Changes in the Rotational Axes of the Tibiofemoral Joint Caused by Resection of the Anterior Cruciate Ligament

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ABSTRACT: Kinematic alignment is a method of aligning implants in total knee arthroplasty (TKA) that strives to restore the native flexion–extension (F–E) and longitudinal rotation (LR) axes of the tibiofemoral joint. The anterior cruciate ligament (ACL) is typically resected at the time of TKA, which might change the position, and orientation of these axes from that of the native knee. Our objective was to determine whether resecting the ACL causes changes in the F–E and LR axes. A custom designed and validated instrumented spatial linkage (ISL) measured the F–E and LR axes in nine cadaveric knees before and after ACL resection. Changes in these axes were computed for knee flexion from 0° to 120°. For the F–E axis, the two statistically significant yet relatively small changes were internal rotation of 0.5° ($p = 0.02$) and posterior translation of 0.3 mm ($p = 0.04$). For the LR axis, the statistically significant and relatively large change was medial translation of 2.1 mm ($p = 0.01$). Changes to the LR axis in both medial-lateral position and varus-valgus orientation varied widely; 77% of a population of knees would have a medial–lateral position change greater than 1 mm, and 53% of a population of knees would have a varus–valgus orientation change greater than 1°. Knowledge of changes of the F–E and LR axes caused by resecting the ACL provides an important baseline for determining the changes in these axes caused by kinematic alignment and mechanical alignment of bi-cruciate retaining, posterior cruciate retaining, and posterior cruciate substituting implants. © 2016 Orthopaedic Research Society. Published by Wiley Periodicals, Inc. J Orthop Res 35:886–893, 2017.

Keywords: kinematic alignment; total knee arthroplasty; axis of rotation; knee joint

Passive kinematics of the tibiofemoral joint are driven by both the articular surfaces and soft tissue structures.[1] The flexion–extension (F–E) and longitudinal rotation (LR) axes describe the passive kinematics of the tibiofemoral joint.[2] When the medial and lateral femoral condyles are superimposed in a sagittal view, the F–E axis connects the centers of two coaxial cylinders fit to the outlines and is parallel to the tibiofemoral joint line of the femur.[3–7] The LR about which internal-external rotation occurs axis is fixed in the tibia approximately anterior and perpendicular to the F–E axis and the tibiofemoral joint line.[2,8]

The conventional method for aligning implants in total knee arthroplasty (TKA) termed "mechanical alignment" strives to create an "average" limb alignment (also termed 0° mechanical axis or neutral hip-knee-ankle angle) in the coronal plane at 0° of flexion where the centers of the hip, knee, and ankle lie on a straight line and an "average" alignment of the tibiofemoral joint where the joint line is perpendicular to the 0° mechanical axis. However, 98% of the population with native, healthy limbs has neither a 0° mechanical axis[4,9] nor a joint line perpendicular to the 0° mechanical axis.[10–13] Hence, creating an average alignment generally requires release of soft tissue structures of the knee and changes the alignments of the limb and joint line from those of the pre-arthritic knee.[14] The changes to the alignments of the limb and joint line in conjunction with release of soft tissue structures such as the collateral and retinacular ligaments can result in persistent pain, instability, stiffness, and loss of range of motion, and have been suggested as a reason that as many as 20% of patients with a mechanically aligned TKA report dissatisfaction.[15–23]

Kinematic alignment is a new method used in TKA that strives to restore the native F–E and LR axes of the tibiofemoral joint by restoring alignments of the limb and joint lines to those of the pre-arthritic knee.[24–32] A level one randomized trial and national multicenter study showed that patients treated with kinematically aligned TKA reported significantly better pain relief, function, flexion, and a more normal feeling knee than patients treated with a mechanically aligned TKA.[23,31] Although releases of collateral and retinacular ligaments are not usually required in kinematically aligned TKA, the anterior cruciate ligament (ACL) is typically resected as it is in mechanically aligned TKA when posterior cruciate retaining implants are used. Knowledge of the magnitude and frequency of occurrence of changes in the position and orientation of the F–E and LR axes caused by resection of the ACL would provide an important baseline for determining the changes in these axes caused by kinematic alignment and mechanical alignment of bi-cruciate retaining, posterior cruciate retaining, and posterior cruciate substituting implants. Accordingly, our objective was to determine whether resecting the ACL causes changes in the

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position and orientation of the F–E and LR axes from that of the native knee.

