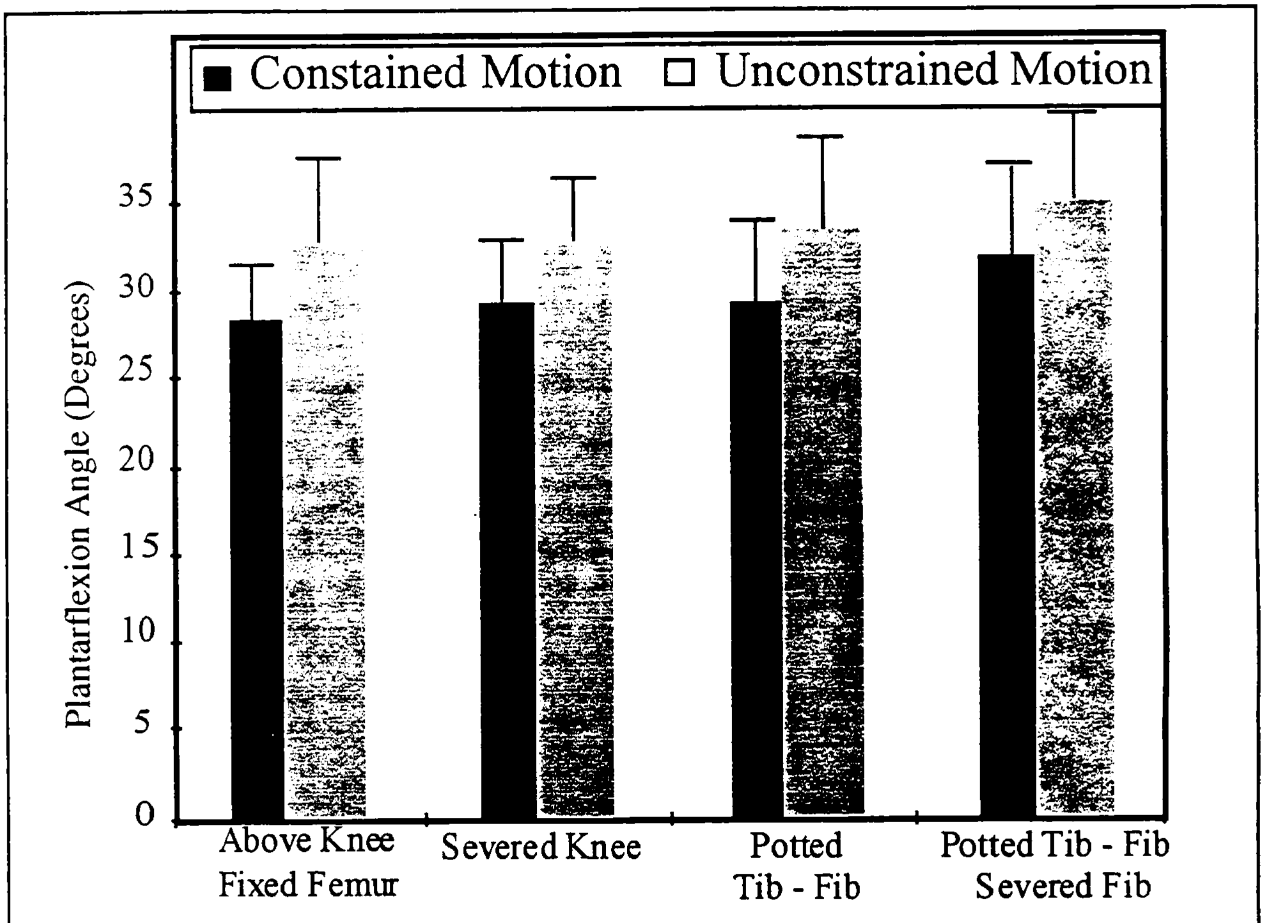

Figure 12. Plantarflexion results with varying boundary conditions and degrees of freedom

CONCLUSIONS

Passive resistance from the soleus and the gastrocnemius muscles plays an important role in limiting the range of ankle dorsiflexion. The condition of the knee fully extended used in this study represents the case where these muscles exhibit the greatest influence on the ankle response. It should be noted that the passive resistance of the gastrocnemius will vary significantly with knee joint angle, providing progressively less resistance with knee flexion.

For the test conditions in this study, plantarflexion appears to be unaffected by fixation boundary conditions, indicating that plantarflexion ROM is primarily a function of local ankle constraints such as ligaments and the joint capsule. At higher levels of loading, however, the musculature may play a more dominant role in determining ankle response and thresholds of injury.

Motion of the fibula relative to the tibia appears to influence ankle flexion response, although in this study the role of this interaction has not been isolated from the influence of muscle groups that attach between the tibia mid-diaphysis and the tibial plateau. In order to preserve the interaction between the tibia and fibula in controlling the ankle mortise, it is recommended that lower limb boundary condition occur superior to the proximal tibio-fibular joint.

