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Original article

Lateral extra-articular reconstruction length changes during weightbearing knee flexion and pivot shift: A simulation study

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ABSTRACT

Introduction: Variations in the length of lateral extra-articular reconstruction (LER) have been widely investigated during knee flexion but there is no information about length changes during pivot shift. This study sought to assess the changes in LER tension during weightbearing knee flexion in a normal knee and in a computer-simulated pivot-shift scenario.
Hypothesis: Placing the femoral tunnel posterior and proximal to the lateral femoral epicondyle allows the LER to tighten early in the flexion range during weightbearing (squatting motion) and simulated pivot-shift.
Material and methods: A computer model was used to simulate weightbearing knee flexion and pivot shift scenarios. Changes in LER tension were calculated in both scenarios by estimating the distance between six femoral attachment sites (posterior and proximal to the lateral femoral epicondyle) and two tibial tunnel locations: Gerdy's tubercle (GT) and the anterolateral ligament (ALL) anatomic attachment site.
Results: Independent of the location of the femoral and tibial tunnels, the LER tightened by up to 22% of its resting length during the early portion of weightbearing knee flexion and then relaxed from 40° to 60° of knee flexion. The ALL tibial tunnel position allowed complete LER relaxation at 60° flexion whereas LER using the GT tibial tunnel position remained tighter. In the simulated pivot-shift test, and for all femoral tunnel locations, the LER tightened by 20% to 34% of its resting value for the GT tibial tunnel position and by 11% to 26% for the ALL tibial tunnel position.
Discussion: During weightbearing knee flexion, placing the femoral tunnel proximal and posterior to the femoral epicondyle was associated with LER tightening in the early degrees of flexion and LER relaxation between 40 and 60° flexion. LER tightening occurred during a simulated pivot-shift test supporting the concept that a posterior and proximal femoral LER tunnel position is most effective during weightbearing knee flexion and altered knee kinematics.

1. Introduction

Return to sport after anterior cruciate ligament (ACL) reconstruction is not often satisfactory since only 63% of patients resume their pre-injury level of sports participation [1] and even then, they have a higher risk of re-injury [2–4]. One of the possible causes of these suboptimal outcomes is a persistent lack of rotational and translational stability of the knee even after ACL reconstruction [5,6]. Consequently, lateral extra-articular reconstruction (LER) has generated renewed interest [7–11] and is increasingly being performed to better control tibial internal rotation and anterior translation relative to the femur [12–14].

There has been considerable debate regarding the anatomy of the anterolateral structures of the knee. Nevertheless, there is a growing consensus that the native anterolateral ligament (ALL)

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is inserted proximal and distal to the femoral epicondyle, and between the fibular head and Gerdy's tubercle (GT) on the tibia. In addition, the native ALL has an anisometric behavior: the ligament is tightened in knee extension and relaxed in flexion [12,15,16].

However, the optimum positioning of the femoral and tibial tunnels for LER is still being debated. These should be located in a position that results in physiological knee kinematics, specifically restoring rotational control while avoiding over-constraining the knee [12]. The recent literature, including in vivo and in vitro studies, describes an array of different femoral tunnel positions ranging from directly proximal to the lateral epicondyle [10,17,18], to posterior and proximal [13,19] or even posterior and distal [20]. There appears to be a growing consensus that the posteroproximal femoral attachment allows the most desirable behavior, meaning the LER is tightened during knee extension and relaxed during flexion [12,20]. As for the tibial tunnel position, a previous study [18] reported that during a weightbearing squat, the most isometric point was located at 37% of the anteroposterior width of the tibial plateau.

While all of these studies yield precious information about the optimum positioning of LER grafts during physiological knee flexion, none of them has assessed the LER length changes occurring in the presence of altered knee kinematics such as persistent internal rotation and anterior translation instability following ACL reconstruction. To the best of our knowledge, only Imbert et al. [13] has investigated the effect of knee rotation on LER length. Among the three femoral tunnel positions tested, the posteroproximal position had the greatest LER length variation when a 2 Nm internal rotation torque was applied with the knee at 90°. However, this study was performed in vitro and may not reflect LER behavior during weightbearing knee flexion. Furthermore, LER length variations have never been measured during coupled knee internal rotation and anterior translation that corresponds to the knee instability observed during a pivot shift test. A desirable behavior would be that the LER graft tightens during the pivot-shift test to control the knee's rotational and translational instability.

