Technical considerations in lateral extra-articular reconstruction coupled with anterior cruciate ligament reconstruction: A simulation study evaluating the influence of surgical parameters on control of knee stability

Y. Blache, R. Dumas, J. de Guise, A. Saithna, B. Sonnery-Cottet, M. Thaunat

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Technical Considerations in Lateral Extra-Articular Reconstruction coupled with Anterior Cruciate Ligament Reconstruction: A Simulation Study Evaluating the Influence of Surgical Parameters on Control of Knee Stability

Blache Y[1]. (PhD), Dumas R[2]. (PhD), de Guise J[3]. (PhD), Saithna A[4,5] (MD), Sonnery-Cottet B[6]. (MD), Thaunat M[6] (MD).

[1] Univ Lyon, Université Claude Bernard Lyon 1 ; Laboratoire Interuniversitaire de Biologie de la Motricité – EA 7424, France

[2] Univ Lyon, Université Claude Bernard Lyon 1, IFSTTAR, LBMC UMR_T9406, F69622 Lyon, France

[3] Laboratoire de recherche en imagerie et orthopédie (LIO), Centre de recherche du Centre hospitalier de l'Université de Montréal (CRCHUM), et École de technologie supérieure, Montréal , Canada

[4] Advanced Orthopedics and Sports Medicine, Kansas City, USA

[5] School of Science and Technology, Nottingham Trent University, United Kingdom

[6] Centre Orthopédique Santy- Group Ramsay-Générale de Santé - Hôpital privé Jean Mermoz, Lyon, France

Corresponding author

Yoann BLACHE : yoann.blache@univ-lyon1.fr

Word Account

Abstract: 287

Introduction: 799

Methods: 764

Results: 472

Discussion: 1475

Conclusions: 171

TOTAL: 3681

Abstract

Background Surgical parameters such as the selection of tibial and femoral attachment site, graft tension, and knee flexion angle at the time of fixation may influence the control of knee stability after lateral extra-articular reconstruction. This study aimed to determine how sensitive is the control of knee rotation and translation, during simulated pivot-shift scenarios, to these four surgery settings.

Methods A computer model was used to simulate 625 lateral extra-articular reconstructions based upon five different variations of each of the following parameters: femoral and tibial attachment sites, knee flexion angle and graft tension at the time of fixation. For each simulated surgery, the lateral extra-articular reconstruction external rotation moment at the knee joint center was computed during simulated pivot-shift scenarios. The sensitivity of the control of knee rotation and translation to a given surgery setting was assessed by calculating the coefficient of variation of the lateral extra-articular reconstruction external rotation moment.

Findings Graft tension had minimal influence on the control of knee rotation and translation with less than 2.4% of variation across the scenarios tested. Control of knee rotation and translation was the least affected by the femoral attachment site if the knee was close to full extension at the time of graft fixation. The choice of the tibial attachment site was crucial when the femoral fixation was proximal and posterior to the femoral epicondyle since 15 to 67% of variation was observed in the control of knee rotation and translation.

Interpretation Femoral and tibial attachment sites as well as knee flexion angle at the time of fixation should be considered by surgeons when performing lateral extra-articular reconstruction. Variation in graft tension between the ranges 20-40N has minimal influence on the control of knee rotation and translation.

Key Terms: simulated pivot-shift; femoral attachment site; tibial attachment site; knee flexion at surgery, graft tension at surgery; anterior-cruciate ligament

1. Introduction

Anterior-cruciate ligament (ACL) ruptures are one of the most common knee injuries in individuals participating in sports activities. Most injured athletes will undergo ACL reconstruction, but there is an important risk of re-rupture (Paterno et al., 2014; Salmon et al., 2005) and only 65% of patients are able to return to their pre-injury level of sport (Ardern et al., 2014). In order to decrease the risk of a re-rupture, lateral extra-articular reconstruction (LER) is being performed with increasing frequency (Cerciello et al., 2018; Slette et al., 2016), since such a reconstruction is believed to improve the control of knee stability with respect to internal rotation and anterior translation (Inderhaug et al., 2017a, b; Katakura et al., 2017; Noyes et al., 2017; Sonnery-Cottet et al., 2017; Sonnery-Cottet et al., 2015).

The optimum surgical technique used to perform LER is not clearly defined and is a topic of great debate (Slette et al., 2016). Many variations in surgical settings differentiate the common LER procedures and therefore, their likely influence on the control of knee rotation and translation. However, four surgery settings are often put forward in the literature as being of potential importance (Geeslin et al., 2017; Inderhaug et al., 2017a, b; Katakura et al., 2017): the femoral and tibial attachment sites, graft tension, and the knee flexion angle at the time of graft fixation.

