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Primary and coupled motions of the native knee in response to applied varus and valgus load

Brian P. Gladnick [a,*], James Boorman-Padgett [b], Kyle Stone [b], Robert N. Kent III [b], Michael B. Cross [a], David J. Mayman [a], Andrew D. Pearle [a], Carl W. Imhauser [b]

[a] Department of Orthopaedic Surgery, Hospital for Special Surgery, 535 E. 70th Street, New York, NY 10021, United States
[b] Department of Biomechanics, Hospital for Special Surgery, 535 E. 70th Street, New York, NY 10021, United States

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ABSTRACT

Background: Knowledge of the complex kinematics of the native knee is a prerequisite for a successful reconstructive procedure. The aim of this study is to describe the primary and coupled motions of the native knee throughout the range of knee flexion, in response to applied varus and valgus loads.
Methods: Twenty fresh-frozen cadaver knees were affixed to a six degree of freedom robotic arm with a universal force-moment sensor, and loaded with a 4 Nm moment in varus and valgus at 0, 15, 30, 45, and 90° of knee flexion. The resulting tibiofemoral angulation, displacement, and rotation were recorded.
Results: For each parameter investigated, the knee joint demonstrated more laxity at higher flexion angles. Varus angulation increased progressively from zero (2.0° varus) to 90 (5.2° varus) degrees of knee flexion ($p < 0.001$). Valgus angulation also increased progressively, from zero (1.5° valgus) to 90 (3.9° valgus) degrees of knee flexion ($p < 0.001$). At all flexion angles, the magnitude of tibiofemoral angle deviation was larger with varus than with valgus loading ($p < 0.05$).
Conclusions: We conclude that the native knee exhibits small increases in coronal plane laxity as the flexion angle increases, and that the knee has generally more laxity under varus load than with valgus load throughout the Range of Motion (ROM). Larger differences in laxity of more than 2 to 3°, or peak laxity specifically during the range of mid-flexion, were not found in our cadaver model and are not likely to represent normal coronal plane kinematics.
Level of Evidence: Level V, biomechanical cadaveric study.

1. Introduction

Knowledge of the complex kinematics of the native knee is a prerequisite for a successful reconstructive procedure, because preservation of the native knee kinematics is likely to result in superior clinical outcomes [1–5]. The behavior of the knee in the coronal plane has recently become of particular interest, as several authors have shown that failure to restore proper coronal plane knee kinematics during reconstructive knee surgery may result in specific patterns of medial–lateral knee instability, especially in the range of mid-flexion (30 to 45°) [6–8].

Avoidance of pathologic coronal plane instability after reconstructive surgery requires an understanding of the degree of “normal” coronal plane laxity present in the native knee in response to varus/valgus load through the entire range of knee flexion. Joint laxity includes primary motion in the direction of the applied load, resulting in tibiofemoral angulation in varus or valgus from a defined neutral position. It also includes coupled motions of the tibia relative to the femur in directions other than that of the applied load, such as coupled medial or lateral displacements, or coupled axial rotation of the tibia in relation to the femur (internal or external rotation). Previous studies have investigated primary and coupled motions in response to applied varus and valgus loads. For example, Markolf et al. applied compressive loads to native knees, superimposed with frontal plane moments, after medial or lateral meniscectomy, at full extension and at 20° of flexion [9]. Wang and colleagues similarly assessed primary and coupled motions at zero, 30°, and 90° of flexion [10]. However, a description of primary and coupled motions of the native knee throughout the range of knee flexion is lacking in the literature. A more complete study that assesses the coronal plane primary and coupled motions of the native knee through a large range of flexion, in response to applied varus and valgus loads is needed to fill this knowledge gap.

Thus, this study addressed the following research questions regarding laxity of the native knee in response to varus and valgus loads: 1) does the magnitude of primary and coupled motions change through a functional range of motion from 0 to 90° flexion; 2) is laxity increased during the mid-flexion range (30° to 45° flexion) in the native knee; and 3) is laxity symmetric through a functional range of motion from 0 to 90° flexion?

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[*] Corresponding author at: Department of Orthopaedic Surgery, Hospital for Special Surgery, 535 E. 70th Street, New York, NY 10021, United States. Tel.: +1 212 606 1466; fax: +1 212 606 1477.
E-mail address: gladnickb@hss.edu (B.P. Gladnick).