The aim of this study was to assess the changes in LER tension during weightbearing knee flexion in a normal knee and in a computer-simulated pivot shift scenario. It was hypothesized that a posteroproximal femoral attachment site allows the LER to tighten in knee extension and release in flexion and then tighten during altered knee internal rotation and anterior translation.

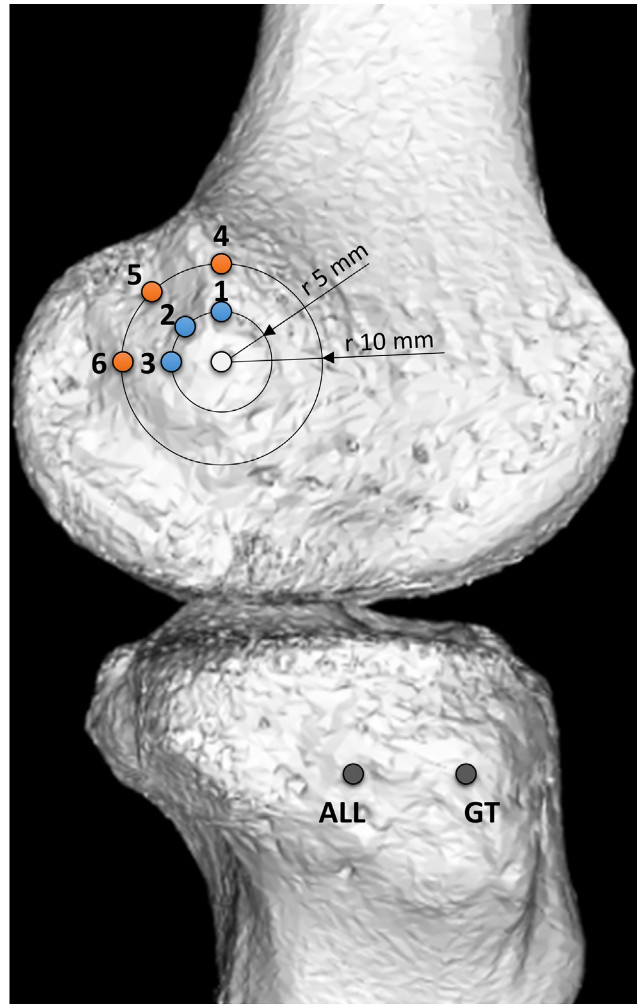

Fig. 1. Lateral view of the right knee with the femoral and tibial attachment sites of the simulated lateral extra-articular reconstruction. ALL: anterolateral ligament anatomic position, GT: Gerdy's tubercle.

2. Patient and methods

2.1. Computer model

An adapted Opensim computer model was implemented (Opensim 3.3, Delp et al. [21]). The bony geometry of the modelled knee was extracted from a CT scan (0.6 mm slice thickness, Siemens Somaton, Erlangen, Germany) of a single healthy male participant (age: 35 years, height: 1.75 m, mass: 80 kg). The participant had no history of lower limb injury and gave informed consent to participate in this study, which was previously approved by the Institutional Review Board of the "Hôpital Privé Jean-Mermoz" (#2017-02). The model also included a spherical wrapping object surrounding the lateral epicondyle to ensure the ligament path followed the bone geometry.

In addition, biplanar x-ray images (EOS Imaging Inc., Paris, France) of the participant's legs were used to obtain the physiological weightbearing knee kinematics during quasi-static squats at 0, 10, 20, 30 and 60° of knee flexion (one trial per knee position) [22]. Then, a cubic spline interpolation was performed (Matlab, The MathWorks Inc., Natick, MA) to introduce in the computer model the couplings between the physiological knee flexion angle and the five other degrees of freedom, namely, internal/external rotation, abduction/adduction, superior/inferior translation, anterior/posterior translation and medial/lateral translation [23].