LER tension during knee internal rotation and flexion, has been shown to be sensitive to the femoral attachment site (Katakura et al., 2017). A more favorable behavior was observed when the graft was fixed proximally to the lateral femoral epicondyle in comparison to a graft located distally to the lateral femoral epicondyle (Imbert et al., 2016; Katakura et al., 2017). Knee flexion angle at the time of graft fixation has also been reported to potentially influence the ability of a LER to control knee stability. Inderhaug et al. (2017a) observed that knee rotation and translation were restored after LER with an anterolateral ligament (ALL) procedure (Sonnery-Cottet et al., 2016), only when the graft was fixed in full knee extension. By contrast, the control of knee rotation and translation after LER with a modified Lemaire procedure was not influenced (Inderhaug et al., 2017a) or was only moderately (Geeslin et al., 2017) sensitive to the knee flexion angle at the time of fixation. Finally, the influence of graft tension at the time of fixation on the control of knee stability is controversial. Inderhaug et al. (2017b) highlighted that the sensitivity of the control of knee rotation and translation to the graft tension at the time of fixation was dependent on the type of LER procedure (i.e. McIntosh, deep or superficial Lemaire or ALL) whereas Geeslin et al. (2017) observed no difference in knee kinematics after an ALL procedure performed with graft tension at 20 and 40N.

Although previous studies have yielded important information about the sensitivity of control of knee stability after LER to some surgery settings, some limitations remain. Firstly, most of the studies assessing the effect of one surgery setting have compared several LER procedures. Consequently, the influence of the tested surgery setting may be subject to confounding factors such as differences in the characteristics of grafts used for different techniques (e.g. Iliotibial band vs. Gracilis tendon), the number of strands (single vs. double strand) or the path of the lateral tenodesis (superficial vs. deep to the lateral collateral ligament). Secondly, the sensitivity to one surgery setting has typically been assessed either alone or coupled to a single additional surgery setting. However, none of the previous studies have assessed the more likely clinical scenario of possible interactions between all four of the surgery settings described above. Although this is something that could be evaluated in a cadaveric study, the advantage of computer simulation is that it is possible to perform a very large number of virtual surgeries to comprehensively evaluate the nature of these interactions while bypassing the cost, time constraints and inter-specimen variation posed by a cadaveric approach.

The purpose of this study was therefore to determine how sensitive is the control of knee rotation and translation, during a simulated pivot-shift scenarios, to four surgery settings: the femoral and tibial attachment sites, and the knee flexion angle and graft tension at the time of graft fixation. To that end, a computer model was used to simulate all surgeries procedures regarding the four settings, and then to calculate LER forces and moments during simulated pivot shift scenarios. Regarding the literature, it was hypothesized that the control of knee rotation and translation was sensitive to the femoral and tibial attachment site as well as the knee flexion angle at the time of graft fixation, while graft tension at the time of fixation should minimally influence the control of knee rotation and translation during the simulated pivot-shift scenarios.

2. Methods

2.1. Computer model

An adapted Opensim computer model was implemented (Opensim 3.3, Delp et al. (2007)) (Figure 1). The bony geometry of the modelled knee was extracted from a CT-scan (slice of 0.6 mm, Siemens Somaton, Erlangen, Germany) of a single healthy male participant (Age: 35 years, Height: 1.75 m, Mass: 80 Kg). The participant declared no history of lower limb injury and gave informed consent to study participation, which was previously approved by the Institutional Review Board of “Hôpital Privé Jean Mermoz” (# 2017-02). The model included also a spherical wrapping object surrounding the lateral epicondyle in order to make the ligament path follow the bone geometry (Figure 1).

In addition, EOS® bi-planar images (EOS Imaging Inc., Paris, France) of the participant were used to obtain the physiological weight bearing knee kinematics during quasi-static squats at 0, 10, 20, 30 and 60° of knee flexion (one trial per knee pose) (Clement et al., 2015). Then, a cubic spline interpolation was performed (Matlab R2017b, The MathWorks Inc., Natick, MA) to introduce in the computer model the couplings between the physiological knee flexion angle (from 0 to 60°) and the five other degrees of freedom, namely, internal-external rotation, abduction-adduction, superior-inferior translation, anterior-posterior translation and medial-lateral translation (Wu et al., 2002) (Figure 1 and supplementary_file_1.docx).

2.2. Simulated lateral extra-articular reconstruction

In order to assess the sensitivity of LER behavior to the four surgery settings, a total of 625 surgeries were simulated based upon five different variations of each of the following parameters: femoral attachment site, tibial attachment site, knee flexion angle at the time of fixation, and graft tension at the time of fixation. Each simulated surgery was performed using a single-strand gracilis graft with a stiffness of 65 N.mm (Wytrykowski et al., 2016).

Femoral attachment sites- five femoral attachment sites were tested with regards to the isometric behavior of the lateral tenodesis described in the literature (Kittl et al., 2015; Krackow and Brooks, 1983; Sonnery-Cottet et al., 2017; Van de Velde et al., 2016; Wieser et al., 2017). They were located on a half-circle of 1cm diameter posterior to the lateral epicondyle (Figure 2).

