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

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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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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: $Fx = Fy = 0.125$ N, $Fz = 0.25$ N, $Tx = Ty = Tz = 0.007$ 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).

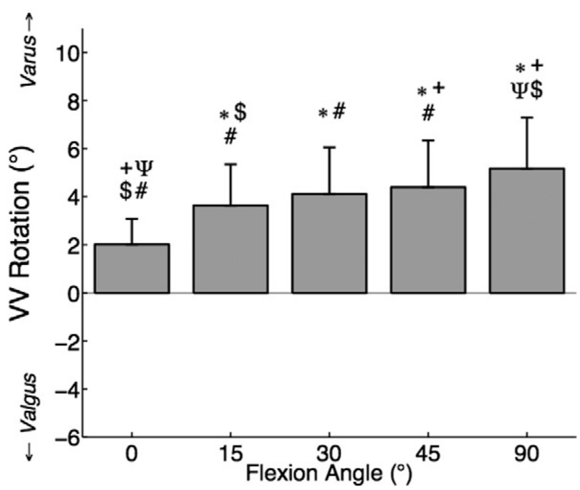

Figure 2. Mean varus rotation of the tibia in degrees in response to an applied varus moment. Whiskers correspond to 1 standard deviation. A positive value indicates varus rotation. The following symbols denote $p < 0.05$ in comparison to 0° (*), 15° (+), 30° (Ψ), 45° ($), or 90° (#) of flexion.

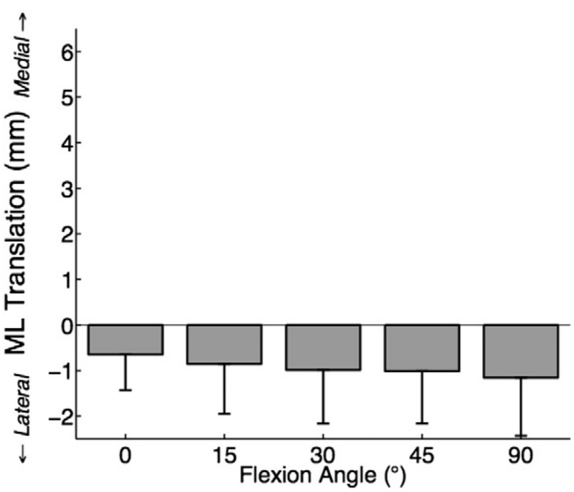

Figure 4. Mean coupled lateral translation of the tibia in millimeters in response to an applied varus moment. Whiskers correspond to 1 standard deviation. A negative value indicates lateral translation. The following symbols denote $p < 0.05$ in comparison to 0° (*), 15° (+), 30° (Ψ), 45° ($), or 90° (#) of flexion.

Similarly, coupled tibial translations increased with varus/valgus loading as a function of knee flexion. The four-Newton-meters varus moment caused small lateral translations of the tibia, ranging from 0.6 ± 0.8 mm at full extension to 1.2 ± 1.3 mm at 90° flexion; these differences were not statistically different across flexion angles ($p = 0.095$) (Figure 4). With valgus loading, there was increasing medial tibial translation from full extension (1.2 ± 0.9 mm) to 90 (3.1 ± 1.9 mm) degrees of flexion ($p < 0.001$) (Figure 5). All coupled anterior–posterior translations of the tibia averaged <1 mm, and exhibited variability of up to ±1.6 mm and ±1.8 mm in response to varus and valgus loads, respectively (Figures 6 and 7).

Finally, the coupled axial rotation of the tibia relative to the femur also increased with varus/valgus loading as a function of flexion angle. The four-Newton-meters varus moment resulted in 1.3 ± 2.8° internal rotation at full extension, which progressed to 3.4 ± 5.8° external rotation at 90° of flexion ($p < 0.001$) (Figure 8). Likewise, the four-Newton-meters valgus moment caused 0.6 ± 2.4° internal rotation at full extension, which progressed to 11.7 ± 7.8° internal rotation at 90° of flexion ($p < 0.001$) (Figure 9).

3.2. Laxity in response to applied varus and valgus loads in mid-flexion (30 to 45° flexion)

No increase in laxity in terms of primary and coupled motions occurred in the range of mid-flexion (30 and 45° flexion) in response to the applied four-Newton-meters varus and valgus moments. The four-Newton-meters varus moment resulted in varus rotation of 4.1 ± 2.0° and 4.4 ± 2.0° in mid-flexion at 30 and 45° flexion, respectively. The four-Newton-meters valgus moment resulted in valgus rotation of 2.3 ± 0.7° and 2.4 ± 0.9° at 30 and 45° flexion, respectively (Figures 2 and 3). Both varus and valgus angulation in response to respective varus and valgus loading was greater than that measured at full extension, but less than that measured at 90° of flexion (all $p \leq 0.03$).

