

The Limits of Passive Motion Are Variable Between and Unrelated Within Normal Tibiofemoral Joints

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ABSTRACT: Patient-to-patient differences should be accounted for in both clinical evaluations and computational models of knee laxity. Accordingly, the objectives were to determine how variable the laxities are between knees by determining the range of the internal–external (I-E), varus–valgus (V-V), anterior–posterior (A-P), and compression–distraction (C-D) limits of passive motion, and how related the laxities are within a knee by determining whether these limits are correlated with one another. The limits in I-E (± 3 Nm), V-V (± 5 Nm), A-P (± 45 N), and C-D (± 100 N) were measured in 10 normal human cadaveric knees at 0° to 120° flexion in 15° increments using a six degree-of-freedom load application system. The ranges from 15° to 120° flexion of the I-E limits were greater than 3.6°, of the A-P limits were greater than 1.8 mm, and of the varus limits were greater than 1.4°. The ranges from 30° to 120° flexion of the distraction limits were greater than 2.0 mm. Twenty-four of the 28 pair-wise comparisons between the limits had a correlation coefficient less than 0.65. These results demonstrate that a patient-specific approach, including all degrees of freedom of interest, is necessary during clinical evaluations of laxity and when creating and validating computational models of the tibiofemoral joint. © 2015 Orthopaedic Research Society. Published by Wiley Periodicals, Inc. *J Orthop Res*

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It is important to characterize the patient-to-patient differences in the laxities of the tibiofemoral joint of the normal human knee in various degrees of freedom. The laxities of the normal human knee are often used both as a benchmark by orthopedic surgeons when evaluating laxities before, during, and after surgical interventions (e.g., total knee arthroplasty)¹ and as a gold standard by researchers when validating computational models of the tibiofemoral joint.^{2,3} Passive kinematics of the tibiofemoral joint are guided by the interaction between the soft tissue restraints and the articular geometry. However, the restraints from both the soft tissues and articular geometry are different between individuals.⁴ Because the laxities are a measure of the function of the soft tissue restraints and the articular geometry, abnormal laxities indicate abnormal function. Therefore, it is critical to characterize the patient-to-patient differences in the laxities so they may be accounted for during clinical evaluations of laxity and when creating computational models of the knee to study the behavior of the soft tissue restraints.

There are two types of patient-to-patient differences that are of interest with regards to the laxities of the tibiofemoral joint. The first is the variability of the laxities between knees. If there is a wide variability as characterized by a wide range of the laxities, then a patient-specific approach would be necessary both during clinical evaluations of laxity and when creating computational models of the knee to study the behavior of the soft tissue restraints. The second is the relationship between the laxity in one degree of freedom and

the laxity in another degree of freedom within a knee. Often the laxities in only a few degrees of freedom are used by surgeons to evaluate whether laxity is correct after a surgical intervention^{5,6} and by researchers to validate computational models.^{2,3} One recent study showed that the anterior laxity is related to the laxity in internal, external, varus, and valgus rotation at 20° flexion.⁷ If this result holds true over a range of flexion angles, then including only a few degrees of freedom during clinical evaluations of laxity and when validating computational models would be justified. However, if one laxity is not related to another laxity over a range of flexion angles, then it would be important for (1) surgeons to evaluate laxity in multiple degrees of freedom to determine whether the laxities have been restored to normal after an intervention and (2) researchers to validate computational models using laxity in multiple degrees of freedom.

Previous studies have characterized the laxities of the tibiofemoral joint using the limits of passive motion.^{4,8–10} Using applied loads that just engage the soft tissue restraints, the limits of passive motion for a single degree of freedom are quantified as the extremes of the bidirectional motions of the tibia relative to the femur about a neutral position over a range of flexion angles.⁴ However prior studies were limited in that they (1) included a limited number of degrees of freedom,^{4,8,11} (2) measured the limits of passive motion over a limited range of flexion angles,^{4,8,11} (3) constrained coupled motions,^{9,11} and/or (4) did not address both types of patient-to-patient differences in the limits of passive motion.^{4,8–11}

Accordingly, the primary objective of the present study was to determine how variable the limits of each degree of freedom are between knees by characterizing the range of the limits of passive motion of the normal tibiofemoral joint in each of four degrees of freedom

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over the full range of flexion without constraining coupled motions. The four degrees of freedom include internal–external (I-E) rotation, varus–valgus (V-V) rotation, anterior–posterior (A-P) translation, and compression–distraction (C-D) translation. A secondary objective was to determine how related the limits of passive motion are within a knee between different degrees of freedom.

