Anterior opening wedge high tibial osteotomy: the effect of increasing posterior tibial slope on ligament strain

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Background: Although a previous study showed that anterior opening wedge high tibial osteotomy (HTO) for sagittal plane correction induced no increased strain in the anterior cruciate ligament (ACL), we hypothesized that other ligamentous restraints of the knee may be subjected to increased strain.

Methods: We mounted 6 cadaveric knees at 15° flexion in a testing apparatus that provided compressive and anterior loading. We measured the strain in the ACL, posterior (PCL), medial (MCL) and lateral (LCL) ligaments for 6 randomized loading combinations and 3 conditions: intact, after anterior opening wedge HTO with a 5-mm plate and with a 10-mm plate.

Results: The mean ACL strain decreased from 0.84% (standard deviation [SD] 1.50%) at baseline to –6.28% (SD 5.40%) with a 5-mm anterior opening wedge osteotomy and to –6.77% (SD 4.79%) with a 10-mm osteotomy. Stepwise regressions yielded no significant effect of compression, anterior loading or osteotomy on PCL, MCL or LCL strain.

Conclusion: Increasing the posterior slope via HTO did not increase strain in the PCL, MCL or LCL.

Contexte: Une étude antécédente a démontré que l'ostéotomie tibiale antérieure d'ouverture (HTO) pour la correction tibiale dans le plan sagittal n'a induit aucune augmentation de la déformation subie par le ligament croisé antérieur (ACL). Nous posons l'hypothèse que d'autres structures ligamentaires du genou subissent ainsi des forces plus élevées après l'ostéotomie antérieure tibiale d'ouverture.

Méthodes: Six genoux cadavériques ont été placés en flexion à 15 degrés dans un appareillage d'essai produisant des charges en compression et en translation antérieure. Les déformations ont été mesurées dans les croisés antérieurs et postérieurs ainsi que dans les collatéraux externes et internes pour 6 combinaisons randomizées de mise et charge et 3 conditions expérimentales: spécimen intact, spécimen avec ostéotomie antérieure de 5 mm ou de 10 mm.

Résultats: Les déformations subies par le croisé antérieur ont diminuées de 0.84 % (écart-type [ET] 1.50 %) au départ à –6.28% (ET 5.40 %) avec une ostéotomie antérieure de 5 mm et à –6.77 (ET 4.79%) avec une ostéotomie de 10 mm. Les régressions linéaires par échelons n'ont rapporté aucun effet significatif ni de la charge en compression, de la charge en antérieure ou de l'osteotomie sur les déformations subies par le croisé postérieur ou les ligaments collatéraux.

Conclusion: L'augmentation de la pente postérieure par l'intermédiaire de l'ostéotomie antérieure d'ouverture n'a pas augmenté les déformations subies par le croisé postérieur ou les ligaments collatéraux.

High tibial osteotomy (HTO) has traditionally been used as a valgus-producing surgical procedure in an attempt to change the mechanical weight-bearing axis and alter loads carried through the knee. The conventional indications for HTO were for correction of coronal alignment in the presence of unicompartmental osteoarthritis. More recently, the indications for HTO have been expanded to include chronic ligament deficiencies and primary or secondary malalignment. Recent evidence suggests that joint alignment may be crucial in maintaining joint stability in the presence of chronic ligamentous injury.[1–4] Untreated malalignment in this scenario can worsen ligamentous laxity and lead to symptomatic instability. In addition, failure to address malalignment at the time of ligamentous reconstruction can lead to increased contact pressure and failure of the reconstructed structures. As a consequence, HTO has received increased attention for correction of sagittal plane alignment in addition to traditional coronal plane correction. Sagittal plane knee joint stability is governed by a number of passive structures, including the cruciate ligaments, menisci, articular surface geometry and the knee joint capsule.[5–13] In particular, the natural posterior tibial slope is an important contributor to sagittal plane stability.