When the knee was loaded in four Newton meters of varus, no differences in coupled lateral tibial translation were detected in mid-flexion compared to either full extension or 90° of flexion ($p = 0.095$) (Figure 4). Under valgus load, we measured 1.6 ± 1.3 and 1.7 ± 1.5 mm of coupled medial tibial translation at 30 and 45° flexion, respectively, which was not different from that seen in full extension ($p > 0.1$) but was at least 1.3 ± 1.2 mm less than the coupled medial tibial translation at 90° ($p < 0.001$) (Figure 5).

With the four-Newton-meters varus load, coupled internal tibial rotation at 30 and 45° flexion was 1.6 ± 6.6° and 0.2 ± 6.7°, respectively. This was not different than coupled internal rotation at full extension (1.1 ± 5.8°) ($p = 0.4$), while 3.4 ± 5.8° external rotation occurred at 90° of flexion (all $p < 0.002$) (Figure 8). With the four-Newton-meters valgus load, coupled internal tibial rotation at 30 and 45° flexion was 4.1 ± 4.4° and 5.5 ± 5.0°, respectively. This was at least 3.6 ± 4.0° greater than internal rotation at full extension (all $p < 0.033$), and at least 6.2 ± 7.0° less than that seen at 90° of flexion (all $p < 0.001$) (Figure 9).

3.3. Symmetry of varus/valgus laxity from 0 to 90° flexion

At all flexion angles other than 90°, varus rotation was larger than valgus rotation (all $p < 0.05$). The difference in magnitude of varus and valgus rotation was smallest at full extension (0.5 ± 1.0°). The difference in magnitude of varus and valgus rotation was largest at 45° flexion (2.0 ± 2.1°) followed by 30° flexion (1.9 ± 1.9°). Asymmetry in varus and valgus rotation at 30 and 45° flexion (midflexion) was larger than that at full

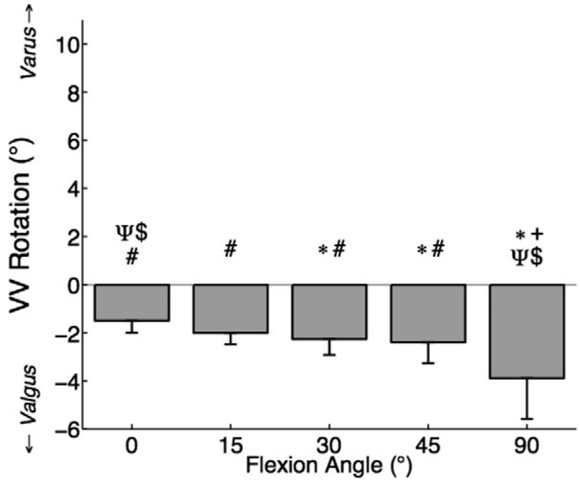

Figure 3. Mean valgus rotation of the tibia in degrees in response to an applied valgus moment. Whiskers correspond to 1 standard deviation. A negative value indicates valgus rotation. The following symbols denote $p < 0.05$ in comparison to 0° (*), 15° (+), 30° (Ψ), 45° ($), or 90° (#) of flexion.

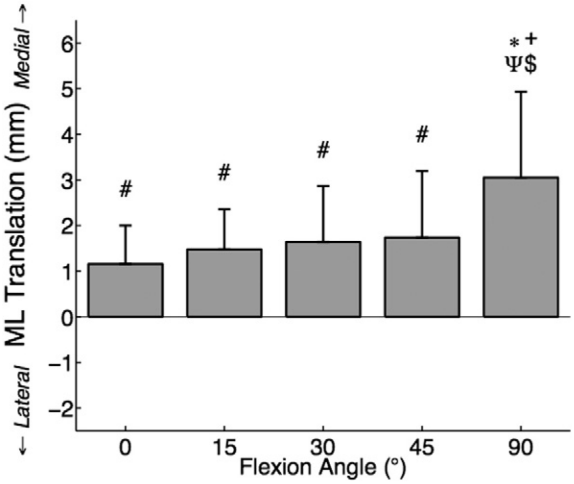

Figure 5. Mean coupled medial translation of the tibia in millimeters in response to an applied valgus moment. Whiskers correspond to 1 standard deviation. A positive value indicates medial translation. The following symbols denote $p < 0.05$ in comparison to 0° (*), 15° (+), 30° (Ψ), 45° ($), or 90° (#) of flexion.