Tibial attachment sites- five tibial attachment sites were tested and were located on a line from Gerdy's tubercle to the projection of the tip of the fibula head (Wieser et al., 2017). These five locations included previously reported tibial attachment sites used in clinical practice (Slette et al., 2016; Sonnery-Cottet et al., 2017) (Figure 2).

Knee flexion angle at the time of graft fixation- five knee flexion angles at the time of graft fixation were tested: 0° (full extension), 15°, 30°, 45° and 60° in line with previous studies (Geeslin et al., 2017; Inderhaug et al., 2017a).

Graft tension at the time of fixation- five graft tensions at the time of fixation were tested, namely 20N, 25N, 30N, 35N and 40N in line with graft tension measured on cadavers (Geeslin et al., 2017; Inderhaug et al., 2017b) or by our team of surgeons during real surgery (data not published).

2.3. LER moments and forces

In line with the range of motions observed by Bull et al. (2002), the computer model was used to place the knee in positions corresponding to pivot-shift scenarios (n=960). The latter corresponded to a knee flexion between 10 and 30° combined with increased internal rotation (from 1 to 8°) and anterior translation (from 1 to 6 mm) with respect to the weight-bearing participant kinematics measured with bi-planar images (Figure 1). For each knee position and the 625 simulated surgeries, reconstructed LER length was calculated using the computer model. Based on LER length and its stiffness (Wytrykowski et al., 2016) (Figure 1), the force produced by LER in the three dimensional directions was computed. Finally, three dimensional LER moments at the knee joint center were calculated as the cross product of LER force and its lever arm relative to the midpoint between medial and lateral femoral epicondyles (Figure 1).

2.4. Sensitivity analysis

The analysis was performed only for the internal-external moment and anterior-posterior force, which are responsible for knee stability. The sensitivity of the LER force and moment to each surgery setting was assessed by computing the coefficient of variation of the LER force/moment for a given surgery setting with regards to the three remaining surgery settings. For instance, the coefficient of variation of the LER moment/force due to the modification of the femoral attachment site was computed for each variable of tibial attachment site, knee flexion angle and graft tension at the time of fixation. The procedure was repeated in order to test all possible combinations of the surgery settings.

3. Results

The sensitivity analysis revealed similar tendencies between the LER internal-external rotation moment and anterior-posterior force variability regardless of the surgery setting.

Graft tension at the time of fixation – The coefficient of variation of LER external rotation moment and posterior force was included between 0% and 2.4% depending on the other surgery settings. These variations corresponded on average to 0.15 N.m (SD 0.03) and 4.4 N (SD 0.9) for the LER external rotation moment and posterior force respectively.

Femoral attachment site – Changing femoral attachment sites resulted in LER average external rotation moment and average posterior force variations (i.e., for all graft tensions at the time of fixation, tibial attachment sites and knee flexions angles) equal to 1.9 N.m (SD 1.3) and 59.2 N (SD 38.7) respectively. The coefficient of variation of the LER external rotation moment and posterior force was between 4.1% and 54.3% depending on the other surgery settings. The sensitivity of LER behavior to the femoral attachment site was the smallest with anterior tibial attachment sites (i.e. near Gerdy's tubercle) when combined with knee flexion angles at the time of fixation smaller than 30°. By contrast, knee flexions angles above 30° combined with a posterior tibial attachment site increased the sensitivity of the LER moment/force to the femoral attachment site (Figure 3).

Tibial attachment site - Changing tibial attachment sites resulted in LER average external rotation moment and average posterior force variations equal to 2.3 N.m (SD 2.4) and 63.4 N (SD 67.6) respectively. The coefficient of variation of the LER external rotation moment and posterior force was between 0.6% and 67.4% depending on the other surgery settings. The sensitivity of LER behavior to the tibial attachment site was smaller for knee flexions angles between 45 and 60° in comparison to knee flexions angles between 0 and 15°. Posterior and postero-proximal femoral attachment sites with knee flexion angles greater than 45° led to the smallest sensitivity of LER moment/force to the tibial attachment site (Figure 4).

Knee flexion angle at the time of graft fixation - Changing knee flexion angle at the time of graft fixation resulted in LER average external rotation moment and average posterior force variations equal to 4.1 N.m (SD 1.9) and 116.9 N (SD 51.9) respectively. The coefficient of variation of the LER external rotation moment and posterior force was between 26.5% and 102.2% depending on the other surgery settings. The smallest sensitivity of LER behavior to variation in knee flexion angle at the time of graft fixation was observed when the graft was fixed distal to the femoral epicondyle and posteriorly on the tibia. When simulating a Lemaire procedure, the coefficient of variation of LER moment/force with regards to knee flexion angle at the time of graft fixation was equal to 70.0%, while a coefficient of variation of 53.6% was observed for ALL procedure (Figure 5).