METHODS

Specimens

Thirty fresh-frozen, human cadaveric knee specimens were screened for inclusion via A–P radiograph; 12 specimens were excluded due to radiographic evidence of degenerative arthritis, chrondrocalcinosis, and/or evidence of previous knee surgery. Nine specimens were excluded at the time of arthrotomy because of cartilage wear or a flexion contracture. The position and orientation of the F–E and LR axes before and after ACL resection were measured in the remaining nine specimens that were obtained from six male and three female donors with an age ranging from 57 to 93 years (mean 68 years).

Specimen Preparation and Testing

To prepare each knee on the day of testing, each specimen was thawed for approximately 14 h. The thigh was transected 200 mm proximal and the shank was transected 250 mm distal to the joint line of the knee. Soft tissues were removed 150 mm proximal and 120 mm distal of the joint line of the knee. The tissues were wrapped with saline-soaked towels to prevent desiccation. A transpatellar approach was performed to gain access to the ACL using a technique that does not affect kinematics. A vertical osteotomy was performed and the medial and lateral halves of the patella were reassembled accounting for the 1 mm kerf of the saw blade with use of two transverse bone screws. The soft tissues were sutured proximal and distal to the patella.[33]

Method for Locating the F–E and LR Axes

An instrumented spatial linkage (ISL)[34,35] was used to locate the F–E and LR axes in each knee specimen using a previously described mathematical axis-finding method.[36] The measurement errors in locating the axes were as follows: for the F–E axis, the position root-mean-square errors (RMSEs) were less than 1 mm and both orientation RMSEs were less than 0.5°; for the LR axis, the position RMSEs were 1.2 mm in the medial–lateral (M–L) direction and less than 1.0 mm in the anterior–posterior (A–P) direction, while the orientation RMSEs were both below 0.25°.[35]

Each knee specimen was tested in two separate pieces of equipment, a load application system and a motion application fixture. Before attaching the ISL to the specimen, each specimen with the patella osteotomy and intact ACL was first mounted and aligned in a load application system (Fig. 1).[37] The load application system allowed unconstrained motion in every degree of freedom except flexion-extension. Designed to embody the clinically relevant coordinate system of Grood and Suntay,[38] this load application system was used to identify the F–E and LR axes of the specimen. The F–E and LR axes were identified by using a functional-axis alignment procedure whereby coupled motions during flexion and internal-external (I-E) rotation were measured and minimized.[39] Once coupled motions were minimized, the F–E and LR axes were aligned approximately with the corresponding axes of the load application system. After alignment, the femur and tibia were cemented in two square metal tubes using methyl methacrylate (COE Tray Plastic, GC America, Inc., Alsip, IL). The F–E axis of the specimen was perpendicular to the side wall of the square metal tube containing the femur and the LR axis coincided with the axis of the square metal tube containing the tibia. The specimen was subjected to a preconditioning protocol[40] after which a 2.5 Nm extensor moment was applied to define full extension.[41] The specimen was removed from the load application system. Once the specimen was cemented in the aluminum tubes and removed from the load application system, the F–E and LR axes could be identified in relation to the tubes which facilitated generating rotations about these axis using a motion application fixture described in the next paragraph.