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2. Methods

Cadaveric knees were prepared and tested using previously published methods [11]. Twenty fresh-frozen cadaver knees (14 male, seven right) were thawed at room temperature for a period of 36 h prior to testing. Mean age of the cadavers was 45 ± 14 years (standard deviation) (range, 20 to 64). Specimens were sectioned at the midshaft of the tibia/fibula and femoral diaphysis. The skin and subcutaneous tissues were removed. The surrounding soft tissues, including the deep fascia, ligamentous, and capsular structures, remained intact. This methodology is consistent with the work of Whiteside et al., who used a similar cadaver model as a "normal" control in their investigations on ligament balancing in total knee replacement [12]. All anatomic specimens were free of anatomic defect, gross instability, deformity, cartilage defect, osteophytes, malalignment, or previous injury. This was confirmed through review of the cadaver medical history, by performing a computed tomography scan on the specimen at our institution, and upon gross inspection at the time of dissection via medial parapatellar arthrotomy, which was subsequently repaired.

A carpenter screw was drilled proximally across the tibia and fibula, stabilizing the tibiofibular articulation with the fibula fixed anatomically relative to the tibia. The tibial and femoral shafts were then potted in bonding cement (Bondo, 3 M, St. Paul, MN), and carpenter screws were drilled across each shaft to ensure adequate fixation between the cement and bone. Each cadaver knee was loaded using a six degrees of freedom robotic manipulator with ±0.3 mm repeatability [11] (ZX165U; Kawasaki Robotics, Wixom, MI). The robotic arm (Figure 1) was equipped with a universal force-moment sensor (Theta; ATI, Apex, NC: resolution: $F_x = F_y = 0.125$ N, $F_z = 0.25$ N, $T_x = T_y = T_z = 0.007$ Nm). The potted femur was attached to a pedestal affixed to the floor, while the tibia was secured to the end effector of the robotic manipulator using a custom fixture.

An anatomical coordinate system was adapted from the convention previously described [11,13]. Anatomic landmarks were pinpointed using a three-dimensional digitizer with 0.23 mm accuracy (MicroScribe G2X, Solution Technologies, Inc., Oella, MD) to define the anatomical coordinate system. The landmarks were: the femoral epicondyles, the distal tibia, the fibular insertion of the lateral collateral ligament, and the superficial Medial Collateral Ligament (MCL) approximately 15 mm below the tibial joint line. These landmarks were identified via palpation and visual inspection. The long axis of the tibia was used to describe internal and external rotation. The femoral epicondyles were used to define the flexion axis to express medial–lateral translations and flexion/extension. The common perpendicular to both of these axes was directed posteriorly, which allowed measurement of anterior/posterior translation and varus/valgus. Tibiofemoral translations were measured relative to the midpoint of the femoral condyles. The path of passive knee flexion from full extension to 90° flexion in one degree increments was then determined using previously-described algorithms [11]. Subsequently, for each knee, a four-Newton-meters moment was applied in both varus and valgus; the four-Newton-meters applied moment approximates a surgeon applying eight Newtons (1.8 lbs) of medial and lateral force to the foot, assuming a distance from knee to foot of 0.5 m, in order to approximate the force experienced by the knee during a typical clinical exam. The resulting primary and coupled plane motions in response to the applied varus and valgus loads were analyzed using computer software (MATLAB, Natick, MA). Specifically, we measured primary motions in the direction of the applied load (varus/valgus angulation). Additionally, we measured coupled motions in directions other than that of the applied load, including coupled coronal plane tibial translation (medial or lateral) relative to the femur and coupled internal or external rotation of the tibia relative to the femur. Each of these outcome parameters was determined at 0, 15, 30, 45, and 90° of knee flexion. Each of these outcomes was measured at 0, 15, 30, 45, and 90° of flexion relative to the neutral position as defined by the path of passive flexion. The primary or coupled motion in response to applied anterior–posterior forces was not reported, as these data have been well described in the literature. [14,15].

Figure 1. Cadaver knees were loaded using a robotic manipulator equipped with a universal force-moment sensor.

Means and standard deviations were reported for each outcome measure. Each outcome measure was compared across all flexion angles tested using one-way repeated measures analysis of variance (ANOVA) test with Student–Newman–Keuls post hoc pairwise comparisons (SigmaPlot 12.3, Systat Software, San Jose, CA). To assess the symmetry of the varus and valgus rotation, paired t-tests were performed at each flexion angle that was tested. In all cases, statistical significance was set at $p < 0.05$.

3. Results

3.1. Laxity in response to applied varus and valgus loads (primary and coupled motions)

The applied varus/valgus load resulted in a progressive increase in the tibiofemoral angle as a function of knee flexion. The four-Newton-meters varus moment caused increasing varus angulation of the knee from zero (2.0 ± 1.1° varus) to 90 (5.2 ± 2.2° varus) degrees of flexion ($p < 0.001$) (Figure 2). With the four-Newton-meters valgus moment, there was increasing valgus deviation of the knee from zero (1.5 ± 0.5° valgus) to 90 (3.9 ± 1.7° valgus) degrees of flexion ($p < 0.001$) (Figure 3).