4. Discussion

This study aimed to determine how sensitive is the control of knee rotation and translation, during a simulated pivot-shift, to four surgery settings: the femoral and tibial attachment sites, and the knee flexion angle and graft tension at the time of graft fixation. The main findings of this study were that graft tension at the time of fixation barely influenced the control of knee rotation and translation when ranging between 20 and 40 N, while the femoral or tibial attachment sites and knee flexion angle at the time of fixation may drastically influence the control of knee internal rotation and anterior translation during a pivot-shift scenario.

4.1. Evaluation of model outputs

Kinematics of the knee computed from extrapolation of the quasi-static poses are similar to those depicted in previous studies focusing on squat movement. As indicated by Abdel-Jaber et al. (2016) and Miyaji et al. (2012), we observed that knee internal rotation and anterior translation were coupled with knee flexion. To the best of our knowledge, no gold standard data (i.e., intracortical pins or fluoroscopy) are available concerning knee abduction/adduction, cranio/caudal and medio/lateral translation during squat movements. Nevertheless, our results are in the range of those found in the literature for dynamic activities (Gasparutto et al., 2017). In addition, similar to Kernkamp et al. (2017), we denoted that LER lengthened during the early degrees of knee flexion and started to shorten at about 35 degrees of knee flexion when the femoral graft was located posteriorly and proximally to the femoral epicondyle and the tibial graft positioned on the gerdys's tubercle or anatomical insertion of the anterolateral ligament (supplementary_file_2.docx). In addition, previous cadaveric studies (Geeslin et al., 2017; Inderhaug et al., 2017a, b) pointed out that LER controlled knee rotation and anterior translation. Another way to consider these outcomes is that increasing knee internal rotation and/or anterior translation would involve an increased LER external rotation moment and/or posterior force (since the ligament is a passive structure depending only on its lengthening). Our results are in accordance with this statement since LER external rotation moments and posterior forces were the smallest when the knee was positioned without exaggerated rotation or translation (i.e., poses corresponding to the physiological weight-bearing knee flexion). In contrast, LER external rotation moments and posterior forces increased for knee positions with an exaggerated internal rotation or anterior translation.

4.2. Sensitivity analysis

The influence of graft tension at the time of fixation on the control of knee rotation and translation has been controversial. Geeslin et al. (2017) reported no difference in knee kinematics between a graft fixed at 20 or 40 N when performing an ALL procedure (Sonnery-Cottet et al., 2016) in a cadaveric study. In contrast, also for ALL reconstruction, Inderhaug et al. (2017b) observed that, a graft tension of 20 N under-constrained knee rotation and anterior translation, while at 40 N, knee kinematics were almost restored. It was also observed that for modified Lemaire or McIntosh procedures, knee stability was not influenced by graft tension at the time of fixation (Inderhaug et al., 2017b). Our results suggest that graft tension at the time of fixation barely influences the control of knee internal rotation and translation during a pivot-shift scenario. Additional findings to previous studies (Geeslin et al., 2017; Inderhaug et al., 2017b) are that our conclusions are the same whatever the femoral, tibial attachment sites and knee flexion angle at the time of fixation. In consequence, whatever the procedure, surgeons performing LER should not focus on graft tension at the time of fixation whether the latter ranges between 20 and 40 N.

The control of knee internal rotation has been shown to be sensitive to the femoral graft attachment site when LER was fixed on the tibia at mid distance between Gerdy's tubercle and fibula head, and at 20° of knee flexion (Katakura et al., 2017). For a similar configuration, we observed that, indeed the tested femoral attachment site led to variations, ranging between 10 and 30%, in the control of both knee internal rotation and anterior translation. Nevertheless, the influence of the tested femoral attachment sites on knee stability, during a pivot-shift scenario, depended also on both knee flexion angle at the time of fixation and the tibial attachment site. The main applications were that, firstly if surgeons want to limit the influence of the femoral attachment site on the control of knee stability, the graft should be fixed in full extension or 15° of flexion. Secondly, when the tibial attachment site is between the ALL location and Gerdy's tubercle with a knee close to full extension (below 15°), the tested femoral attachment sites involved less than 15% of variation in the control of knee rotation and translation. By contrast, if surgeons choose posterior tibial attachment sites for LER, the location of the femoral attachment site would have more influence on the control of knee stability during a pivot-shift scenario.

From previous works (Inderhaug et al., 2017a; Wieser et al., 2017), it may be hypothesized that tibial attachment site has a small influence on the control of knee stability. Indeed, Inderhaug et al. (2017a) compared two LER procedures (ALL and Lemaire) with different tibial attachment sites, and pointed out that both procedures make it possible to restore knee kinematics. However, ALL and Lemaire procedures were not performed with the same graft (2 strands Gracilis vs. Ilio Tibial Band), which may bias the hypothesis made on the influence of the tibial insertion on the control of knee stability. Our results suggest that tibial attachment site influences the control of knee rotation and translation during a pivot-shift scenario. Especially, we pointed out that when surgeons fix the graft posteriorly and proximally to the femoral epicondyle (Sonnery-Cottet et al., 2017), the choice of the tibial attachment site is crucial since 15 to 67% of variation was observed in the control of knee stability. In addition, the choice of the tibial attachment site was more predominant if the graft was fixed with the knee in full extension.