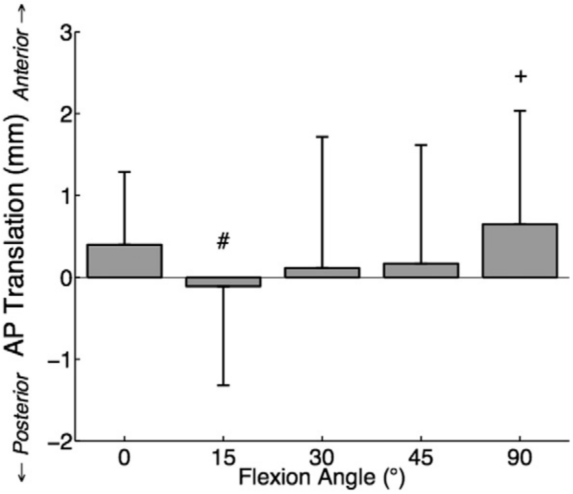

Figure 6. Mean coupled anteroposterior translation of the tibia in millimeters in response to an applied varus moment. Whiskers correspond to 1 standard deviation. A positive value indicates anterior translation. The following symbols denote p < 0.05 in comparison to 0° (*), 15° (+), 30° (Ψ), 45° ($), or 90° (#) of flexion.

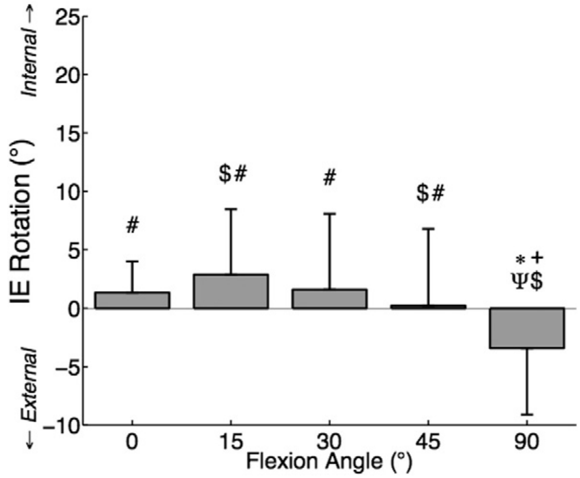

Figure 8. Mean coupled axial rotation of the tibia in degrees in response to an applied varus moment. Whiskers correspond to 1 standard deviation. A positive value indicates internal rotation. The following symbols denote p < 0.05 in comparison to 0° (*), 15° (+), 30° (Ψ), 45° ($), or 90° (#) of flexion.

extension by 1.3 ± 1.3° and 1.5 ± 1.6°, respectively (all $p < 0.001$). However, asymmetry at midflexion was not greater than at 90° flexion (Figure 10).

4. Discussion

A more comprehensive understanding of the coronal plane kinematics of the native knee in terms of primary and coupled motions is important for surgeons who wish to restore normal knee function [16,17]. In this study involving native cadaver knees, we sought to determine 1) does the degree of coronal plane laxity, in terms of both primary and coupled motions, change as the knee is ranged from 0 to 90°; 2) is coronal plane laxity (both primary and coupled motions) increased particularly during the mid-flexion range (30° to 45°); and 3) is coronal plane laxity symmetric under varus/valgus loading as the knee is ranged from 0 to 90 degrees? Our findings show that primary varus and valgus angulation is greater in response to respective varus and valgus loading when the knee is at 90° of flexion (by 3.1° and 2.4°, respectively) than when the knee is loaded in full extension (all $p < 0.001$). In addition, under valgus loading there was increased coupled medial translation of the tibia (by 1.9 mm) at 90° of flexion compared to valgus loading in full extension ($p < 0.001$). Finally, we noted that with varus loading the coupled external tibial rotation was 5.3° greater at 90° of flexion than at full extension, and under valgus loading, the coupled tibial internal rotation is 11.8° more at 90° of flexion than at full extension (all $p < 0.001$). Taken together, these data indicate that, although the differences are small, native knee laxity increases in response to applied varus and valgus loads as the knee is flexed from 0 to 90°.

Importantly, knee laxity in neither primary nor coupled motions in response to applied varus and valgus loads increased during the range of mid-flexion (30 to 45°) compared to extension and flexion. This suggests that in the native knee, instability in response to applied varus and valgus loads should not occur at these flexion angles. However, we did observe that the largest differences of up to 2.0° between primary varus and primary valgus laxity occurred in the mid-flexion range compared to 90° of flexion (1.3°, $p > 0.10$) and at full extension (0.5°, $p < 0.001$).

