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Short communication

Transient and long-time kinetic responses of the cadaveric leg during internal and external foot rotation

Alexander R. Mait*, Adwait Mane, Jason L. Forman, John Paul Donlon, Bingbing Nie, Richard W. Kent

Department of Mechanical and Aerospace Engineering University of Virginia, Center for Applied Biomechanics, 4040 Lewis and Clark Drive, Charlottesville, VA 22911, USA

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ABSTRACT

The purpose of this study was to determine the long-time and transient characteristics of the moment generated by external (ER) and internal (IR) rotation of the calcaneus with respect to the tibia. Two human cadaver legs were disarticulated at the knee joint while maintaining the connective tissue between the tibia and fibula. An axial rotation of 21° was applied to the proximal tibia to generate either ER or IR while the fibula was unconstrained and the calcaneus was permitted to translate in the transverse plane. These boundary conditions were intended to allow natural motion of the fibula and for the effective applied axis of rotation to move relative to the ankle and subtalar joints based on natural articular motions among the tibia, fibula, talus, and calcaneus. A load cell at the proximal tibia measured all components of force and moment. A quasi-linear model of the moment along the tibia axis was developed to determine the transient and long-time loads generated by this ER/IR. Initially neutral, everted, inverted, dorsiflexed, and plantarflexed foot orientations were tested. For the neutral position, the transient elastic moment was 16.5 N-m for one specimen and 30.3 N-m for the other in ER with 26.3 and 32.1 N-m in IR. The long-time moments were 5.5 and 13.2 N-m (ER) and 9.0 and 9.5 N-m (IR). These loads were found to be transient over time similar to previous studies on other biological structures where the moment relaxed as time progressed after the initial ramp in rotation.

1. Introduction

Excessive rotation of the foot injures the foot–ankle complex in the human leg, specifically the distal tibiofibular syndesmosis joint (Bloemers and Bakker, 2006; Funk, 2011; Wei et al., 2012). Previous experiments investigated the effects of foot rotation on leg kinetics and the syndesmosis joint (Markolf et al., 1989; Michelson et al., 1997; Wei et al., 2012; Xenos et al., 1995), but with limitations. Though Xenos et al. (1995) allowed the fibula to move freely, the leg was rigidly constrained in four locations. This created an unclear axis of rotation in the ankle by preventing the foot from translating naturally during foot rotation. Wei et al. (2012), Markolf et al. (1989), and Michelson et al. (1997) disarticulated the tibia and fibula mid-shaft, thus disrupting the proximal interosseous membrane (IOM) and tibiofibular joint. These studies rigidly fixed the tibia and fibula together, preventing the fibula from moving freely during rotation, therefore altering ankle mechanics (Skraba and Greenwald, 1984).

The transient behaviors of biological structures have been studied previously (Funk et al., 2000; Kent et al., 2009; Lucas et al., 2008), though, to the authors' knowledge, not for kinetic responses to applied foot rotation. The current study aimed to determine the long-time and transient characteristics of the moment generated about the tibia during foot external rotation (ER) and internal rotation (IR). Imposing functionally relevant boundary conditions on the leg was also a goal of the study, such that a more realistic anatomic configuration is created where the fibula is unconstrained and foot translation is permitted. Transient and long-time relationships between cadaveric leg kinetics and foot rotation was hypothesized. With imposing boundary conditions designed to recreate a more realistic loading within the leg, reliable kinetic data responses to applied rotation will be used to inform future experiments aimed at describing ankle injury characteristics. Understanding the loads throughout the leg during more realistic motion also facilitates future injury-prediction model development on a current finite element (FE) model (Nie et al., 2015).

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* Corresponding author. Fax: +1 434 297 8083.
E-mail address: arm7sb@virginia.edu (A.R. Mait).