METHODS

Specimen Selection and Preparation

Ten fresh-frozen, human cadaveric knees (mean age = 69 years, range = 52–93 years; six male and four female) were included. A power analysis confirmed that strong correlations with a correlation coefficient of 0.71 ($r^2 = 0.5$)¹² could be detected with $\alpha = 0.05$ and $(1-\beta) = 0.7$.¹³ The inclusion of both males and females from this age range provided a sample representative of the population of patients typically undergoing total knee arthroplasty. Before inclusion, each specimen was screened using an anteroposterior radiograph of the knee and a visual inspection of the ligaments and articular surfaces following testing. Specimens were excluded when there were signs of degenerative joint disease (i.e., marginal osteophytes, joint space narrowing, chondrocalcinosis, subchondral sclerosis, and/or cartilage lesions) and/or evidence of previous surgery to the knee. On the day of testing, each knee was prepared by first rigidly fixing the fibula to the tibia using a transverse screw 12 cm below the joint line. Second, the thigh was transected 20 cm proximal to the joint line and shank was transected 25 cm distal to the joint line. Third, all tissues more than 15 cm proximal and 12 cm distal to the joint line were removed. Fourth, the fibula was transected just distal to the transverse screw fixing it to the tibia. Finally, intramedullary rods were cemented into the medullary canals of both the femur and tibia, and each knee was wrapped in saline-soaked cloth to prevent dehydration of the tissues.¹⁴

Description of Load Application System

The limits of passive motion were measured using a six degree-of-freedom load application system (Figs. 1 and 2).¹⁵ The load application system embodies the coordinate system of Grood and Suntay.¹⁶ Hence, the flexion-extension (F-E) axis is fixed in the femoral assembly and medial-lateral (M-L) translation occurs parallel to the F-E axis. The I-E axis is fixed in the tibial assembly and C-D translation occurs parallel to the I-E axis. The V-V axis is the floating axis, which is perpendicular to both the F-E and I-E axes, and A-P translation occurs parallel to the V-V axis. Loads are applied by stepper motor actuators, which run under full closed-loop control. Each degree of freedom, with the exception of M-L translation, is instrumented with both a load cell and a displacement sensor. M-L translation was not actuated in this study, so it was only instrumented with a displacement sensor. Loads are measured using commercially available load cells with stated accuracies of 2.2 N for A-P, 8.9 N for C-D, 0.01 Nm for I-E, 0.02 Nm for V-V, and 0.06 Nm for F-E. Motions are measured using either linear variable differential transformers or rotary variable differential transformers with stated accuracies of 0.25 mm for the translations or 0.08° for the rotations.

Description of Functional Alignment Procedure

The alignment of the specimen relative to the coordinate system of the load application system is set using a functional

alignment procedure. The goal of the functional alignment procedure is to align the F-E and longitudinal rotation axes of the tibiofemoral joint with the F-E and I-E axes of the load application system, respectively. This alignment procedure is justified because the F-E rotation axis of the tibiofemoral joint is fixed in the femur and the longitudinal rotation axis of the tibiofemoral joint is fixed in the tibia.^{17,18}

Iterative six degree-of-freedom adjustments of the position and orientation of the femur and tibia were made manually using alignment fixtures that connect the intramedullary rods to the load application system until coupled motions were within tolerance. For alignment of the F-E axes, the coupled A-P and proximal-distal translations and the coupled V-V rotation of the tibia were observed while flexing the knee from 10° to 110°, which is the range where the radii of the medial and lateral femoral condyles are both constant and equal.¹⁹ The tolerances for coupled motions during knee flexion were ≤ 1 mm for A-P translation, ≤ 5 mm for C-D translation, and $\leq 1^\circ$ for V-V rotation. For alignment of the I-E and longitudinal rotation axes, the coupled A-P and M-L translations and V-V rotation were observed while rotating the tibia in I-E between about $\pm 10^\circ$ of rotation (amount of I-E rotation dependent upon I-E stiffness of knee) at 30° of flexion, which is the flexion angle where the I-E laxity is near maximum. The tolerances for coupled motions during I-E rotation were ≤ 1 mm for A-P translation and M-L translation and $\leq 1^\circ$ for V-V rotation. Once all coupled motions were within tolerance, the femur and tibia were potted within square aluminum tubes using methyl methacrylate to fix the position and orientation of each bone relative to the load application system during testing.