Finally, our study found that at every flexion angle, varus laxity was greater than valgus laxity by 0.5 to 2.0° on average (all $p < 0.05$). Thus, coronal plane laxity is not symmetric in the native knee; rather, some

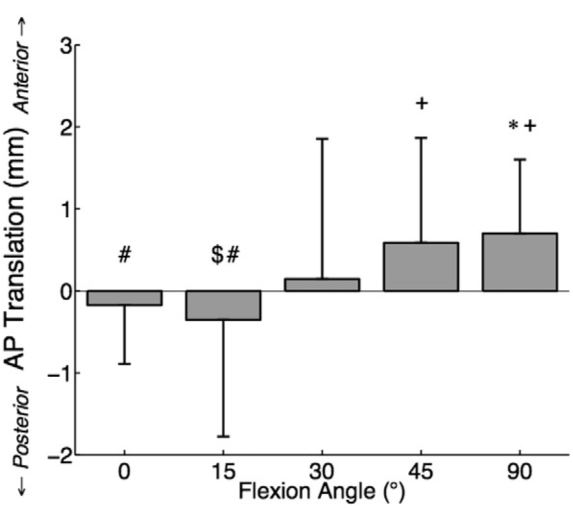

Figure 7. Mean coupled anteroposterior translation of the tibia in millimeters in response to an applied valgus moment. Whiskers correspond to 1 standard deviation. A positive value indicates anterior translation. The following symbols denote p < 0.05 in comparison to 0° (*), 15° (+), 30° (Ψ), 45° ($), or 90° (#) of flexion.

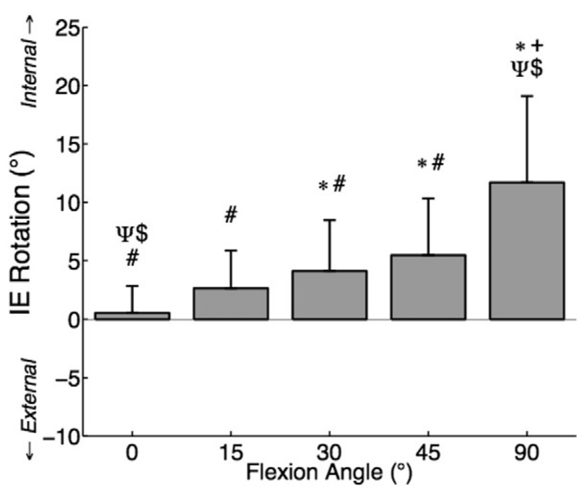

Figure 9. Mean coupled axial rotation of the tibia in degrees in response to an applied valgus moment. Whiskers correspond to 1 standard deviation. A positive value indicates internal rotation. The following symbols denote p < 0.05 in comparison to 0° (*), 15° (+), 30° (Ψ), 45° ($), or 90° (#) of flexion.

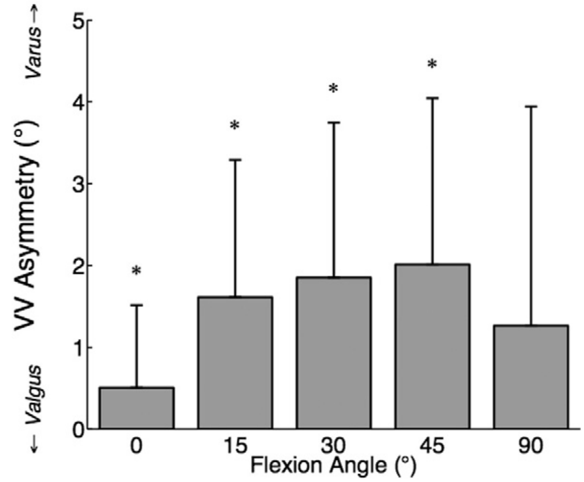

Figure 10. Mean differences in magnitude of primary varus and valgus rotations in response to applied four-Newton-meters varus and valgus loads, respectively. Whiskers correspond to 1 standard deviation. A positive value corresponds to greater varus rotation under varus load than valgus rotation under valgus load. An * indicates statistically significant asymmetry ($p < 0.05$).

increased laxity is normally present on the lateral side of the knee, which is not necessarily perceived by the patient as clinical instability.

These results may provide clinically relevant "normal" baseline data for determining whether a reconstructed knee joint exhibits proper coronal plane kinematics. According to our data, minimally increased varus and valgus laxity of 2° to 3° at higher flexion angles (i.e. at 90° flexion), or slightly increased laxity of 1° to 2° with varus load compared to valgus load, are normal findings in the native knee. Laxity in the mid-flexion range (30° to 45°) should not be maximal compared to extension and flexion.