Potting the tibia alone, with the fibula sectioned at the mid-diaphysis creates an instability in the ankle joint. The fibula is not able to form a structural mortise for the ankle and exaggerated internal/external rotation during ankle flexion.

Constraining ankle rotation to the sagittal plane suggests a decrease in plantarflexion ROM relative to the unconstrained condition, but no statistically significant differences were obtained. This effect may become more pronounced as the magnitude of the applied moment increases. No discernible change in dorsiflexion ROM occurs for the constrained versus unconstrained case with the gastrocnemius structure intact. With the elimination of the gasctrocnemius muscle, however, a decreased ROM was noticed for the constrained rotation versus unconstrained rotation.

The results of this testing suggest that studies of ankle dorsiflexion must use lower extremities amputated proximal to the knee joint. Since the musculature, bony, and ligamentous resistance that control the response are more distal, plantarflexion studies appear to be less sensitive to the anatomical boundary condition. The data also indicate that flexion studies of the ankle should permit biofidelic rotations and translations and should not constrain motion to a fixed plane.

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REFERENCES

Begeman, Paul C., and Priya Prasad, "Human Ankle Impact Response in Dorsiflexion", SAE 902308, 1990.

Begeman, Paul C., Aekbote Krishnakanth, Robert Levine, and Albert King, "Human Ankle Response in Internal and External Rotation", 4th CDC Injury Prevention through Biomechanics, Detroit, MI, 1994.

Begeman, Paul C, Pradeep Balakrishnan, Robert Levine, and Albert King, "Dynamic Human Ankle Response to Inversion and Eversion", SAE 933115, 1993.

Begeman, Paul C, Balakrishna, P., King, A., "Human Ankle Response in Dorsiflexion", 2nd CDC Injury Prevention through Biomechanics, Detroit, MI 1992.

Rastegar, J., Miller, N., Barmada, R., "An Apparatus for Measuring the Load-Displacement and Load-Depenent Kinematic Characteristics of Articulating Joints-Application to the Human Ankle Joint", J. Biomechanics, Vol. 102, pp. 208-213 August 1980.

Cawley, Patrick W., O.P.A., R.T. and Paul France, Ph.D., "Biomechaincs of the Lateral Ligaments of the Ankle: An Evaluation of the Effects of Axial Load and Single Motions on Ligament Strain Patterns", Foot and Ankle Injury, Vol. 12, No. 2, pp. 92-99, 1991.

Siegler, Sorin, Jie Chen, and C. D. Schneck, "The Three-Dimensional Kinematics and Flexibility Characteristics of the Human Ankle and Subtalar Joints - Part 1: Kinematics", *Journal of Biomechanical Engineering*, Vol. 110, November, pp. 364-385, 1988.

Rasmussen, Ove, and Claus Kromann-Andersen, "Experimental Ankle Injuries; Analysis of the Traumatology of the Ankle Ligaments", Acta Orthop. Scand., Vol. 54, 1983, pp. 356-362.

Markolf, Keith L., Thomas P. Schmalzried, and Richard D. Ferkel, "Torsional Strength of the Ankle *In Vitro*: The Supination-External-Rotation Injury", *Clinical Orthopaedics and Related Research*, Number 246, November, 1989, pp. 266-271.

Allinger, Todd L., and Jack R. Engsberg, "A Method to Determine the Range of Motion of the Ankle Joint Complex, *In Vivo*", *Journal of Biomechanics,* Vol. 26, No. 1., pp. 69-76.

Parentau, Chantal S., David C. Viano, and Per Lovsund, "Foot-Ankle Injury: Epidimiological and Biomechanical Studies", Presented at the International Conference on Pelvic and Lower Extremity Injuries (PLEI), Washington, D.C., December 5, 1995.

Lundberg, Arne, Goldie, Ian, Kalin, Bo, and Selvik, Goran, "Kinematics of the Ankle/ Foot Complex: Plantarrflexion and Dorsiflexion", Foot and Ankle, Vol. 9, No. 4, 1989.

Portier, Laurent, Philippe Petit, Xavier Trosseille, Claude Tarriere, and Francois LaVaste, "An Experimental Research Program for Lower Injuries in Frontal Car Crashes", Presented at the International Conference on Pelvic and Lower Extremity Injuries (PLEI), Washington, D.C., December 5, 1995.

Norkin, C. C., Levangie, P. K, Joint Structure and Function: A Comprehensive Analysis, F. A. Davis Company, Philadelphia, PA, 1992.

Stiehl, J. B., Inman's Joints of the Ankle, Williams and Wilkins, Baltimore, MD 1991.

DISCUSSION

PAPER: **The Effects Of Lower Extremity Boundary Conditions On Ankle Response During Joint Rotation Tests**

PRESENTER: Jeff Crandall, University of Virginia

QUESTION: Frank Pintar, Medical College of Wisconsin

Very nice study, Jeff. I guess, I'm a little surprised at those results of when you leave the tissue attached versus how significantly how it changes when you amputated the knee if I understood that right. You just had dissection at the knee because all your posterior muscle mass in your calf is still there isn't it?