Measurement of the Limits of Passive Motion

Prior to measuring the limits of passive motion, each knee was subjected to a preconditioning protocol consisting of first cycling the knee five times between ± 2.5 Nm in F-E and then extending the knee under 2.5 Nm to define 0° flexion.²⁰ Next, the knee was moved to a flexion angle randomly selected from 0°, 60°, and 120° and then cycled five times between the prescribed loads for each degree of freedom in a random order²¹; the prescribed loads for each degree of freedom were ± 3 Nm for I-E⁴, ± 5 Nm for V-V,⁹ ± 45 N for A-P,⁸ and ± 100 N for C-D.¹⁰ The magnitude of each load was set to just engage the soft tissue restraints (i.e., load to the onset of the high/terminal stiffness region of the tibiofemoral joint's force-deformation curve in each degree of freedom^{8,9}). The preconditioning protocol was repeated for the other two flexion angles also in a random order.

After preconditioning, the limits of passive motion for I-E, V-V, A-P, and C-D were determined over a range of flexion angles from 0° to 120° in 15° increments using the prescribed loads listed above. A 45 N compressive tare load was applied throughout testing to simulate the passive compression across the joint that is generated by the muscles crossing the knee.²² First, the knee was moved to a randomly selected flexion angle. Second, for a randomly selected degree of freedom, the prescribed positive load was applied followed by the prescribed negative load; both resulting positions were recorded. The knee was then unloaded, and the resulting position was recorded. Next, the prescribed negative load was applied followed by the prescribed positive load; both resulting positions were

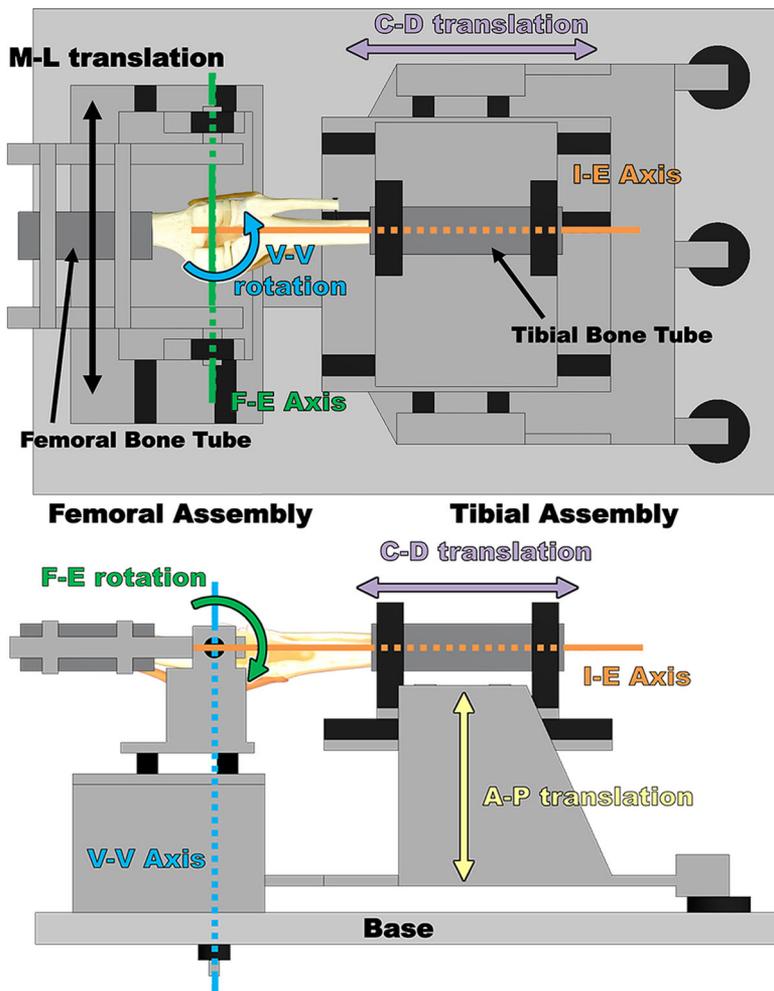


Figure 1. Schematic of a knee model mounted in the six degree-of-freedom load application system¹⁵ used to measure the limits of passive motion of the tibiofemoral joint. An image of a model knee is included to show the location of the knee relative to the load application system; anterior points down toward the base. The degrees of freedom follow the coordinate system of Grood and Suntay¹⁶ so that the flexion–extension axis is fixed to the femoral assembly and the longitudinal rotation axis is fixed to the tibial assembly. Accordingly, the femoral assembly provides two degrees of freedom, flexion–extension (F-E) rotation and medial–lateral (M-L) translation. The tibial assembly provides the remaining four degrees of freedom, including internal–external (I-E) and varus–valgus (V-V) rotations and anterior–posterior (A-P), and compression–distraction (C-D) translations. Stepper motor actuators (omitted for clarity) are used to apply loads in all degrees of freedom except M-L. The loads applied by the actuators are measured with commercially available load cells. Motions in all degrees of freedom are enabled through the use of low-friction bearings. The motions are measured with linear variable differential transformers (LVDTs) for translations and rotational variable differential transformers (RVDTs) for rotations (both omitted for clarity).

recorded. Finally, the knee was unloaded and the resulting position was recorded. The neutral position was computed as the average of the two recorded positions of the unloaded knee. The positive and negative limits were computed as the difference between the average of the two

recorded positions of the knee under the prescribed positive and negative loads respectively and the neutral position (Fig. 3). This procedure was repeated for all randomly ordered combinations of the flexion angles and degrees of freedom.