2.2. LER tunnel position

Based on the ALL expert group consensus [12], the femoral tunnels were located posterior and proximal to the lateral femoral epicondyle in the simulation. Specifically, six femoral tunnel positions were located on two quarter-circles with a radius of 5 and 10 mm and centered on the femoral lateral epicondyle (Fig. 1). For the tibia, two locations were considered. The first sought to replicate procedures using the iliotibial band, thus the tunnel was located directly at its GT attachment. The second sought to replicate the most anterior location of an ALL graft, 1 cm posterior to GT [7] (Fig. 1).

2.3. Analysis

LER length was computed by assuming the ligament remained in contact with the bone structures throughout the movement. In this configuration, LER shortening corresponded to relaxation of the graft while LER lengthening corresponding to tightening of the graft. LER length changes estimated during weightbearing knee

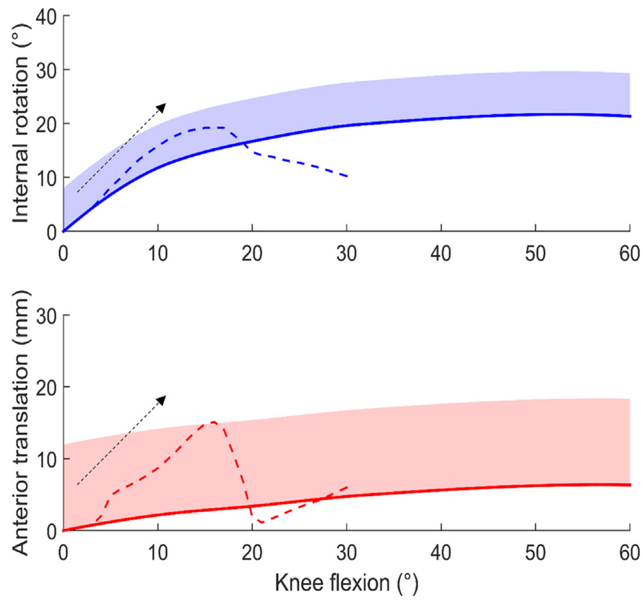

Fig. 2. Tibial internal rotation (solid blue line) and anterior translation (solid red line) during weightbearing knee flexion. The shaded blue and red zones correspond to knee positions with exaggerated knee internal rotation and anterior translation. The blue and red dashed lines correspond to the tibial internal rotation and anterior translation measured during a simulated pivot-shift test by Amis et al. [5]; the movement direction corresponds to the black arrow.

flexion were normalized to LER length in a resting position with the knee fully extended (Eq. 1):

$$\Delta LER_{length} = \frac{LER_{length}^{i,j,k} - LER_{length}^{Full\ \ extension}}{LER_{length}^{Full\ \ extension}}$$

where i, j, and k refer to a given knee flexion, internal rotation and anterior translation position, respectively.

Secondly, LER length was calculated in a scenario of altered kinematics, namely, increased internal rotation (up to 8°) and anterior translation (up to 12 mm) of the tibia [24]. Next, the average length LER change was calculated for two volumes representative of potential knee kinematics during a simulated pivot shift test. The first volume corresponded to a combination of knee flexion between 10° and 30°, rotation between 1° and 8°, and anterior translation between 1 mm and 6 mm. The second volume corresponded to the same knee flexion and rotation values but to anterior translation between 7 mm and 12 mm. Lastly, a specific combination of knee flexion, internal rotation and anterior translation was simulated based on the pivot-shift curves reported by Amis et al. [5] (Fig. 2).