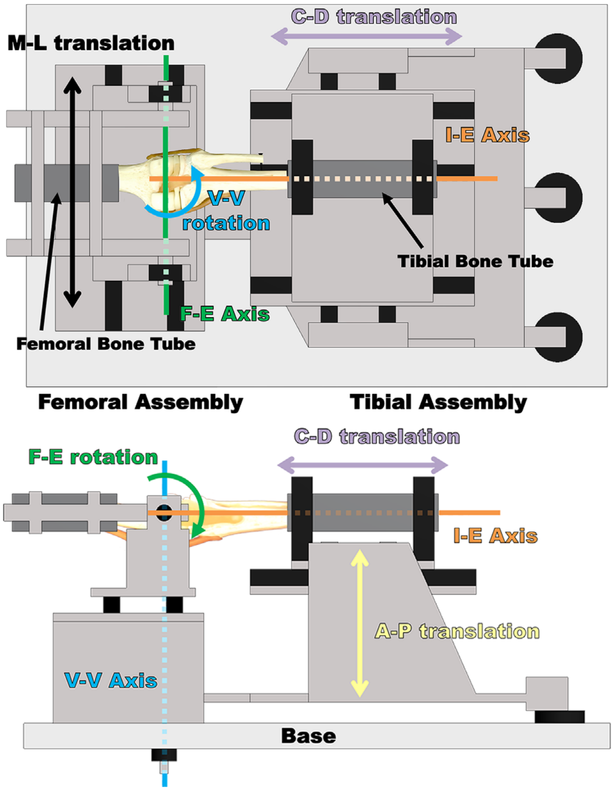

Figure 1. A schematic of the load application system.[37,40] The system consists of two assemblies. The femoral assembly allows two degrees of freedom, flexion–extension (F–E) rotation and medial–lateral (M–L) translation. The remaining four degrees of freedom are anterior–posterior (A–P) translation, compression–distraction (C–D) translation, varus–valgus (V–V) rotation, and internal–external (I–E) rotation and are allowed by the tibial assembly. Each degree of freedom is actuated by a stepper motor. Transducers measure both load and motion in each degree of freedom. The system embodies the coordinate system of Grood and Suntay.[38] Without the ISL attached, the F–E and LR axes were determined by aligning the specimen so that the axes coincided with those of the load application system. The femur and tibia were cemented into square aluminum tubes and the specimen was removed from the load application system. The process of identifying the F–E and LR axes and cementing the bones into tubes enabled the specimen to be installed in a separate motion application fixture so the F–E axis of the specimen was aligned approximately with that of the motion application fixture.

With the ISL attached, the specimen was mounted in a motion application fixture (Figs. 2 and 3) which was used to apply prescribed rotations about the F–E and LR axes without constraining the tibia in varus–valgus (V–V) rotation, M–L translation, A–P translation, and proximal–distal (P–D) translation. The motion application fixture consisted of an adjustable bracket attached to the femur and a stationary upright beam, which constrained the flexion angle of the tibia relative to the femur without constraining other degrees of freedom. To further minimize the application of motions

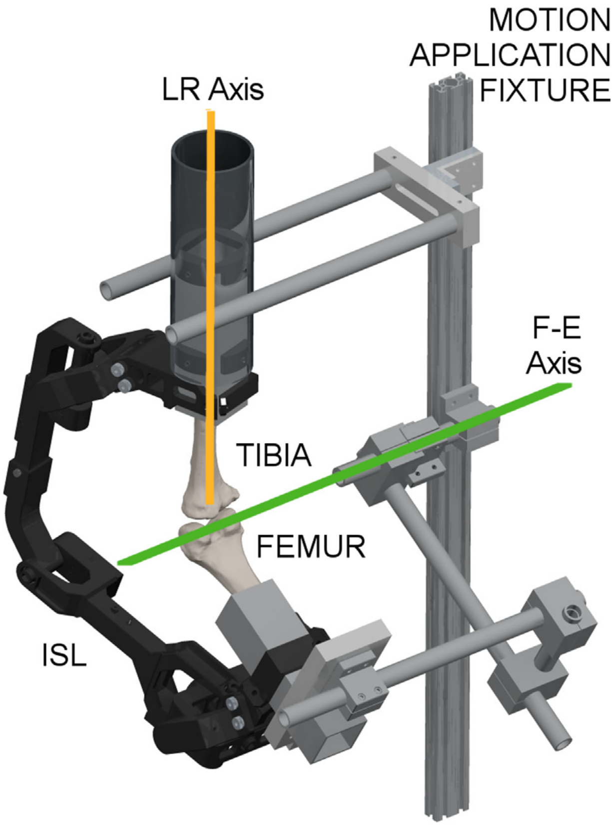

Figure 2. A schematic of the motion application fixture with the ISL attached. The square aluminum tube in which the femur was cemented was fixed to the adjustable bracket. The tibia was oriented downward and was not fixed; thus the fixture simultaneously allowed for the placement of the femur at any flexion angle while maintaining a downward orientation of the tibia at any flexion angle. The square aluminum tube in which the femur was cemented was aligned in the fixture such that the tibia displayed minimal coupled motion during applied flexion.