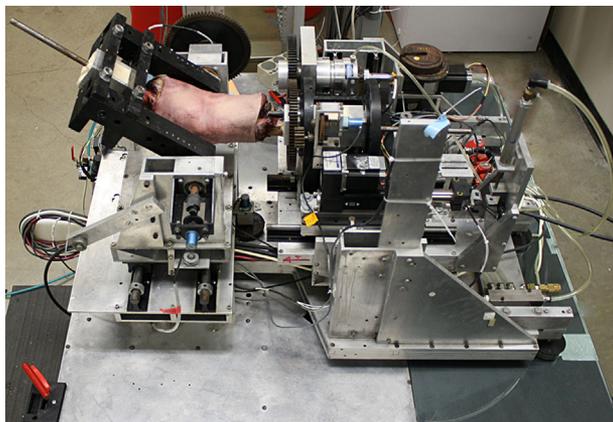


Figure 2. Photograph of cadaveric knee specimen aligned in the six degree-of-freedom load application system.¹⁵ Anterior points down toward the base of the load application system.

Statistical Analysis

Each limit was described by the mean and the standard deviation of that limit for the 10 cadaveric knees at each of the nine flexion angles. All data were found to be normally distributed using the Shapiro–Wilks test except for external rotation and compression translation at 15° flexion and posterior translation at 0° and 45° to 90° flexion. To address the first objective, the variability was quantified by the range, R_{ij} (Equation 1), of each of the eight limits (four degrees of freedom and two limits per degree of freedom, l_{ijk} , $i = 1, \dots, 8$) at each of the nine flexion angles ($j = 1, \dots, 9$) over all 10 knees ($k = 1, \dots, 10$).

$$R_{ij} = \max[|l_{ij1}|, \dots, |l_{ij10}|] - \min[|l_{ij1}|, \dots, |l_{ij10}|] \quad (1)$$

To address the second objective, the relationships between the limits within a knee were quantified by a correlation matrix consisting of all pair-wise correlations between the sums, $S_{i,k}$, of each of the eight limits (l_{ijk} , $i = 1, \dots, 8$), over all

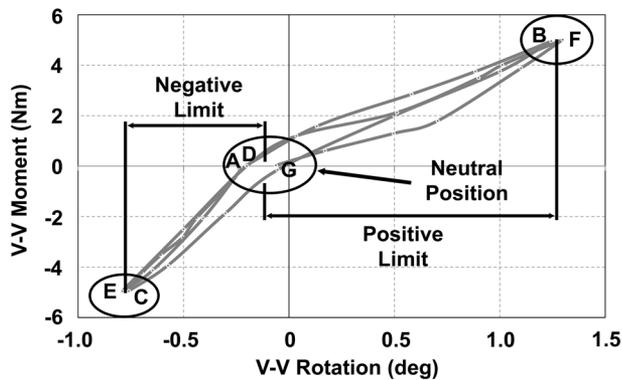


Figure 3. Line plot shows a typical loading cycle to measure the varus–valgus limits of passive motion: (1) knee is loaded to the positive limit (A–B), (2) knee is loaded to the negative limit (B–C), (3) knee is unloaded (C–D), (4) knee is loaded to negative limit (D–E), (5) knee is loaded to positive limit (E–F), and (6) knee is unloaded (F–G). The neutral position is the average of the two unloaded positions (D and G). The positive limit is the difference between the average of the two positive limits (B and F) and the neutral position. The negative limit is the difference between the average of the two negative limits (E and C) and the neutral position.

nine flexion angles ($j=1, \dots, 9$) for each of the 10 knees ($k=1, \dots, 10$) (Equation 2).

$$S_{i,k} = \sum_{j=1}^9 l_{ijk} \quad (2)$$

RESULTS

Both the mean I-E limits were the smallest at 0° flexion and remained nearly constant from 30° flexion to 120° flexion (Fig. 4). The range of the internal limit was largest at 90° flexion (10.8°). The range of the external limit was largest at 105° flexion (16.3°). The descriptive statistics for all eight limits at all flexion angles can be found in Supplement Tables S-1, S-2, S-3, and S-4.