Knee flexion angle at the time of graft fixation may influence the control of knee rotation and translation depending on the type of LER procedure. In a cadaveric study, for the Lemaire procedure, knee flexion angle at the time of graft fixation did not influence knee kinematics, but for the ALL procedure, knee stability was restored only when the graft was fixed in full extension (Inderhaug et al., 2017a). In the present study, we also observed that the control of knee internal rotation and anterior translation during a pivot-shift scenario was influenced by knee flexion angle at the time of graft fixation depending on both the femoral and tibial attachment site. When considering the bone attachment sites used for ALL (Sonnery-Cottet et al., 2016) and Lemaire (1967) procedures, different knee flexion angles at the time of graft fixation involved variations in the control of knee rotation and translation (up to 70%). These results suggest that knee flexion angle at the time of graft fixation is an important surgery setting to take into consideration by surgeons when performing LER either for ALL or Lemaire procedure. Our results are similar to those of Inderhaug et al. (2017a) for ALL procedure, while they differ for Lemaire procedure. An explanation may be that Inderhaug et al. (2017a) applied external forces to the tibia and evaluated knee kinematics, while in our study, the knee was placed in a pivot-shift scenario and we measured LER forces and moments. The two conditions may involve different load on LER, which may preclude direct comparison between the two studies.

The current study displayed some limitations that warrant discussion. Firstly, only one participant took part in this study to build the numerical model used for sensitivity analysis. However, the analysis performed in our study explores a large range of internal rotations and anterior translations (i.e. pivot-shift volume) and encompasses the kinematic variability that would have been observed in a larger cohort study. Moreover, the post-operative kinematics depending on the different surgery settings remains unknown. Nevertheless, only pivot-shift scenarios were simulated which corresponded to an exaggerated internal rotation and anterior translation. It was assumed that such post-operative exam would produce knee positions that fall within the range tested within the sensitivity analysis. Secondly, all simulated surgeries were performed with a Gracilis graft characterized by a linear stiffness of 65 N.mm, while Gracilis stiffness is patient dependent. Furthermore, for the Lemaire procedure a different graft stiffness is observed since the Ilio tibial band is used instead of the Gracilis tendon. To overcome this limitation, we have repeated the experimentation with a graft stiffness corresponding to an Ilio tibial band and we observed similar results (see supplementary_file_3.docx). Finally, contrary to finite element models, our computer model was composed of frictionless structures. Consequently, contact forces between the ligaments and the bones were not taken into consideration in the computation of knee joint moments.

5. Conclusions

Computer modeling made it possible to simultaneously test the influence of four surgery settings, namely, femoral and tibial attachment sites, and knee flexion angle and graft tension at the time of fixation on the variability of the control of knee internal and anterior translation during pivot-shift scenarios. Graft tension at the time of fixation ranging between 20 and 40N barely influenced the control of knee stability whatever LER procedure. The influence of the femoral attachment site on the control of knee rotation and translation was reduced if the graft if fixed with the knee near full extension and for tibial attachment sites between ALL location and the Gerdy's tubercle. The choice of tibial attachment site is crucial when the graft is fixed proximally and posteriorly to the femoral epicondyle because large variations in the control of knee rotation and translation was observed. The control of knee rotation and translation has been shown to be sensitive to knee flexion angle at the time of graft fication both for ALL and Lemaire procedures.

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Conflict of interest statement

Yoann Blache, Raphaël Dumas and Jacques de Guise declare no conflict of Interest.

Mathieu Thaunat, Bertrand Sonnery-Cottet and A.S. are consultant for Arthrex.

Figure 1. A) Anterior (left) and lateral (right) view of the computer model of the knee used for the simulations. The model is composed of two bones the femur (F) and the tibia (T), one ligament representing the lateral extra-articular tenodesis (one example is presented here) and a wrapping object (blue sphere) to avoid bone penetration. The reference coordinate system is represented with the rotations used to compute three dimensional knee joint moments produced by the lateral extra-articular tenodesis. Z_{float} corresponds to the cross product of X_F and Y_T. Antero-posterior forces were computed along Z_T axis. **B)** Knee internal/external rotation (blue) and antero/posterior translation (red) with respect to knee flexion. The dots correspond to kinematics obtained from the bi-planar images during the physiological squat poses, and the thick lines demonstrate the cubic spline interpolation. Shaded zones depict the simulated exaggerated internal rotation (blue) and anterior translation (red). The vertical dotted lines identify the knee positions corresponding to pivot-shift scenarios for which knee joint moment produced by the lateral extra-articular tenodesis were computed. **C)** Lateral extra-articular (LER) force-strain relationship with regards to the literature.