Previous work by Giffin and colleagues[14] demonstrated the effects of increased posterior tibial slope on the cruciate ligament forces. Counterintuitively, they found that increased posterior slope did not lead to concomitant increases in anterior cruciate ligament (ACL) loading. In a second study, they found that increasing posterior tibial slope reduced tibial sag by shifting the resting position of the tibia anteriorly.[15] These findings were also corroborated by the study by Agneskirchner and colleagues,[16] who found that posterior subluxation of the tibia in posterior cruciate ligament (PCL) deficiency was decreased by increasing posterior tibial slope. Finally, the effects of altering the posterior tibial slope on ACL strain and knee kinematics were also investigated by Fening and coworkers.[17] They showed that the increased posterior tibial slope created by anterior opening wedge osteotomy resulted in an anterior shift in the tibial resting position, increased external tibial rotation and decreased ACL strain.

Anterior opening wedge HTO is mainly used as a procedure to alter sagittal plane alignment in pathological cases of hyperextension recurvatum. This procedure can be performed as a primary procedure, as the initial part of a staged reconstruction or simultaneously at the time of ligament reconstruction to address an important contributor to sagittal plane stability in knees with posterior, posterolateral or combined ligament insufficiency.

The purpose of the study was to determine the effect of increasing the posterior tibial slope on the strains of the major ligamentous restraints of the knee (anterior [ACL], posterior [PCL], medial [MCL] and lateral [LCL] ligaments). We hypothesized that the secondary ligamentous stabilizers (PCL, LCL, MCL) of anterior translation would have increased strain. We also aimed to correlate changes in ligament strain with changes in knee kinematics.

Methods

Specimen preparation

We used 6 fresh-frozen human cadaveric knees in this study. Specimens were thawed at room temperature overnight before instrumentation and testing.[18] The specimens were then amputated transtibially and transfemorally 15 cm from the joint line. The fibula was also sectioned below the level of the fibular neck and transfixed to the tibia. The skin and subcutaneous fat were removed, and anatomic dissection along surgical planes exposed the collateral ligaments and cruciate ligaments. The joint capsule was kept intact, except for a medial parapatellar arthrotomy to expose the ACL and a posterior arthrotomy to expose the PCL. We inspected each specimen visually and fluoroscopically to exclude any specimens with ligamentous or osseous abnormalities. We calculated an initial measurement of posterior tibial slope using landmarks on lateral fluoroscans using a previously described technique.[7] After the dissections were performed, the remaining femoral and tibial portions of the specimens were potted in aluminum tubing with polymethylmethacrylate (Patterson Dental) and transfixed with perpendicular bicortical pins.

Following specimen preparation, we mounted each specimen in a custom loading apparatus at 15° flexion (Fig. 1) The tibial cylinder was rigidly secured to an immovable universal force sensor (Theta 190 #S1–25000N-400Nm; ATI Industrial Automation), which in turn was firmly secured to an immovable base. The femoral sided cylinder was attached to a custom load application mechanism, capable of producing combinations of compressive and anterior–posterior (AP) shear load.

Strain measurement protocol

Differential variance reluctance transducers (DVRTs; Microstrain) were secured to the ACL, MCL, LCL and PCL to quantify ligament load in terms of strain (Fig. 2). The ACL strain gauge was positioned on the anterome-

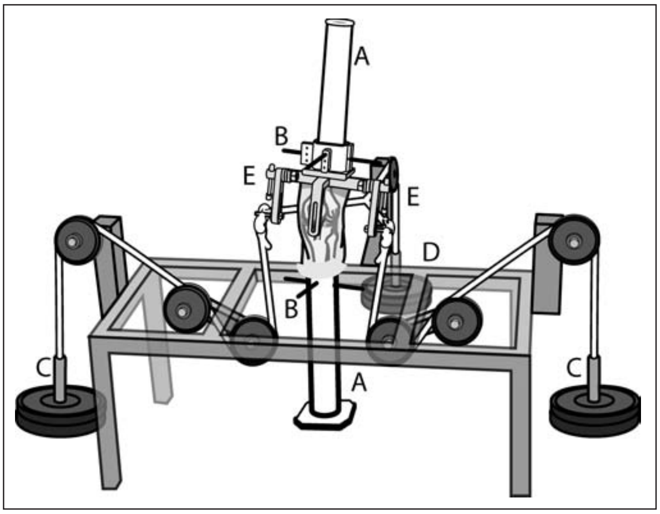

Fig. 1. Schematic showing the axial and anterior–posterior (AP) loading of intact knee specimens before and after anterior opening wedge high tibial osteotomy: (**A**) potted bone, (**B**) transfixion pins, (**C**) axial load application via weights, (**D**) AP load application via weights and (**E**) femoral markers. An overhead camera was used to track the motion of the femoral markers.