As with I-E, both the mean V-V limits were smallest at 0° flexion and increased nearly linearly with flexion; the

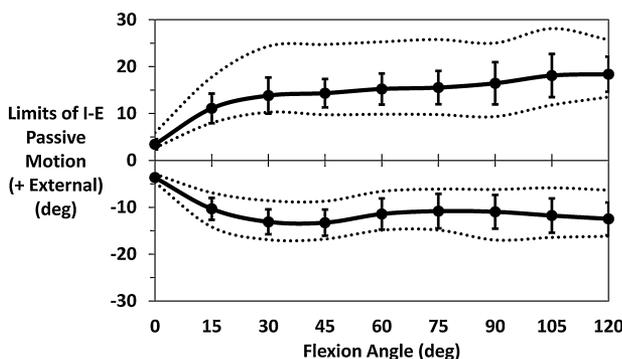


Figure 4. Line plot shows the mean (solid line), standard deviation (error bars), and range (dotted lines) of each I-E limit of passive motion ($N=10$). The limit at each flexion angle is measured relative to the neutral position determined at that flexion angle.

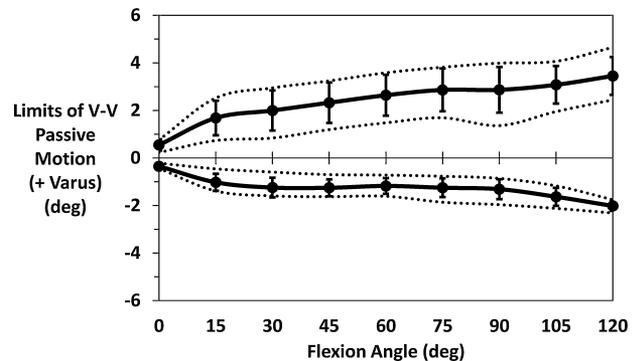


Figure 5. Line plot shows the mean (solid line), standard deviation (error bars), and range (dotted lines) of each V-V limit of passive motion ($N=10$). The limit at each flexion angle is measured relative to the neutral position determined at that flexion angle.

varus limit increased more rapidly than the valgus limit (Fig. 5). The ranges of the varus and valgus limits were both largest at 90° flexion (2.6° and 1.1°, respectively).

As with I-E and V-V, both mean A-P limits were smallest at 0° flexion. The anterior limit was greatest at 30° flexion, but the posterior limit remained nearly constant between 15° and 120° flexion (Fig. 6). The range of the anterior limit was largest at 75° flexion (5.5 mm). The range of the posterior limit was largest at 45° flexion (5.6 mm).

As with the other degrees of freedom, both the mean C-D limits were smallest at 0° flexion. The mean compression limit increased linearly with flexion. The distraction limit increased linearly up to 45° flexion and then remained fairly constant throughout the rest of flexion (Fig. 7). The range of the compression limit was largest at 120° flexion (1.2 mm). The range of the distraction limit was largest at 45° flexion (2.9 mm).

Twenty-four of the 28 pair-wise comparisons had a correlation coefficient less than 0.65 (Table 1). Only the correlations between the valgus limit and the internal rotation limit ($r=0.74, p=0.015$) and

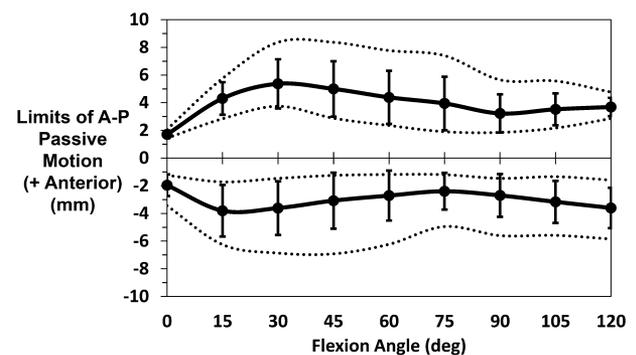


Figure 6. Line plot shows the mean (solid line), standard deviation (error bars), and range (dotted lines) of each A-P limit of passive motion ($N=10$). The limit at each flexion angle is measured relative to the neutral position determined at that flexion angle.