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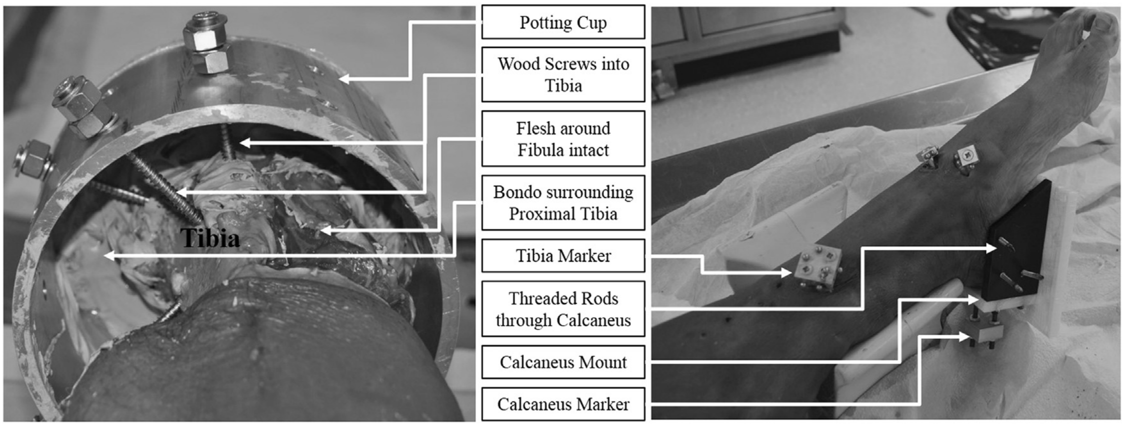

Fig. 1. Potted tibia of a specimen with Bondo body filler covering the anterior, posterior, and medial sides of the proximal tibia and wood screws driven into the shank of the tibia at varying heights and angles along the potting cup. Soft tissue was left undisturbed around the fibula and lateral aspect of the tibia to preserve the IOM and proximal tibiofibular ligament connections. Placement of the tibia and calcaneus markers as well as the open-faced mount around the calcaneus with threaded rods driven from lateral to medial are shown. The lateral face of the calcaneus mount had several holes for threaded rods to pass through to accommodate different sizes of specimens, whereas the medial face was made of solid polyvinyl chloride for the threaded rods to anchor.

2. Methods

2.1. Specimen preparation

Experiments were conducted on fresh-frozen left lower limbs from two male cadavers (Table 1). The specimens were acquired with the approval of and prepared in accordance with the policies and procedures of the UVA Center for Applied Biomechanics Oversight Committee (Ethics Approval #: CAB2014-07). The subjects were confirmed free of infectious diseases including HIV and Hepatitis B/C. Computed tomography (CT) scans of each specimen were taken prior to testing to confirm the absence of bony trauma. Limbs were stored at $-15\,^{\circ}\mathrm{C}$ and thawed to room temperature for 48 h before test preparation. The tibia and fibula were disarticulated at the knee while retaining an intact proximal IOM and tibiofibular joint ligaments. Soft tissue was cleared from the tibial plateau.

The proximal tibia was rigidly attached to a potting cup using wood screws and Bondo body filler (part #261, 3 M Company, St. Paul, MN, USA) with the fibula left free (Fig. 1). A mount assembled with acetal homopolymer resin and polyvinyl chloride, reinforced with machine screws, was fixed to the calcaneus using threaded rods passing from lateral to medial directly tapping into the polyvinyl chloride (Fig. 1).

2.2. Testing procedure

A custom rig was designed to rotate the specimen to a desired effective angle of foot rotation in the global X–Y–Z coordinate system, defined where the center of the tibial plateau was fixed to the center of the potting cup, and apply a constant compressive load down the Z-axis (Fig. 2A). The potting cup around the proximal tibia was attached to a rotary index table which was used to manually impart the desired quasi-static effective foot rotation about the Z-axis. A bi-directional linear rail system attached to the calcaneus mount allowed the foot to translate in the global X and Y directions, and linear bearing tracks permitted motion in the Z-axis (vertical direction), thus allowing the Z-axis of rotation to adjust to the natural axis of rotation in the leg (Fig. 2B). The foot was mounted to this rail system using two gimbals with orthogonal rotation axes, originally parallel to the global axes in a neutral foot position when specimens were placed into the test apparatus. The gimbals allowed the foot to be locked in this neutral orientation or in varying degrees of eversion, inversion, dorsiflexion, and plantarflexion. These foot orientations were defined grossly as rotations of the calcaneus relative to the tibia. The gimbals (fixed to the calcaneus mount) rotated the calcaneus into eversion, inversion, dorsiflexion, or plantarflexion within a nominal range of 10–20°, used since within physiological range of motion of the ankle joint (Nigg et al., 1990; Roaas and Andersson, 1982), at increments of 5°. A 6-axis load cell (Model #5024J, Robert A Denton, Inc., Rochester Hills, MI, USA) and rotary potentiometer (Model #SP22GS, ETI Systems, Carlsbad, CA, USA), aligned between the centers of the potting cup and index table, measured forces and moments acting at the proximal tibia and the imposed effective foot rotation (Fig. 2B). These functionally relevant boundary conditions (fibula not fixed to tibia and foot translation permitted) address deficiencies in previous studies (Markolf et al., 1989; Michelson et al., 1997; Wei et al., 2012; Xenos et al., 1995), so that the leg is not artificially constrained and more realistic interactions among ankle bones and ligaments are attained.