A: But it's not attached.

Q: The whole thing is that gastrocnemius or that large posterior muscle originates at the femoral condyles.

A: Yes. So, as soon as you break that attachment there is no resistance so it is crucial that stays intact.

Q: So, you think that's pretty much the muscle resistance. Is the skin adding some effect too, you think?

A: I think it is primarily the musculature. You can see, if you don't attach the femur. If you leave the musculature intact, run a test. You'll just see the femur raise up. You have to hold the femur.

Q: OK.

A: But it is dependent. The length of that muscle depends on the flexion axis. The degree of flexion on the knee. If you all want to try a test sometime, try dorsiflexion your foot without bending your knee and then bend your knee and find out how far you can and you'll see a drastic difference.

Q: Have you ever tried any tests where you actually take some of those tendons and apply a load to them and find out what that effect is?

A: We've tried. The problem has been relaxation. We apply a load and it relaxes in the muscles so we've been working a lot with lower extremity muscle tensing by artificial means. Greg Klopp showed earlier some tether systems.

Q: That's very nice work. Thank you.

A: Thank you.

Q: Tyler Kress, University of Tennessee

I enjoyed your presentation, Jeff. I'm just kind of curious. You mentioned future work with the injury thresholds and response tests. I'm wondering what type of injuries you're going to be looking at and for what specifics you mean.

A: Yes. The types of injury we'll be trying to introduce or induce actually, are the rotational type injuries. They're trying to develop a criterion; either a degree of rotation criteria or a moment or force criteria where first initiate and what I think is required based on these preliminary results is that we go and we try to define those with biofidelic boundary conditions, purely rotational.

Q: Mostly dynamic type ligamentous and tendon type injuries.

A: Yes. We'll do both quasi static and dynamic 160 degrees per second is the rate we'll be loading at.

Q: Very good. Thank you.

A: Thank you.

Q: Guy Nusholtz, Chrysler Corporation

How many samples did you have in each of your test configurations constrained, unconstrained? What type of variance?

A: Yes. I forgot to show you or tell you about that, rather. If you saw these little bars coming up off the top of the graph, those were standard deviations. There were four legs tested at each condition and we tested the statistical significance and I should have mentioned that those plots showed some standard deviation on one standard deviation plot.

Q: That was about 20 percent then for each of those.

A: No. Not 20 percent. Maybe for some of the smaller values but for some of the larger ones, between 10 and 20 percent.

Q: Andrew McIntosh, The University of New South Wales

It was a good presentation. I'm curious to know what the effects of the soleus muscle is on the range of dorsiflexion because once you've taken the femoral attachment of the gastrocnemius attachment away, you've still got the soleus attached to the fascia.

A: The effect, if you look at the difference between the above knee amputation, primarily the difference is that the gastrocnemius have been incised and you're left with the soleus. I believe the gastrocnemius are primarily the most powerful of the two muscles and contribute actively to the largest portion. I think what we've shown here is passively as well.

Q: They're quite different. I think they've got a different function because of the muscle fiber topping. Of the two muscles, one's got a more postural, one's more for exercising, things like jumping and running so if you've taken the gastrocnemius away, how much do you think the soleus are? What is the increased range of motion?

A: What this show is that the gastrocnemius are by far the most pronounced effect. There was maybe a four or five times increase in the degree of dorsiflexion by simply removing the gastrocnemius muscles.

Q: OK. Thanks.

Q: Srini Sundararajan, Ford Motor Corporation
I've got one question. In the test condition, this knee is straight or bended?

A: The test condition I've shown today is straight. We are currently conducting tests where we vary the degree of flexion of the knee so we are varying the knee flexion now and that does have an effect.

What you'll see is we ran two tests. The above knee had the leg straight or the lower extremity straight and then we ran the severed knee and what you'll see is, as you vary the knee flexion, your response will go between the lower extremity straight and the knee severed so depending on the knee flexion, your response will be between those two.

Q: Thank you.

Q: Janusz Kajzer
I have one question to you. So, your suggestion is also to take into consideration muscles, especially when you are working with extremities, muscles are gravity high. Did you try to make any investigations to put muscle in tension?

A: We've tried various both experimental and simulation techniques to reproduce active muscle tension and we've been much more successful obviously, with simulation than we have with experimental. We've come up with some external apparatus to simulate a tether system that Greg showed earlier to stimulate muscle tension and we're currently trying to develop one that applies muscle tension not only to the ankle but to the knee and to the hip as well so we're working on a device at this time.

Q: But you don't make any tests with results how they influence this.

A: We've made some test results, we've performed some tests, both sled and the pendulum test Greg showed earlier and muscle tensing has two basic effects. One is, it increases the effective mass of the lower extremity so rather than just the distal parts of the lower extremity being an effective mass, as you tense up, sort of the whole lower extremity acts as a unit. That's one effect.

And the other effect is obviously, you can press two to three times body weights per lower extremity so you can induce great preload or forces so that's really two combined effects.

Q: Yes. Thank you. That was very interesting.

A. Thank you.