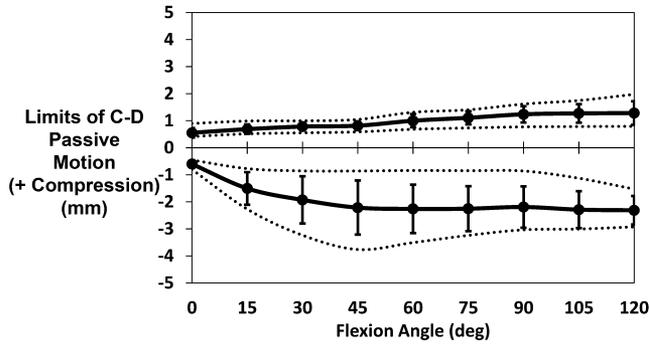


Figure 7. Line plot shows the mean (solid line), standard deviation (error bars), and range (dotted lines) of each C-D limit of passive motion ($N=10$). The limit at each flexion angle is measured relative to the neutral position determined at that flexion angle.

between the distraction limit and the varus limit ($r = -0.69, p = 0.028$), the anterior limit ($r = -0.69, p = 0.028$), and the posterior limit ($r = 0.81, p = 0.004$) were significant.

DISCUSSION

The objectives of the present study were to determine how variable the eight limits of passive motion are between knees based on the range of each limit and how related the limits of passive motion are within a knee based on the correlations between pair-wise comparisons of the sums over all nine flexion angles of each of the eight limits for each of the 10 knees. The first key finding concerns whether the range of a particular limit varied widely. This determination was made in the context of clinical importance to total knee arthroplasty. The threshold for classifying the I-E and A-P limits as having a wide range was based on a study that showed a 40% increase in polyethylene wear when the I-E laxity increased by 3.6° and the A-P laxity increased by 1.8mm.²³ The threshold for classifying the V-V limits as having a wide range was based on a study that showed patients with osteoarthritis who reported having an unstable knee had 1.4° more laxity in V-V than those that did not report instability.²⁴ The threshold for classifying the C-D limits as having a wide range was based on the standard thickness increment of 2mm of the tibial liner. In this context, the limits of passive motion varied widely in posterior translation at all flexion angles, in internal rotation, external rotation, varus rotation, and anterior translation at all flexion angles except 0° , and in distraction translation at flexion angles greater than 30° . Neither compression translation nor valgus rotation varied widely at any flexion angle. The second key finding was that a majority of correlation coefficients were less than 0.65 indicating that the sum of the limits of the different degrees of freedom are not related to one another within a knee.

Before interpreting the results of the present study, five limitations should be discussed. First, this set of

Table 1. Correlation Matrix for the Sums of the Limits of Passive Motion for Each Specimen Over All Nine Flexion Angles for Each of the Eight Limits of Passive Motion

	External Limit	Internal Limit	Varus Limit	Valgus Limit	Anterior Limit	Posterior Limit	Compression Limit	Distraction Limit
External limit	1.00	0.15 (0.68)	0.53 (0.12)	-0.08 (0.88)	0.41 (0.25)	-0.62 (0.06)	-0.33 (0.35)	-0.41 (0.24)
Internal limit	0.15 (0.68)	1.00	-0.55 (0.10)	0.74 (<0.02)	-0.42 (0.22)	0.13 (0.72)	-0.22 (0.54)	0.51 (0.13)
Varus limit	0.53 (0.12)	-0.55 (0.10)	1.00	-0.32 (0.36)	0.52 (0.12)	-0.53 (0.11)	-0.23 (0.53)	-0.69 (<0.03)
Valgus limit	-0.08 (0.83)	0.74 (<0.02)	-0.32 (0.36)	1.00	-0.29 (0.41)	0.13 (0.71)	-0.25 (0.49)	0.38 (0.28)
Anterior limit	0.41 (0.25)	-0.42 (0.22)	0.52 (0.12)	-0.29 (0.41)	1.00	-0.63 (0.05)	0.24 (0.50)	-0.69 (<0.03)
Posterior limit	-0.62 (0.06)	0.13 (0.72)	-0.53 (0.11)	0.13 (0.71)	-0.63 (0.05)	1.00	0.03 (0.93)	0.81 (<0.01)
Compression limit	-0.33 (0.35)	-0.22 (0.54)	-0.23 (0.53)	-0.25 (0.49)	0.24 (0.50)	0.03 (0.93)	1.00	-0.20 (0.57)
Distraction limit	-0.41 (0.24)	0.51 (0.13)	-0.69 (<0.03)	0.38 (0.28)	-0.69 (<0.03)	0.81 (<0.01)	-0.20 (0.57)	1.00

Bold values highlight the coefficients that were statistically significant. The corresponding p -value is shown in parentheses next to each correlation coefficient. Each comparison is shown twice so that all pair-wise comparisons involving a particular limit are shown in a single row/column.

specimens may have provided a conservative estimate of the range of the limits of passive motion. As the sample size grows, the range of the limits possibly increases. However, this did not impact the interpretation of the results because the sample included was large enough to obtain normally distributed limits of passive motion in all degrees of freedom at nearly all flexion angles and was large enough to detect strong correlations between the limits within a knee.