3. Results

During the physiological weightbearing knee flexion task, knee flexion was associated with a knee internal rotation ranging from 0° to 21.7°, and with anterior tibial translation ranging from 0 to 6.3 mm (Fig. 2). During this trial, the LER tightened (lengthened) by up to 22% of its resting length during the early portion of physiological weightbearing knee flexion and then relaxed (shortened) from 40 to 60° of knee flexion, independent of the femoral and tibial tunnel positions (Fig. 3). For all femoral tunnel positions, placing the tunnel on the posterior portion of the tibia (ALL position) resulted in less LER tightening throughout knee flexion than with the GT tibial tunnel position ($-7.72 \pm 0.77\%$ on average).

In the case of simulated altered knee kinematics, increased tibial internal rotation, particularly after 20° of knee flexion resulted in the LER tightening no matter the tunnel position. In the same way, the LER tightened with increased anterior tibial translation (Fig. 4 and Supplementary file). In the pivot-shift scenario (increased internal rotation and anterior translation between 10 and 30° of knee flexion), the LER tightened between 20 and 34% of the resting value when the most anterior GT tunnel was used and between 11 and 26% when the more posterior ALL tunnel was used (Table 1). While the tibial tunnel position impacted the LER tension, only very small differences were observed between the femoral tunnel sites (i.e. less than 1.4 cm and 2.3 cm of variation for GT and ALL, respectively) as long as they were located posterior and proximal to the femoral epicondyle.

Lastly, when replicating the specific knee kinematics recorded for a pivot shift test [5], the LER tightened during the early phase of the test (up to 15° of knee flexion), with maximum values corresponding to the peaks of anterior translation and internal rotation, regardless of the femoral tunnel position.

4. Discussion

The main findings of this study are that placing the femoral tunnel proximal and posterior to the femoral epicondyle allows the LER to tighten at the start of weightbearing knee flexion and to relax between 40° and 60° flexion. Secondly, when a posteroproximal femoral tunnel site is used, the LER tightens during a simulated pivot-shift test. Thirdly, when the LER has a GT tibial tunnel location, it tightens more during weightbearing knee flexion and pivot shift than when an ALL tibial tunnel location is used.

Although this study was based on a single participant, the kinematics recorded during physiological weightbearing knee flexion are representative of a healthy male population. Normal kinematics during a weightbearing squatting task are usually characterized by tibial internal rotation and anterior translation [25]. In our study, our subject's knee kinematics were consistent with these previous reports since 0° to 20° internal rotation and 0 to 6 mm anterior translation were observed during knee flexion.

LER is performed to improve the control over knee rotation and translation [12,26]. The results of the current study are consistent with previous reports that posteroproximal femoral tunnels are associated with LER tightening in extension and relaxation in flexion [6,13,20]. The LER grafts also tightens during simulated internal rotation and anterior translation of the tibia. Like in a previous study [20], we showed that an ALL tibial tunnel location led to a more relaxation close to 60° knee flexion than when the graft was fixed at the GT. This suggests the ALL tibial tunnel position results in more desirable behavior than the GT position since it is less likely to over-constrain physiological internal rotation in the flexed knee.

Interestingly, this behavior was observed regardless of the specific location of the femoral tunnel as long as it was posterior and proximal to the femoral epicondyle. As consequence, surgeons can safely shift the entry point by up to 5 mm when drilling the femoral epicondyle tunnel. These results are consistent with those of Imbert et al. [13] who observed LER tightening when an internal rotation torque was applied.

The LER also tightened during a simulated pivot-shift test, namely, a combination of tibial internal rotation and anterior translation. Maximum tightening was observed when the maximum anterior translation and internal rotation occurred during the simulated pivot-shift test as described by Amis et al. [5]. This is consistent with the findings of Inderhaug et al. [27], who demonstrated significant improvement in knee kinematics in cadaver knees after LER. Therefore, the tightening behavior of LER observed in the current study reinforces the concept that LER could be indicated to better control knee stability after ACL rupture when the patient has a grade 2 or 3 pivot-shift [12]. Nevertheless, LER tightening is only