Figure 3. A photograph of the motion application fixture with a knee specimen at full extension with the ISL attached.

other than F–E and I–E rotation (i.e., V–V rotation, P–D translation, M–L translation, or A–P translation), and to inhibit femoral condylar lift-off, a compressive axial force of 45 N was applied to the tibia via a 4.6 kg mass. This compressive force applied to the tibia ensured contact between the femoral condyles and the tibial plateau and prevented condylar lift-off.[41] The ISL thus indicated the relative 3D position and orientation of the femur and tibia during the motions applied by means of this motion application fixture.

The kinematic data necessary to locate the F–E and LR axes were acquired by moving the specimen through a prescribed pattern of discrete I–E rotation and flexion angles.[34] The range of flexion was 0–120° in 5° increments. For I–E rotation, at each flexion angle increment the tibia was first rotated externally in approximately 5° increments until a small increase in rotational stiffness was felt; the tibia was then rotated internally in approximately 5° increments until a small increase in rotational stiffness was felt, and then externally back to the neutral position. Because rotational stiffness is minimal within the limits of passive I–E rotation but rapidly increases at the limits,[42] this protocol ensured that data were collected only for passive motion. At each increment of rotation with the specimen stationary, the position and orientation of the tibia relative to the femur were recorded by the ISL in the form of a homogeneous transformation matrix, computed using the kinematic model of the ISL which was previously determined.[35]

The fixed locations of the F–E and LR axes were computed using the entire set of recorded kinematic data across all discrete flexion and I–E rotations.[35,36] Using the previously described pattern of flexion and I–E rotation, at least 200 3D relative positions and orientations of the femur and tibia were included for each specimen. The location of the F–E axis was described by two positions (A–P and P–D) and two orientations (I–E and V–V projection angles) relative to the coordinate system of the end of the ISL that was fixed to the femur (Fig. 4).[35,36] The location of the LR axis was described by two positions (A–P and M–L) and two orientations (F–E and V–V projection angles) relative to the coordinate system of the end of the ISL that was fixed to the tibia (Fig. 5).[35,36]

After locating the axes in the native knee, the ISL was removed from the specimen, the specimen was removed from the motion application fixture, the ACL was resected using the previously described surgical procedure, and the specimen was re-attached to both the motion application fixture and the ISL. Because the femur and tibia remained cemented in the square tubes during resection, the relative position and orientation between each end of the ISL and the femur and tibia remained constant after resection. The F–E and LR axes were located using the same procedure used before resection of the ACL.

The changes in the F–E and LR axes after ACL resection were computed for each specimen. For each dependent variable describing the position of either the F–E or LR axis, the difference between the position before ACL resection and

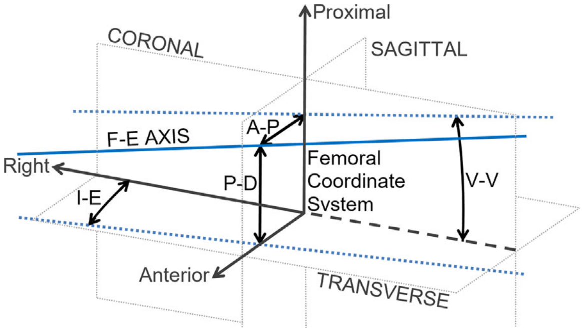

Figure 4. A diagram of the dependent variables describing the position and orientation of the F–E axis. The V–V orientation of the F–E axis was computed from the projection of the F–E axis on the coronal plane of the femur, and the I–E orientation of the F–E axis was computed from the projection of the F–E axis on the transverse plane of the femur. The femoral coordinate system was fixed relative to the end of the ISL attached to the femur. The sagittal plane was both parallel to and centered between the medial and lateral sides of the square aluminum tube attached to the femur. The coronal plane was parallel to the anterior and posterior sides of the square aluminum tube attached to the femur and contained the F–E axis as determined by alignment in the load application system. The transverse plane was mutually perpendicular to both the sagittal and coronal planes and contained the F–E axis as determined by the load application system.