dial bundle of the midsubstance. The anteromedial bundle was chosen to allow for comparisons between previously published experimental designs on ACL strain characteristics.[17,19,20] The other strain gauges were secured to the posteromedial bundle of the PCL midsubstance, the superficial MCL at the level of the joint line, and the LCL at the level of the joint line. The specimens were placed in the experimental position, and the gauge locations were verified. In particular, the ACL strain gauge was checked for the absence of impingement in the intercondylar notch. A prophylactic minimal notchplasty was performed for each specimen before gauge insertion to limit the possibility of ACL gauge impingement.

Experimental protocol

Prior to testing, we took each specimen through 10 complete flexion–extension cycles to ensure that viscoelastic preconditioning had taken place.[21] The knees were positioned statically at 15° flexion to approximate the typical knee angles of the midstance phase of the walking cycle. A set of predetermined joint forces were then applied to the knee using the custom-made loading apparatus via a system of weights and pulleys.[17,22–26] The load set included 3 levels of anterior (AP plane) load (18N, 108N, 209N) and 2 levels of compressive load (216N and 418N). The testing protocol was randomized, with the following 2 restrictions: for each specimen, testing began with a native specimen without osteotomy; and each testing series started and ended with the knee in a relaxed state (0N compressive, 18N AP). All possible combinations of anterior and compressive loading (i.e., 6 combinations) were applied to each knee for each plating condition (no osteotomy, 5-mm plate and 10-mm plate), resulting in 18 total test combinations for each specimen. Ligament strains of the ACL, PCL, MCL and LCL, as well as anterior tibial shift (ATS), anterior tibial translation (ATT) and external tibial rotation, were recorded for each load and plating condition.

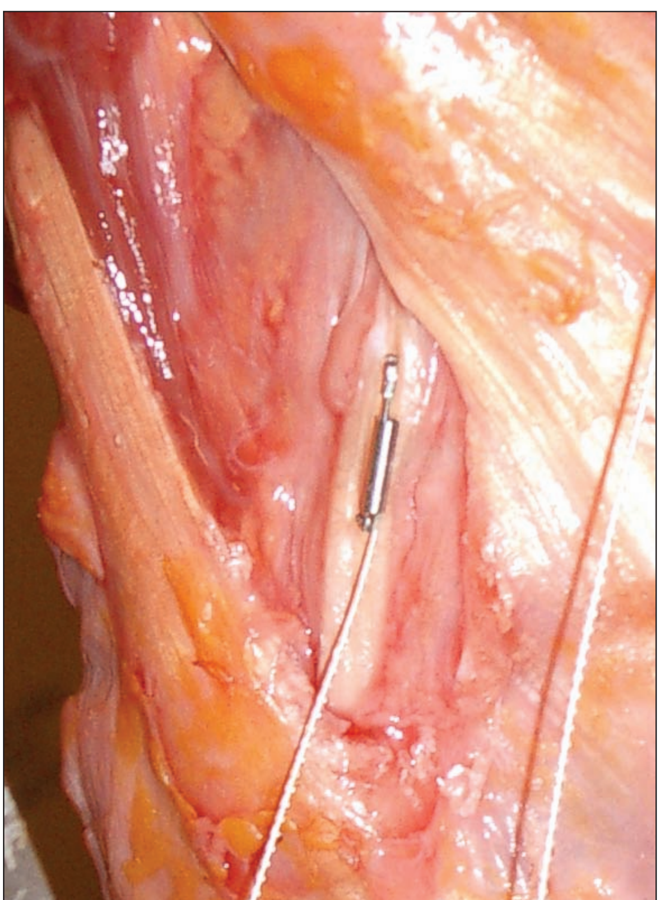

Fig. 2. Placement of a differential variance reluctance transducer strain gauge on the lateral collateral ligament.