Table 1
Specimen anthropometric data: gender, age at time of death, and whole-body height and weight of the two specimens used in this study.

Specimen ID#	Gender	Age (yr)	Height (cm)	Weight (kg)
616L	Male	46	177	113
743L	Male	31	188	100

Note: L indicates a left leg specimen.

Specimens were initially placed in a nominally neutral position, such that the distal end of the first phalanx, the approximate centroid of the calcaneus, and the long axis of the tibia formed a right angle in the sagittal plane (Fig. 2B). A compressive preload of approximately 110 N, chosen to not overly constrain the leg but still initiate ligaments and joint congruency, was applied via static weight to the calcaneus mount. Maximum effective foot rotation of $\pm 30°$ was determined to be non-injurious (Wei et al., 2012), yet greater than physiological range of motion (Nigg et al., 1990). In this neutral position, all specimens were preconditioned before testing by rotating the index table for 10 cycles from $+30$ to $-30°$. The specimens were then either kept in neutral or placed into a desired configuration of eversion, inversion, dorsiflexion, or plantarflexion, and rotated to the predetermined degree of quasi-static effective foot rotation by the index table. This position was held while the orientation and position of the specimen's tibia was scanned with a three-dimensional laser scanner (ROMER Absolute Arm, Hexagon Metrology, Inc., RA-7330SI-2), throughout which kinetics were measured by the load cell. A marker was rigidly attached to the tibia using wood screws and to the calcaneus mount. Each bone's orientation and position was defined in a local x–y–z coordinate system based on the marker position as detailed by Shaw et al. (2009) (Fig. 2B). The difference between the initial and final position of these markers was used to determine the rotation of the tibia caused by the effective foot rotation input from the index table. In this test rig, there was a fixed boundary condition at both the proximal tibia and the calcaneus (Fig. 2A). After applying the index table effective foot rotation through the fixed proximal tibia, the true foot rotation, defined as ER and IR, was measured as the axial rotation of the fixed calcaneus about the tibia's z-axis.

Post-test necropsies were performed to confirm the lack of ligament damage and bone fracture. The anterior and posterior tibiofibular ligaments, IOM, anterior and posterior talofibular ligaments, calcaneofibular ligament, tibiocalcaneal ligament, and tibionavicular ligament were inspected.

2.3. Kinetic analysis

Force and moment vectors acting within the leg were measured over time at the proximal tibia to determine the leg's kinetic response to an input ER/IR. The moment about the tibial long axis (Mz), defined to be initially coincident with the Z-axis, was of particular interest. Previous studies (Funk et al., 2000; Kent et al., 2009; Lucas et al., 2008) have described the transient and long-time behaviors of biological structures with Fung's quasi-linear viscoelastic (QLV) theory (Fung, 1993). This theory was adapted in the current study to describe the relationship between Mz and rotation. A Supplementary Work section for this manuscript details the derivations for this QLV model. The transient elastic moment response (Mz_0) was calculated from each test's QLV model (Supplementary Work, Equation 2) at all angles of ER/IR. These Mz_0 values were utilized to calculate (Supplementary Work, Equation 4) the long-time moment response (Mz_∞) using the long-time relaxation parameter (G_∞).

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