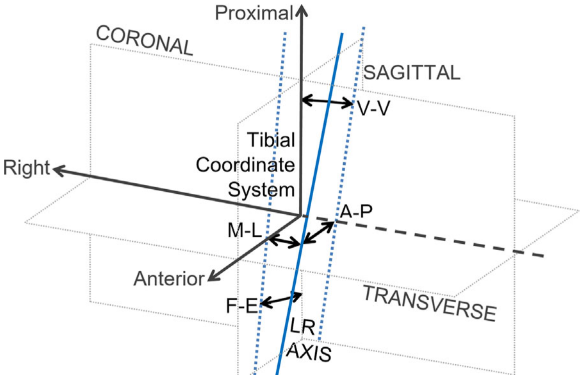

Figure 5. A diagram of the dependent variables describing the position and orientation of the LR axis. The V–V orientation of the LR axis was computed from the projection of the LR axis on the coronal plane of the tibia, and the F–E orientation of the LR axis was computed from the projection of the LR axis on the sagittal plane of the tibia. The sagittal plane was both parallel to and centered between the medial and lateral sides of the square aluminum tube attached to the tibia. The coronal plane was parallel to and centered between the anterior and posterior sides of the square aluminum tube attached to the tibia. The line created by the intersection of these two planes coincided with the LR axis as determined by alignment of the specimen in the load application system. The transverse plane was mutually perpendicular to both the sagittal and coronal planes.

the position after ACL resection was computed. For each dependent variable describing the orientation of either the F–E or LR axis, the difference between the orientation before ACL resection and the orientation after ACL resection was computed.

Statistical Analysis

Software (JMP, version 11.2.0, 64-bit; SAS Inc., Cary, NC, www.jmp.com) was used to compute the sample mean, sample standard deviation, frequency of occurrence of changes deemed to be clinically important, and a statistical test. A paired Student's *T*-Test determined whether the A–P and P–D positions, and I–E and V–V orientations of the F–E axis and the A–P and M–L positions, and F–E and V–V orientations of the LR axis changed before and after ACL resection in the native knee. *p*-values <0.05 were considered statistically significant. The frequency of occurrence (i.e., percentage of knees) that a position changed greater than 1 mm in magnitude and an orientation changed greater than 1° in magnitude was computed following the methods outlined in Ref.[43] A 95% confidence level also was computed for each frequency of occurrence.

RESULTS

Of the changes caused by resection of the ACL for each position (Table 1) and orientation (Table 2) of the F–E axis, the two statistically significant yet relatively small changes were the mean A–P change in position where the axis translated posteriorly 0.3 mm ($p = 0.04$) and the mean I–E change in orientation where the axis rotated internally 0.5° ($p = 0.02$). For the LR axis, only the change in the mean M–L position was statistically significant and relatively large where the axis translated medially 2.1 mm ($p = 0.02$).

The frequencies of occurrence that resection of the ACL in the native knee would cause a change in position greater than 1 mm in magnitude and a change in orientation greater than 1° in magnitude varied widely in a population of knees (Tables 3 and 4). For the position variables, the frequency of occurrence ranged from a low of 4% for the change in A–P position of the F–E axis to a high of 77% for the change in the M–L position of the LR axis (Table 3). For the orientation variables, the frequency of occurrence ranged from a low of 1% for the change in V–V orientation of the F–E axis and for the change in the F–E orientation of the LR axis to a high of 53% for the change in the V–V orientation of the LR axis (Table 4). Hence, the frequency of occurrence of changes greater than 1 mm or 1° in magnitude in the F–E and LR axes caused by resection of the ACL would range from 1% to 77% in a population of knees.