Figure 2- Location of the five femoral and tibial attachment sites for the simulated surgeries.

Figure 3- Sensitivity (coefficient of variation) of LER internal moment to the femoral attachment site with regards to knee flexion angle at the time of fixation and the tibial attachment site. Considering that graft tension barely influence LER internal moment, average values and the standard deviation of the five graft tensions at the time of fixation are represented.

Figure 4- Sensitivity (coefficient of variation) of the LER internal moment to the tibial attachment site with regards to knee flexion angle, graft tension at the time of fixation and the femoral attachment site. Considering that graft tension barely influence LER internal moment,

average values and the standard deviation of the five graft tensions at the time of fixation are represented.

Figure 5- Sensitivity (coefficient of variation) of the LER internal moment and posterior force to the knee flexion at the time of fixation with regards to ALL and Lemaire procedures, and the graft tension at the time of fixation. Considering that graft tension barely influence LER internal moment, average values and the standard deviation of the five graft tensions at the time of fixation are represented.

Highlights

- Computer model was built to simulate several ACL surgeries with lateral tenodesis
- Sensitivity of the control of knee stability to four surgery settings was computed
- Whatever the surgical procedure, knee flexion influenced knee rotation control
- Knee femoral/tibial attachment site should be considered by surgeons
- Graft tension at surgery barely influenced control of knee rotation and translation

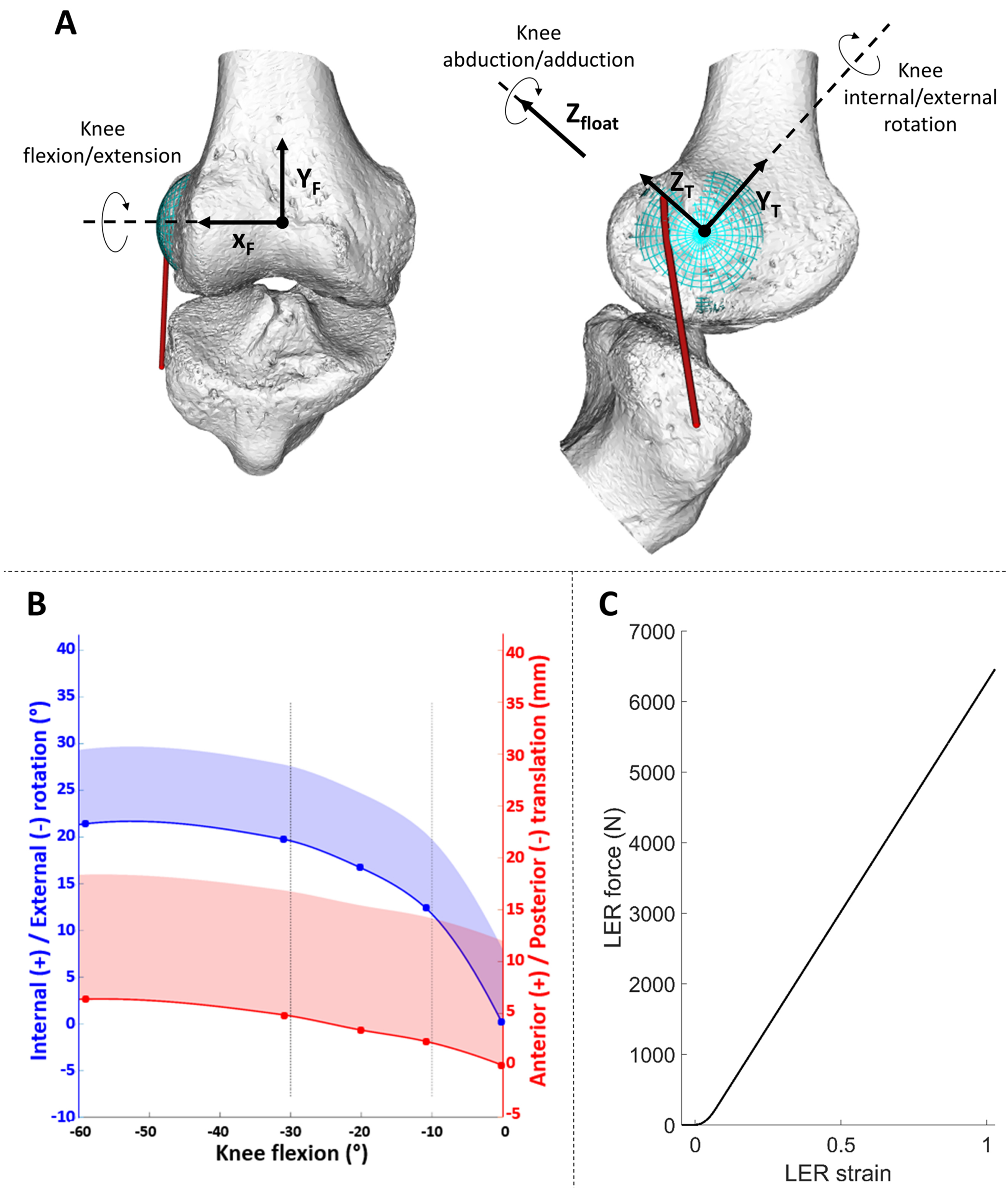
A
Knee flexion/extension
Y_F
x_F
Knee abduction/adduction
Z_{float}
Knee internal/external rotation
Z_T
Y_T
B
Internal (+) / External (-) rotation (°)
Anterior (+) / Posterior (-) translation (mm)
Knee flexion (°)
-60
-50
-40
-30
-20
-10
0
40
35
30
25
20
15
10
5
0
-5
-10
C
LER force (N)
LER strain
7000
6000
5000
4000
3000
2000
1000
0
0.5
1