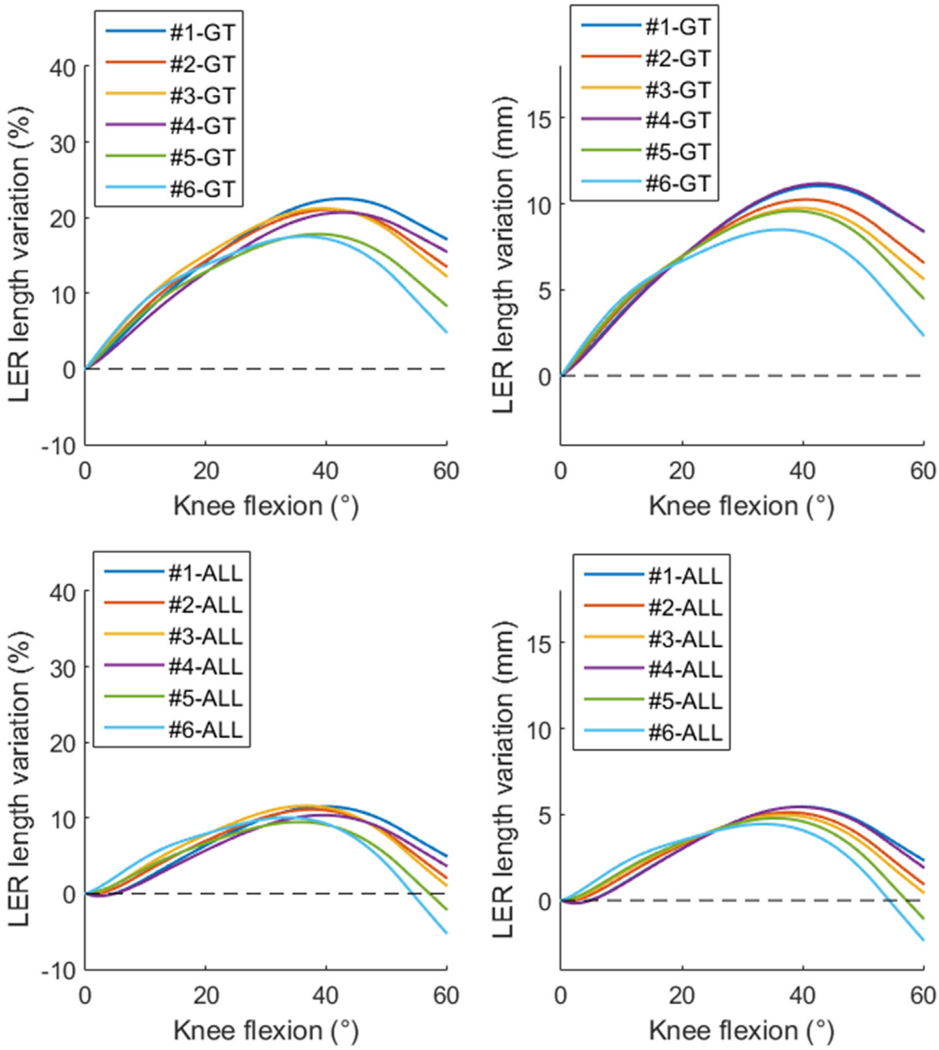

Fig. 3. Relative (left) and absolute (right) lateral extra-articular reconstruction (LER) length variation during weightbearing knee flexion for the six femoral tunnel positions (#1 to #6) and the two tibial tunnel positions (GT and ALL).

Table 1
Mean ± standard deviation of the lateral extra-articular reconstruction (LER) length variation (expressed in absolute and relative values) for two specific volumes corresponding to the pivot-shift kinematics.