DISCUSSION

Although kinematically aligned TKA strives to restore the two fixed axes of rotation of the tibiofemoral joint, the ACL is resected when using posterior cruciate retaining femoral implants thus necessitating characterization of any changes to these axes after resection of the ACL. The purpose of this study was to determine in vitro whether the F–E and LR axes changed in position and orientation after resection of the ACL. Two key findings of this study were as follows: (i) a statistically significant and relatively large medial translation (2.1 mm) of the LR axis and (ii) wide variability in both M–L position and V–V orientation of the LR axis such that the majority of the population would experience translations greater than 1 mm and rotations greater than 1° in magnitude.

There are several limitations in this study. This study only measured changes in the F–E and LR

Table 1. The Mean, Standard Deviation, and Level of Significance for Each Change in Position of the F–E Axis and LR Axis Caused by Resection of the ACL in the Native Knee

	Mean (mm)	Standard Deviation (mm)	p
F–E axis			
Anterior (+), posterior (−)	−0.3	0.4	0.04*
Proximal (+), distal (−)	0.3	0.5	0.18
LR axis			
Anterior (+), posterior (−)	0.4	0.7	0.09
Medial (+), lateral (−)	2.1	1.9	0.01*

*Denotes statistically significant p-values < 0.05.

Table 2. The Mean, Standard Deviation, and Level of Significance for Each Change in Orientation of the F–E Axis and LR Axis Caused by Resection of the ACL in the Native Knee

	Mean (deg)	Standard Deviation (deg)	p
F–E axis			
Varus (+), valgus (−)	−0.1	0.4	0.51
Internal (+), external (−)	0.5	0.6	0.02*
LR axis			
Varus (+), valgus (−)	−0.3	1.6	0.58
Flexion (+), extension (−)	0.0	0.4	0.85

*Denotes statistically significant p-values < 0.05.

Table 3. The Frequency of Occurrence in Percent of the Population With an Absolute Change Greater Than 1 mm in Magnitude for Each Change in Position of the F–E Axis and LR Axis From Resecting the ACL in the Native Knee

	Percent Greater Than 1 mm in Magnitude	95% Confidence Limits on Percent	
		(Upper)	(Lower)
F–E axis			
Anterior–posterior	4	23	1
Proximal–distal	7	27	1
LR axis			
Anterior–posterior	19	47	6
Medial–lateral	77	89	57

Table 4. The Frequency of Occurrence in Percent of the Population With a Change Greater Than 1° in Magnitude for Each Change in Orientation of the F–E Axis and LR Axis From Resecting the ACL in the Native Knee

	Percent Greater Than 1° in Magnitude	95% Confidence Limits on Percent	
		(Upper)	(Lower)
F–E axis			
Varus–valgus	1	11	0
Internal–external	19	43	7
LR axis			
Varus–valgus	53	71	34
Flexion–extension	1	11	0

axes during passive motion, which is the motion in the low-stiffness region where the articular surfaces and soft tissue structures of the tibiofemoral joint constrain the motion[42]; under external loads, changes to the F–E and LR axes after ACL resection may be different. Also, because this study investigated the changes to the axes after surgical resection of the ACL on cadaveric knees, the results would not necessarily apply to the torn ACL which is often accompanied by damage to other soft tissue structures that could lead to additional changes to the F–E and LR axes. Finally, although a post hoc power analysis showed that the sample size was sufficient to detect changes of 1 mm or 1° for most of the dependent variables, only larger changes (greater than 1 mm or 1°) could be detected in both V–V orientation and M–L position of the LR axis due to the wide variability in changes to this axis. However, because the changes in M–L position of the LR axis were statistically significant despite the sample size and because the change in V–V orientation was close to zero and arguably unimportant, confidence can placed in the results of the statistical analysis for all dependent variables.

Measuring the position and orientation of either axis relied on coordinate systems established during an alignment procedure. Imperfect alignment of the specimen within the load application system could cause errors in both the alignment of the femoral coordinate system within the femur and the alignment of the tibial coordinate system within the tibia. However, because the dependent variables were changes in position and orientation of each axis rather than the absolute position and orientation of each axis and because attachment of the ISL was constant for each specimen before and after resection of the ACL, errors due to imperfect alignment were systematic and thus cancelled.