Figure 1

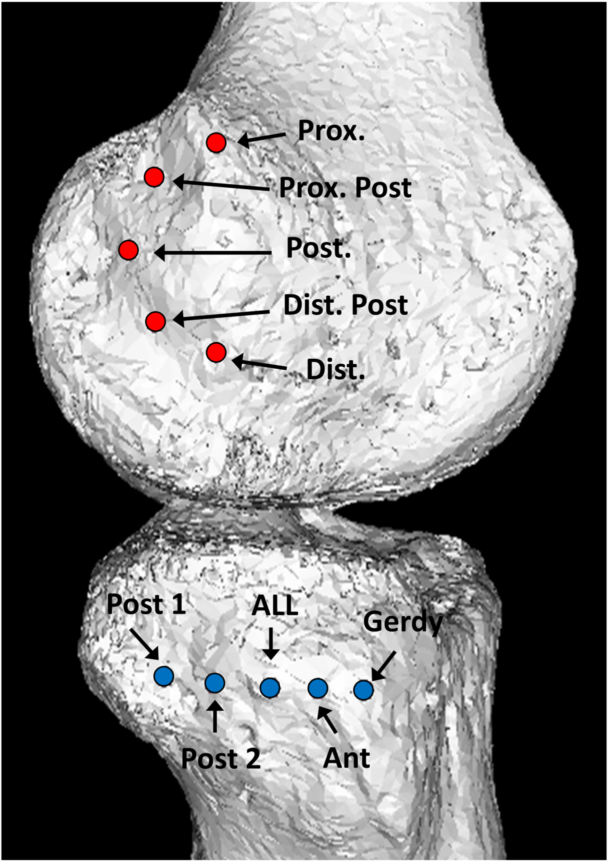

Figure 2


Sensitivity to Femoral Attachment Sites
Tibia: Post 1
Tibia: Post 2
Tibia: ALL
Tibia: Ant
Tibia: Gerdy
Internal Moment Variability (%)
0
10
20
30
40
50
60
70
80
90
100
flex 0
flex 15
flex 30
flex 45
flex 60