	LER femoral tunnel position					
Altered kinematics(+1° to 8° rotation)	#1	#2	#3	#4	#5	#6
+1 to 6 mm translation						
LER_{GT} Δ length (mm)	10.8 ± 1.2	11.1 ± 1.3	11.3 ± 1.3	10.6 ± 1.2	11.2 ± 1.3	11.3 ± 1.4
LER_{ALL} Δ length (mm)	6.0 ± 1.3	6.6 ± 1.1	6.9 ± 1.1	5.9 ± 0.9	7.0 ± 1.1	7.5 ± 1.2
LER_{GT} Δ length (%)	22 ± 2	23 ± 3	25 ± 3	20 ± 2	21 ± 2	23 ± 3
LER_{ALL} Δ length (%)	13 ± 2	14 ± 2	16 ± 3	11 ± 2	14 ± 2	17 ± 3
+7 to 12 mm translation						
LER_{GT} Δ length (mm)	14.8 ± 1.3	15.4 ± 1.4	15.7 ± 1.4	14.5 ± 1.2	15.6 ± 1.4	15.9 ± 1.5
LER_{ALL} Δ length (mm)	9.3 ± 1.1	10.2 ± 1.2	10.7 ± 1.3	9.1 ± 1.1	10.8 ± 1.3	11.6 ± 1.3
LER_{GT} Δ length (%)	30 ± 3	32 ± 3	34 ± 3	27 ± 2	29 ± 3	33 ± 3
LER_{ALL} Δ length (%)	20 ± 2	22 ± 3	25 ± 3	17 ± 2	22 ± 2	26 ± 3

Results are reported for the six simulated femoral tunnel (#1 to #6) and two tibial tunnel (GT and ALL) locations.

one component of the complex inter-play of factors that ensure the control of knee stability. The direction of the LER vector should be determined in future studies to address the assumption that it is indeed LER tightening that improves knee stability.

Lastly, our comparison of ALL or GT tibial tunnel positions showed greater LER tension during simulated increased tibial internal rotation and anterior translation with the GT position. This raised the possibility that a GT tunnel position may over-constrain the knee, particularly because this location was not associated with complete relaxation of the LER in flexion.

The current study has several limitations. The first limitation was the study's conclusions were based on data obtained from a computer model, which involves some simplifications. Nevertheless, in vivo LER length can only be measured during static poses, as there are no tools available to measure LER length dynamically. The second limitation was that only one participant was enrolled