Finally, the axis-finding method assumes that all motion occurs about the F–E axis and LR axes which are fixed in the femur and tibia, respectively,[36] and thus locates two fixed axes regardless of the total motion between the femur and tibia. Although the fixed-axis assumption is valid for the native knee,[2,6,8] it is unknown whether the axes are fixed for the ACL deficient knee. To check the fixed-axis assumption in the ACL deficient knee, the changes in the F–E and LR axes were computed over the flexion angle range of 20°–120°, as well as 0°–120°. Because the ACL influences the screw home motion which occurs during the first 15°–20° of flexion,[42,44–46] the absence of the ACL would be less pronounced in 20°–120° of flexion by eliminating the range in which screw home motion occurs. The differences between the two flexion angle ranges were bounded by 0.1 mm for translations and 0.1° for rotations except M–L translation of the LR axis which was −0.3 mm and I–E rotation of the F–E axis which was −0.3°. These small differences do not call into question the fixed-axis assumption for the ACL deficient knee.

The first key finding was that the only statistically significant change to the LR axis was the M–L position with the axis shifting medially by 2.1 mm. A study by Mannel et al. measured a large M–L translation of a helical axis after ACL transection.[47] Although a helical axis is not directly comparable with the F–E axis, the M–L change in the helical axis could be compared with that of the LR axis. When separating I–E rotation from flexion–extension motion, M–L translation of the F–E axis is irrelevant because the F–E axis is aligned with the M–L direction; only the LR axis, which is partially described by the M–L position, can be compared in the M–L direction. Although the helical axis in the study by Mannel et al. was also substantially aligned with the M–L direction throughout motion,[47] coupled I–E rotation of the joint throughout flexion caused the axis to rotate, thus providing the frustrum waist that allowed them to measure M–L translation. Mannel et al. showed that when using a helical axis of rotation to describe tibiofemoral kinematics, the frustrum waist of the axis moves medially after ACL resection.[47] The trend toward medial translation of the LR axis in our study is consistent with the medial shift in the helical axis.[47]

The second key finding was the wide variability in changes to the LR axis. Except for the F–E change in the LR axis, the distributions of the changes to the LR axis exhibited greater variability (i.e., greater standard deviations) compared to the distributions of the changes to the F–E axis (Tables 1 and 2). More than half of a population of knees with a resected ACL would be expected to have a V–V change greater than 1° in magnitude, and three-quarters would be expected to have a M–L change greater than 1 mm in magnitude (Tables 3 and 4). The loss of the ACL as a soft-tissue constraint evidently introduced this variability which emphasizes the role of the ACL in influencing tibial rotation in the native knee.[45,46] Considering the wide variability, the changes to the LR axis should be evaluated on a subject-specific basis.

In summary, the results of this study provide an important baseline for assessing changes in the F–E and LR axes after TKA, with particular relevance to kinematically aligned TKA which strives to restore the F–E and LR axes to those of the pre-arthritic knee.[24,25] With the ACL resected, the F-E axis changed in both I–E orientation and A–P position and the LR axis changed in M–L position. Of these three changes however, only the mean change in the M–L position of the LR axis had a change greater than 1 mm or 1° in magnitude. Wide variability was found in changes to the LR axis in both M–L position and the V–V orientation. The V–V change in orientation would have a prevalence greater than 1° in magnitude of 53% whereas the prevalence greater than 1 mm in magnitude would be 77% for the M–L position in a population of knees. How kinematically aligned TKA affects the axes remains to be determined and is a subject of our ongoing research.

AUTHORS' CONTRIBUTIONS

D. Bonny designed, fabricated, and validated the instrumented spatial linkage, used the linkage to collect experimental data, and wrote the draft of the manuscript. S. M. Howell was the Co-PI on the grants which funded this study. He co-supervised D. Bonny in the experimental phase of the study and revised the draft of the original manuscript. M. L. Hull was the PI on the grants which funded this study. He supervised D. Bonny in all phases of the study, revised the draft of the original manuscript, revised the draft of the resubmitted manuscript, and approved the resubmitted version. All authors read and approved the submitted version of the manuscript.

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