Our study does not address to what degree these parameters would have to change to be perceived clinically as instability by the patient. For example, it is possible that coronal instability perceived by the patient may be related to a) increased primary and/or coupled motions; b) increased laxity for one of these parameters at specific flexion angles; or c) exaggerations in the subtle asymmetry that is normally observed under varus/valgus loading in primary or coupled motions. These questions could be answered with future investigations directed at the coronal plane stability of the reconstructed knee. In the meantime, the data from this study serve as a useful baseline description of the coronal plane kinematic behavior of the native knee.

Previous authors have reported coronal plane laxity in the native knee. Whiteside and colleagues used loaded cadaver knees in varus and valgus with 10 Nm moments to investigate the effect of specific ligament releases on knee stability [12]. Thorlund and colleagues measured varus/valgus opening in a cohort of 21 healthy knees as part of a larger study on coronal plane stability. Similar to the results in our study, both authors report minimal coronal plane opening when a 4 Nm moment was applied in varus (two degrees opening) or in valgus (two degrees opening) to a typical "normal" patient's knee at 20° of flexion [18]. Greater coronal plane motion was reported when greater moments were applied to the knee (i.e. for a 12 Nm moment, 7.4° varus opening and 5.8° valgus opening). This is in agreement with the work of Markolf et al., who also reported increased varus/valgus laxity of 3 to 4° when the flexed knee was loaded with greater coronal plane moments (10 to 20 Nm) [9]. However, in both cases the authors did not attempt to assess coronal laxity throughout the arc of motion; the reported data are only with the knee in full extension or in 20° of flexion. Similarly, Sharma et al. measured varus–valgus laxity in a cohort of 49 control knees using a custom apparatus that applied a predefined 12 Nm load to the knee with the thigh and ankle immobilized. Consistent with our findings, the authors report minimal varus–valgus rotation in both younger (laxity 2.9° ± 1.0°) and older (laxity 3.4° ± 1.1°) control knees [19]. However, like Thorlund et al., this study only examined knees at 20° of flexion, and did not study coronal translations or axial rotations. Our study is in agreement with the work of Wang et al., who investigated coronal plane stability in 11 cadaver knees at 0, 30 and 90° of flexion with larger applied moments (6 to 10 Nm) in the setting of an axial compressive load (10 to 200 N). Similar to our results, the authors report increased laxity at higher flexion angles, with larger angular deviations under varus stress compared to valgus stress [10]. Our study complements these previous studies by documenting the primary and coupled motions occurring in response to applied varus/valgus moments through additional flexion angles throughout a functional 90° arc of flexion. Finally, our results agree with Roth et al., who showed that the limits of varus/valgus motion increase with flexion [17].

There are several limitations to our study. First, all experiments were performed in cadaver knees, and thus the resulting stability of the knee under applied coronal moments reflects only the contributions of the static knee stabilizers (i.e. bony architecture, ligaments, menisci, and capsule). The relative contributions of the dynamic stabilizers such as the muscle tendon units that cross the joint are not taken into account with this model. However, from a surgeon's perspective, the knee is assessed in the operating room with the patient under anesthesia; therefore, the static stabilizers are indeed the structures actually being tested when determining knee stability. Thus, our model is likely an adequate reflection of coronal plane stability in the anesthetized patient, and thus still has clinical relevance. A second limitation is that the model may not account for the breadth of variability in laxity that occurs in the general patient population. Some patients may have excessive ligamentous laxity at baseline and would exhibit coronal plane motion that exceeds the small changes described in our cadaver population. Our cadavers represented a varied population of normal, uninjured knees with a wide age range (20 to 64 years) and including both male and female specimens; thus, the knee kinematic data as discussed in this paper would likely be clinically relevant to most patients in the general population. We believe that a strength of this paper is that it provides a baseline for the stability of the native knee in response to varus/valgus load in terms of primary and coupled motions, and can be used as a reference for reconstructive surgeons attempting to restore "normal" knee kinematics.

A detailed knowledge of the complex kinematics of the native knee is required for the successful completion of any reconstructive procedure. To detect and avoid coronal plane instability in the reconstructed knee, the surgeon must understand the behavior of the native knee throughout a range of flexion under coronal plane loading. In this biomechanical study, it was demonstrated via a cadaver model 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 between full extension and 90° flexion. 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.

Conflict of interest statement

The authors have no potential conflicts of interest related to this work to disclose.

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