Anterior opening wedge osteotomy

The posterior slope of the tibia was increased via an opening wedge anterior HTO and fixed with a 5-mm or 10-mm buttress plate (Opening Wedge Osteotomy Plates; Arthrex Inc.), as per the randomized study design. Standard surgical protocols and instruments were used to perform the opening wedge osteotomy as recommended by the plate manufacturer. A longitudinal incision was made along the medial border of the patellar tendon. The tibial tuberosity was not detached, and the peripheral capsuloligamentous structures attached to the epiphysis were left undisturbed. The osteotomy began about 3–4 cm distal to the joint line just above the tibial tuberosity. The cut was performed using an oscillating saw and was directed slightly superior to finish distal to the PCL and capsular insertion and level with the proximal tibiofibular joint. The osteotomy was then carefully distracted open against the posterior cortical hinge. A 5-mm or 10-mm 4-hole HTO plate was positioned and rigidly fixed along the medial side of the patellar tendon. We used lateral fluoroscopic images to confirm the adequacy of positioning of the hardware as well as the presence of an intact posterior cortex (Fig. 3). After the osteotomy and plating intervention, we also used the lateral knee fluoroscopic images to measure posterior tibial slope.[7] The experimental protocol was repeated for each of the 6 cadaveric knee specimens.

Data acquisition

The DVRT strain gauges were connected via a fine wire cable to a signal conditioner (Microstrain) and subsequently relayed to a data acquisition board (National Instruments) where the signals were converted from analog to digital. The output signals were collected at a sampling rate of 100 Hz using a custom LabView application (National Instruments). A baseline resting length of the strain gauges was measured with the knee at 15° flexion with 0N of compression and 18N of anterior load. Strain gauges were retained in each ligament until completion of all testing on each specimen, allowing strain data to be compared directly between osteotomies. Strain is a dimensionless geometrical measure of deformation of a material. Prior to implantation, the relation between gauge output and gauge length change was determined so that strain could be quantified. Gauge length data were converted to a measure of ligament strain using equation 1:

$$\varepsilon_k = \frac{\gamma_k - \gamma_0}{\gamma_0}$$

where γ_k and ε_k represent the length of the DVRT and the associated ACL strain estimate for the kth data sample, respectively, and y_0 is the DVRT length with a 0N compression, 18N anterior preload.

To assess transverse plane knee kinematics, 2 markers were rigidly attached to the distal femur and aligned medially and laterally at the level of the joint line while the proximal tibia was immobilized. We used overhead digital photography to capture the position of these markers.[17] The centre point of the knee, which was the basis for all knee kinematic calculations, was evaluated as the midpoint between the 2 markers. We obtained a baseline position measurement before osteotomy with the knee in a relaxed state (0N of compression load and 18N of anterior load). Anterior tibial shift was defined as the shift in resting positions between the relaxed states for the 3 plating conditions. Anterior tibial translation, a measure of joint stability, was defined as the AP translation from the resting position for each case. External tibial rotation was defined as the external rotation of the tibia relative to the femur. To standardize the nomenclature used, we described the motion of the distal segment relative to the proximal segment, despite the distal segment (i.e., the tibia) being rigidly fixed.

Statistical analyses

We excluded 2 of the 6 cadaveric knees from analysis after completion of the experimental protocol. One specimen was found to have excessive valgus alignment and pseudoligamentous instability in the varus–valgus plane and proceeded to dislocate under experimental loading conditions. The second excluded specimen had been randomized to the 10-mm osteotomy group before the 5-mm osteotomy. Upon calculating posterior tibial slope, it was found that the slope had not decreased when the 10-mm plate was changed to the 5-mm plate, the screws having followed the identical path through the specimen for both plating conditions. Therefore, no true 5-mm osteotomy condition existed for this specimen.