A second limitation was that the results presented here apply to the age group of specimens studied. Different age groups may exhibit different trends due to either stiffer or looser soft tissue restraints.²⁵ However, this age group was chosen because it is representative of the patient population commonly undergoing total knee arthroplasty.

A third limitation was that the major muscles crossing the knee were transected to mount the knee in the load application system; hence, the contributions of the passive stiffness of these muscles were not included. Because muscles are not the primary passive stabilizers in I-E, V-V, A-P, and C-D,²⁶⁻²⁸ the loss of the passive restraints of the surrounding muscles did not likely change the limits of passive motion.

A fourth limitation was that some surgeons may apply larger loads when evaluating laxity. Under these higher loads, the stiffness of the tissues plays a larger role in controlling laxity. Therefore, the variability may be greater because of the added variability in the mechanical properties of the soft tissues.

Fifth, the limits of passive motion would vary if a different tare load value was selected. Previous studies of in vitro knee laxity have applied compressive loads ranging from 20 N to 925 N.^{4,22,29-32} Increasing the compressive load decreases laxities in all degrees of freedom^{4,29,30,32} and decreases the contribution of the soft tissue restraints to stability.³² If a larger compressive load had been applied, then it is likely that the variability of the limits would also decrease; therefore, because the tare load used in this study was at the lower range of the tare loads used previously, the results presented in this study likely define an upper bound for the variability in limits of passive motion.

Beyond the limitations, there were two methods issues that could have inflated the patient-to-patient differences found in the present study. The first was the variation in the alignment of the specimen relative to the coordinate system of the load application system using the functional alignment procedure. A previous study by Berns et al.³³ showed that, using the functional alignment procedure, the variation in laxity under the same load between repeated alignments of the same knee was less than 4% of the measured laxity for A-P, less than 4% of the measured laxity in V-V, and less than 5% of the measured laxity in I-E. The variability in the measured laxities within a knee due to the alignment were over an order of magnitude less than the variability in the limits between knees; hence, the variations in the alignment of the speci-

mens do not explain the patient-to-patient differences found in the present study.

The second methods issue that could have inflated the patient-to-patient differences found in the present study was the variability in determining the neutral position. In a pilot study, the neutral positions in I-E, V-V, A-P, and C-D were each determined three times at the flexion angle with the most laxity for that degree of freedom. The range of the neutral position over the three trials in I-E was 0.5° at 120° flexion, in V-V was 0.1° at 120° flexion, in A-P was 0.6 mm at 30° flexion, and in C-D was 0.2 mm at 120° flexion. These ranges set an upper bound on the variation due to determining the neutral position because they were measured at the flexion angle with the greatest laxity for each degree of freedom. The variability introduced by variations in determining the neutral position is around an order of magnitude less than the variability presented in the present study; hence, it did not affect the conclusions of the present study.

The first key finding was that six of the eight limits of passive motion varied widely over some of the range of flexion. Both the mean and the 95% population limits (i.e., mean \pm 2 standard deviations) of the I-E, V-V, and A-P limits measured in the present study are similar to those measured in previous studies that used the same loads because the ranges between the 95% population limits overlap and the means have the same trends over flexion (Fig. 8); a comparison for C-D was not included because no study has measured the C-D limits over a range of flexion in the normal knee using the same loads as the present study. A recent study suggested that future surgical instrumentation could take advantage of a database of limits of passive motion of the normal knee to provide the surgeon feedback intraoperatively about whether the laxities have been restored to normal.¹ However, based on the wide variability shown in the present study, the benchmark used for clinical evaluations of laxity needs to be considered on a patient-to-patient basis. For example, if the varus laxity is determined to be 3° in a patient undergoing total knee arthroplasty, but the surgeon generally believes that the varus laxity should be 1° based on a mean value, then the surgeon may decide to increase the tibial liner thickness to reduce the laxity and also may have to perform a release on the medial side to accommodate this thicker liner. Both of these actions would have been avoided had the surgeon considered the laxity of that patient individually. It is important to note that the true laxities of an individual patient's ipsilateral knee are never known because they are not normal preoperatively. However, it may be possible to use the laxities of the contralateral knee, if healthy, as a benchmark.³⁴ Worst-case, if both knees are diseased, then these data still provide a range of normal which surgeons should strive to obtain postoperatively in their patients. Because the range of each limit is not "wide" at 0° flexion, the average