Figure 3

Sensitivity to Tibial Attachment Site

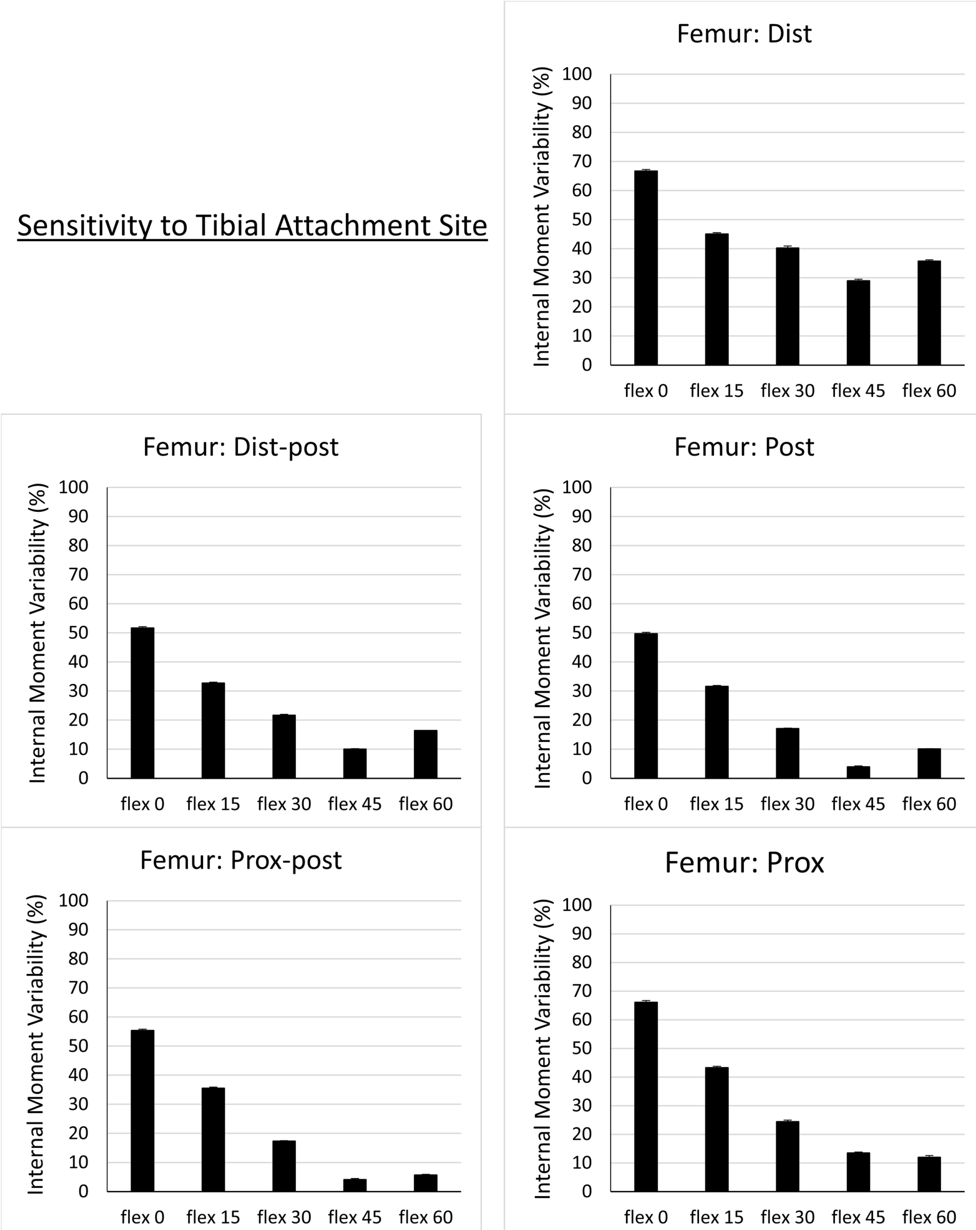

Figure 4

Sensitivity to Knee Flexion at Surgery

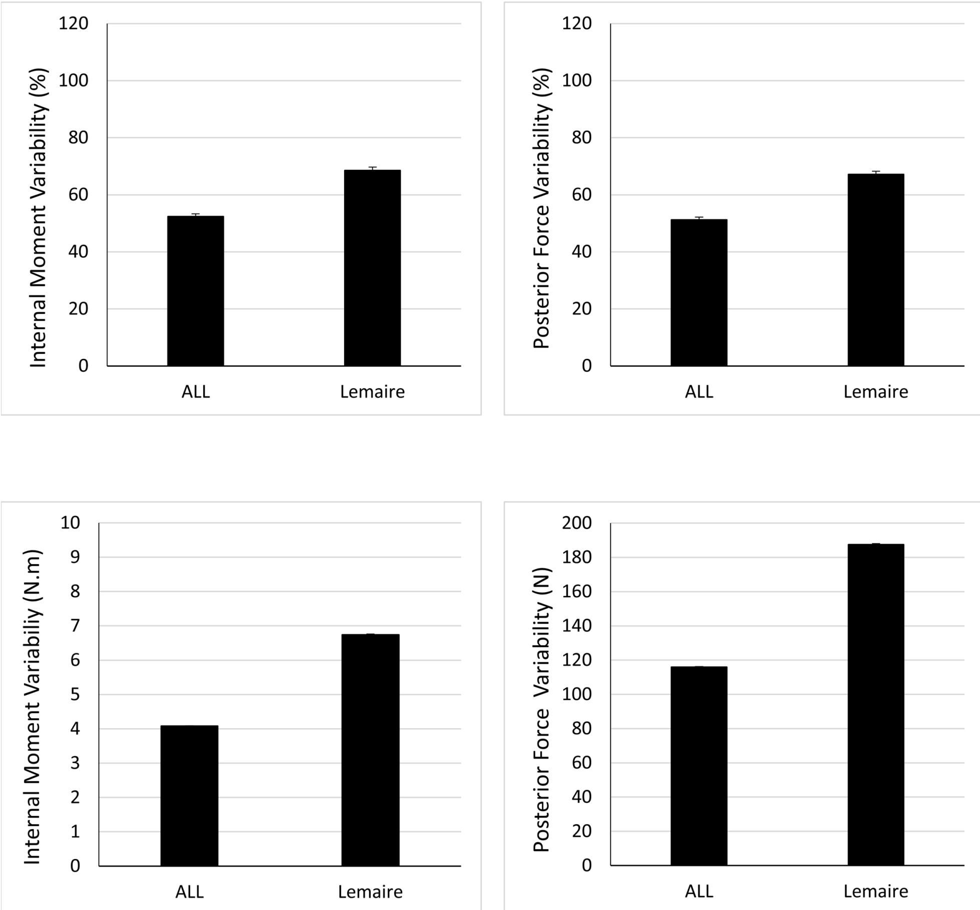

Figure 5