We analyzed the data using the Minitab statistical program (State College, PA, version 13.31). Stepwise linear regressions (forward and backward) were applied to these data to determine the statistical significance of each response from the control factors. The predictors for the regression analysis were osteotomy plate size (3 levels), AP load (3 levels) and compressive load (2 levels). Measured responses included ACL, PCL, MCL and LCL strain, as well as ATS, ATT and external tibial rotation. We also evaluated interactions between the control factors, although the interactions were found to have no statistically significant effect on the responses. The randomized experimental design guarded against confounding experimental variables (plate and loadings) with any uncontrolled systemic variables. Uncontrolled variables contributed only to the overall test variability and not the trending in the measured responses due to the experimental variables. Consequently, the experimental design minimized the number of measurements needed to identify significant trending in the measured responses, while controlling for the effects of any uncontrolled variables. It also allowed for results of statistical significance to be obtained from the analysis of as few as 4 samples. We used an α level of 0.05 for all statistical treatments to denote statistical significance.

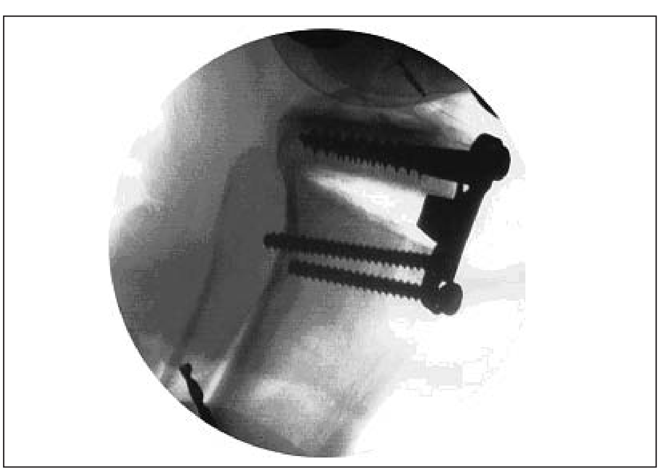

Fig. 3. Lateral fluoroscopic view of and anterior osteotomy with a 10-mm opening wedge plate.

Results

Posterior tibial slope

A significant relation was identified between posterior tibial slope and osteotomy plate size (p = 0.001). The mean baseline posterior tibial slope for the specimens before osteotomy was 8.0° (standard deviation [SD] 2.4°). After anterior opening wedge HTO and fixation with the 5-mm plate, the mean posterior slope increased to 12.1° (SD 3.1°). After fixation with the 10-mm plate, the mean posterior slope increased to 16.3° (SD 3.2°).

Knee kinematics

External tibial rotation was found to be significantly correlated only with the plating condition (p < 0.001), as osteotomy plate size increased external tibial rotation increased. Mean external tibial rotation increased from –1.0° (SD 1.3°) in the native knee to 0.5° (SD 1.6°) after 5-mm osteotomy and to 2.5° (SD 3.0°) after 10-mm osteotomy. Anterior tibial shift, defined as the change in resting position of the tibia in relation to the femur in the anterior–posterior plane after anterior opening wedge HTO, was not significantly related to compressive loading, anterior loading or osteotomy plating condition. Anterior tibial translation was defined as the change in anterior–posterior translation under the experimental loading conditions from the new resting position achieved after osteotomy. Anterior tibial translation was significantly correlated with anterior loading ($p < 0.001$) and plating condition ($p < 0.004$). Mean ATT increased from –2.1 (SD 3.6) mm with 18N of AP load to 1.4 (SD 2.8) mm with 108N of AP load and to 6.7 (SD 3.6) mm with 209N of AP load. Results for ATS and ATT versus plate condition are shown in Table 1.

Ligament strain

Stepwise regressions yielded no significant effects of compression, anterior loading or osteotomy plating condition or any combination thereof on PCL, MCL or LCL strain. However, ACL strain was significantly correlated with the plating intervention ($p < 0.001$). Mean ACL strain decreased from 0.84% (SD 1.50%) in the native knee to –6.28% (SD 5.40%) after 5-mm anterior opening wedge HTO and –6.77% (SD 4.79%) after 10-mm osteotomy (Table 1). Anterior cruciate ligament strain as a function of anterior opening wedge HTO (no osteotomy, 5-mm and 10-mm plate) is shown in Figure 4.