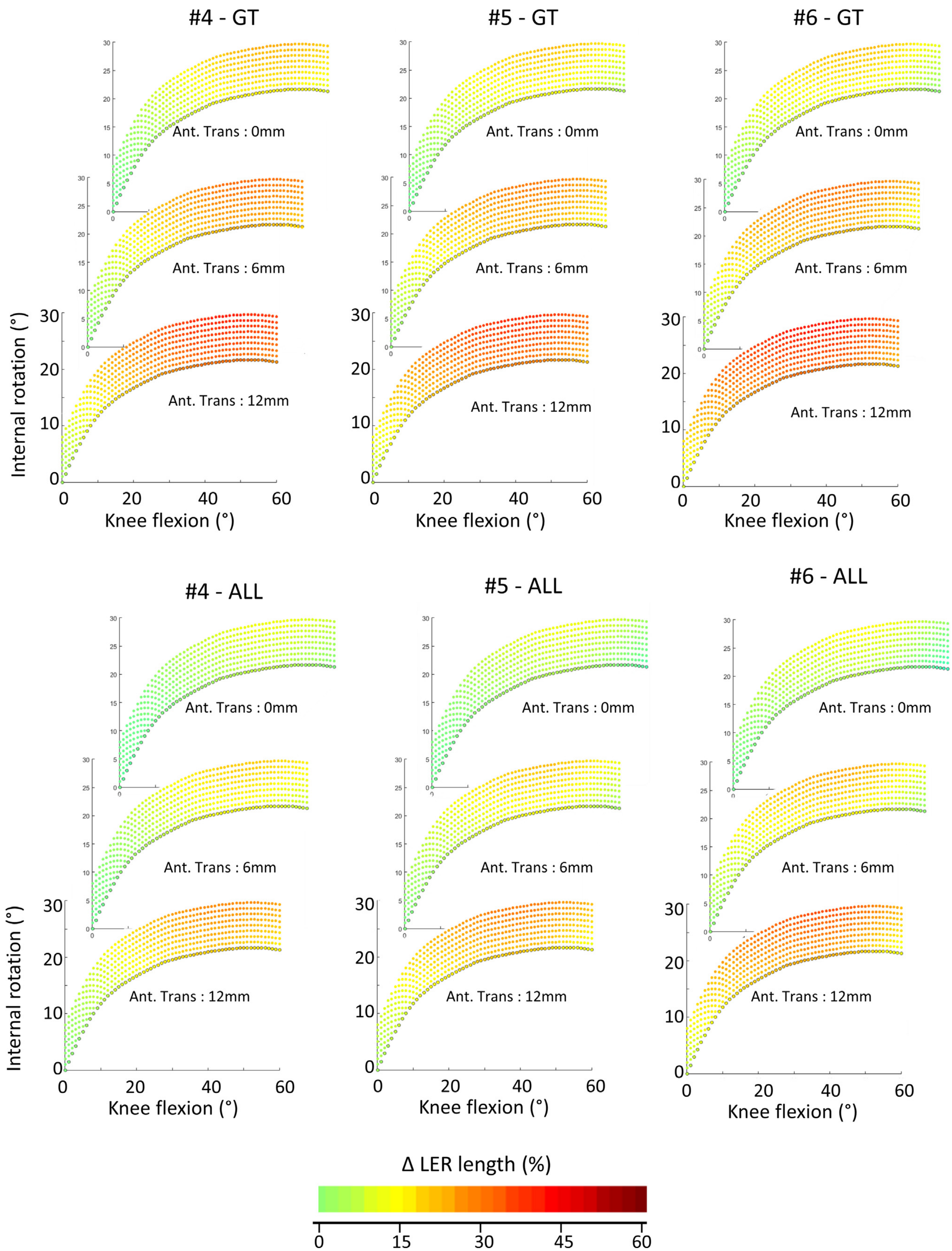

Fig. 4. LER length variation (red for tightened LER and green for relaxed LER) based on knee flexion and internal rotation when the tibia is anteriorly translated by 0 mm, 6 mm and 12 mm for three femoral tunnel positions (#4, #5 and #6) and two tibial tunnel positions (GT and ALL).

in this study. Nevertheless, the analysis performed in our study encompasses a large range of internal rotations and anterior translations; this should capture the kinematic variability that would have been observed in a larger cohort study. Similarly, the wide range of femoral LER tunnel positions evaluated captures interindividual variability in knee anatomy. The third limitation was that altered kinematics were simulated from published data, which may differ from the kinematics observed after ACL reconstruction. Once again, the wide range of kinematics tested should minimize this limitation. Lastly, only two tibial insertion points were tested. These were selected to represent the two most popular tibial tunnel locations in contemporary surgical practice [7,8].

5. Conclusion

Computer modeling allowed us to analyze the changes in LER tension for numerous knee positions corresponding to weightbearing knee flexion, and for the first time, to typical pivot-shift kinematics. During weightbearing knee flexion, placing the femoral tunnel proximal and posterior to the femoral epicondyle was associated with LER tightening in the early range of flexion and relaxation between 40 and 60° flexion. We found that a GT tibial tunnel position increases the risk of over-constraining the knee. Finally, LER tightening occurred during simulated pivot-shift scenarios. These findings confirm that surgeons may want to perform LER for patients with ACL rupture. When such surgery is performed, a posteroproximal femoral LER attachment site is recommended since it provides the desired behavior during both physiological knee flexion and altered knee kinematics.

Disclosure of interest

M. T., B. S. and A. S. are consultant for Arthrex.

The other authors declare that they have no competing interest.

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Contribution

Y. B. devised the study question; processed and analyzed the data; drafted the manuscript and approved the final version. B. K, R. D. and J. de G. performed the experiment; processed the data; reviewed and approved the final manuscript. A. S., B. S. and M. T. analyzed the data; reviewed and approved the final manuscript.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at: https://doi.org./10.1016/j.otsr.2019.02.020.

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