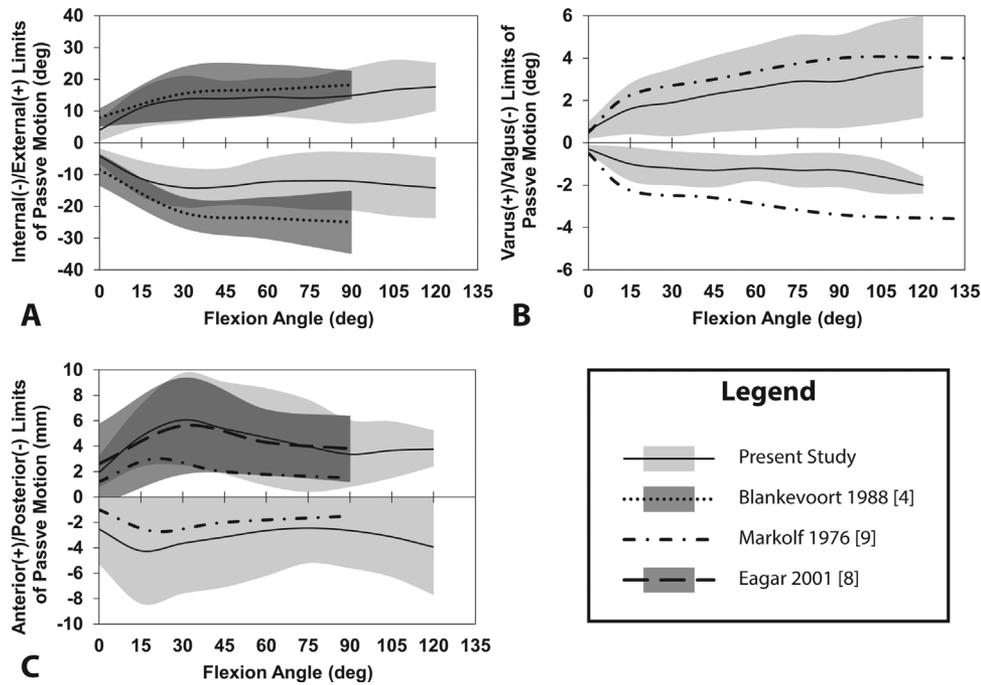


Figure 8. Line plots each show a comparison of the mean (line) and an estimate of the 95% population limits (shaded region, mean ± 2 standard deviations), when available, between the present study and previous studies for (A) the I-E limits, (B) the V-V limits, and (C) the A-P limits. For clarity, the lower 95% population limit of the posterior limit of the present study and that of the anterior limit for Eagar et al.⁸ were truncated at 0 mm; actual values extended beyond the 0 mm line between 0 and 1 mm. Note the C-D was not included because no study has measured the C-D limits in the normal knee using the loads used in the present study.

values for all limits at 0° flexion may be confidently applied to any patient.

The wide range in six of the eight limits also necessitates a patient-specific approach when creating computational models of the tibiofemoral joint to study the behavior of the soft tissue restraints. This finding supports the recent push in the computational modeling field for a more patient-specific approach^{35–38} because a generic computational model of the tibiofemoral joint does not take into account the wide variability in the population and hence is inherently limited. These patient-specific computational models may be useful to both the surgeon and orthopedic companies for preoperative planning.³⁹ Furthermore, this finding suggests that studies investigating the effects of surgical interventions and/or implant designs on the function of the tibiofemoral joint should include a set of models that is representative of the wide range of the limits of passive motion.

The second key finding was that there were few strong correlations between the sums of the limits of different degrees of freedom. Because a majority of the limits are not related to one another, it is important to investigate multiple degrees of freedom within a subject to determine whether (1) laxities have been restored to normal during clinical evaluations, and (2) a computational model is valid. The lack of strong correlations between the eight laxities is not surprising because both the primary restraint(s) to each of the eight laxities are different and vary with flexion

angle,^{26–28} and the mechanical properties of each soft tissue restraint vary widely.^{25,40–42} A recent study showed that anterior laxity was related to I-E and V-V laxities within a subject⁷; however, this study constrained the coupled motions of the tibiofemoral joint and only investigated the laxities at one flexion angle ($\sim 20^\circ$ flexion) which could explain why their results disagree with those of the present study.

In summary, there are large patient-to-patient differences in the limits of passive motion in the normal tibiofemoral joint because both the ranges of six of the eight limits of passive motion vary widely and one limit is not related the other limits within a knee. Hence, a patient-specific approach, including all degrees of freedom of interest, is necessary when both evaluating laxity and creating and validating computational models of the tibiofemoral joint to study the behavior of the soft tissue restraints.

AUTHORS' CONTRIBUTIONS

JDR: Research design, acquisition and interpretation of data; drafting and approval of manuscript. MLH: Research design; interpretation of data; revision and approval of manuscript. SMH: Research design; interpretation of data; revision and approval of manuscript.

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