Discussion

Increasing posterior tibial slope via anterior opening wedge osteotomy has been shown to increase anterior tibial translation.[6,7,14–16] Counterintuitively, Giffin and colleagues[14] found that increases to posterior slope did not lead to concomitant increases in ACL loading. Overall, the effects of anterior opening wedge osteotomy on ACL strain are incompletely understood. Therefore, we sought in a previous study to determine the effect of increasing posterior slope on ACL strain. Contrary to our initial hypothesis, we found no evidence of an increase in strain in the anteromedial bundle of the ACL after anterior opening wedge osteotomy.[17] Consequently, our goal in the present study was to reproduce identical testing conditions to measure ACL strain and the strain in the other 3 major ligamentous restraints of the knee (PCL, MCL and LCL).

Because we previously found that ACL strain decreases with anterior opening wedge osteotomy, our hypothesis was that the other ligamentous restraints of the knee were subject to increased compensatory strain. We reproduced a decrease in ACL strain with increasing anterior HTO size; however, we did not observe any significant increases in strain in the PCL after increasing posterior tibial slope compared with baseline. Although the loading protocol used was mainly designed to optimize the sensitivity of strain measurements on the ACL, we believe that at 15° flexion, a strain gauge positioned on the posteromedial bundle of the PCL should allow for the detection of some changes in strain in this ligament, particularly in the compression loading conditions without anterior load. However, we did not find the anterior opening wedge HTO to significantly alter PCL strain. Another reason for this may be the fact that the PCL is located at the apex of the wedge of the osteotomy; therefore, without disruption of the posterior cortical hinge, large strain changes in the PCL would not be expected to occur. In addition, any measured decreases in strain in the PCL were most likely the result of the anterior loading in our protocol as well as the result

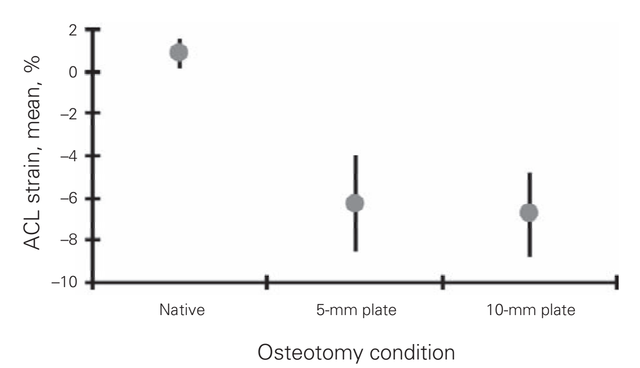

Fig. 4. The effect of osteotomy plating on anterior cruciate ligament (ACL) strain (mean and 95% confidence interval). Strain was significantly dependant on osteotomy condition ($p < 0.001$).

Table 1. Effect of osteotomy condition on strain and transverse plane motion

Osteotomy condition	Effect of osteotomy; mean (standard deviation)						
	ACL strain, %*	PCL strain, %	MCL strain, %	LCL strain, %	External rotation, mm*	Anterior tibial shift, mm	Anterior tibial translation, mm†
Native	0.84 (1.50)	–0.14 (0.70)	–0.13 (0.64)	–0.17 (0.49)	–1.0 (1.3)	4.6 (2.4)	0.6 (5.3)
5 mm	–6.28 (5.40)	0.69 (1.13)	–1.87 (4.10)	–0.47 (1.78)	0.5 (1.6)	6.1 (6.8)	2.1 (4.7)
10 mm	–6.77 (4.79)	–1.21 (5.27)	–1.43 (5.32)	–0.45 (1.87)	2.5 (3.0)	5.0 (11.5)	3.2 (4.6)

ACL = anterior cruciate ligament; LCL = lateral collateral ligament; MCL = medial collateral ligament; PCL = posterior cruciate ligament.
*$p < 0.001$, stepwise regression.
†$p < 0.05$, stepwise regression.

of the anterior translation shift phenomenon seen after increasing posterior tibial slope as initially described by Torzilli and colleagues.[25] This anterior translation shift was observed in our measurements with the resting position of the tibia displacing forward after anterior opening wedge osteotomy.

In terms of the collateral ligaments, no significant changes in strain were seen after increasing the posterior tibial slope. Although this contradicts our hypothesis, it can be expected given the fact that the collaterals play a more important role as secondary stabilizers against anterior translation when a rotatory component is present. The small increase in external rotation found with increasing size of the anterior opening wedge HTO were unlikely to induce recruitment of the collaterals as anterior stabilizers. It is unlikely that increases in external rotation of the magnitude found in our study would be clinically significant. The observation that no increased strain occurred in the collaterals implies that a true sagittal plane corrective osteotomy can be performed without affecting coronal alignment. Conversely, HTOs aimed at correcting coronal deformities induce some sagittal plane malalignment.[2,3,27] However, when performing an anterior opening wedge osteotomy, we recommend that the same care be taken as with a traditional HTO to prevent inducing changes in planes other than the one being corrected.

Overall, the strains measured in the PCL, MCL and LCL were in contradiction to our hypothesis that the major ligamentous restraints experience compensatory increased strain with increasing posterior tibial slope. However, it may be that other soft-tissue restraints, such as menisci, capsule or the muscles crossing the knee, may be subjected to increased strain.

In considering the sources of variability in the experiment, our measurements of strain were subject to potential error because of the problem of defining a reference resting length (y_0). Although our definition of reference length was arbitrary, it was based on the assumption that in the relaxed state, the ligaments of the cadaveric specimens would have similar baseline strains when each is positioned at the same degree of flexion. An arbitrary definition of reference length is also supported in the literature.[28] In addition, it has been argued that slight errors in determining resting length probably have minimal effects on the overall strain calculation. In equation 1, the strain equation, the numerator (change in length) is much less than the denominator (resting length); therefore, slight differences in resting length would not be expected to have a large influence on the calculated strain value.[24]

Anterior opening wedge HTO can also be referred to as flexion osteotomy. Although we chose not to use this nomenclature, it remains important to understand the effects of opening wedge osteotomy on the flexion–extension plane. For example, after the creation of a 10° opening wedge or flexion osteotomy for a given flexion angle, the knee joint itself is theoretically 10° more extended. Therefore, for our specimens, which were statically positioned at 15° flexion for each testing sequence, the knee joint became relatively more extended as the osteotomy increased in size. Thus, it can be hypothesized that the strain patterns for a given flexion angle could reproduce those of a knee in a more extended position after creation of the osteotomy. This hypothesis is difficult to confirm because strain data reported in the literature for the anteromedial bundle of the ACL as the knee moves from flexion to extension are conflicting. Inaccuracies in strain measurement near full extension are difficult to avoid. Some studies report increasing strains when moving from 30° to 0° flexion.[29–31] However, our results agree with those of other authors who reported decreasing strain as the knee progresses from 30° to full extension, and we took specific measures to decrease strain gauge impingement.[24,32]

Our position data did reveal significant changes in rotation of the tibia in relation to the femur. As the osteotomy size increased, a small increase in external rotation was seen of the tibia relative to the femur. This also supports the concept that opening wedge osteotomy reproduces the biomechanics of a more extended knee joint. As the knee joint moves from flexion to full extension, normal external rotation of the tibia should be observed and is an intrinsic part of the screw-home mechanism of the knee.

Conclusion

Although we observed a significant decrease in ACL strain as a result of increasing the size of anterior opening wedge HTO, the increased posterior tibial slope did not lead to altered strain in any of the other major ligamentous restraints of the knee. These data increase our understanding of the effect of altering sagittal plane alignment on ligament strain. Further studies are required to examine the effects of anterior opening wedge HTO on other soft-tissue restraints of the knee. Our improved comprehension of this procedure may help in using this technique to increase sagittal plane stability of knees with pathological sagittal instability.

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Contributors: Drs. Martineau and Fening acquired the data and wrote the article. All authors designed the study, analyzed the data, reviewed the article and approved its publication.

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