An in Vivo Simulation of Isometry of the Anterolateral Aspect of the Healthy Knee

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Background: To assess the isometry of theoretical lateral extra-articular reconstruction (LER), we evaluated theoretical grafts attached to various points on the lateral femoral condylar area and to either Gerdy's tubercle or the anatomic attachment site of the anterolateral ligament to the tibia.

Methods: In 18 subjects, healthy knees with no history of either injury or surgery involving the lower extremity were studied. The subjects performed a sit-to-stand motion (from approximately 90° of flexion to full extension), and each knee was studied using magnetic resonance and dual fluoroscopic imaging techniques. The 3-dimensional wrapping paths of each theoretical LER graft were measured. Grafts showing the least change in length during the sit-to-stand motion were considered to be the most isometric.

Results: The most isometric attachment site on the lateral femoral epicondyle to either of the studied tibial attachment sites was posterior-distal to the femoral attachment site of the fibular collateral ligament. The LER graft had a mean change in length of approximately 3%. Moving the femoral attachment site anteriorly resulted in increased length of the graft with increasing flexion; more posterior attachment sites resulted in decreased length with increasing flexion. Moving the attachment site in the proximal-distal direction had a less profound effect. Moving the tibial attachment site from Gerdy's tubercle to the tibial attachment site of the anterolateral ligament affected the overall isometric distribution on the lateral femoral epicondyle.

Conclusions: The most isometric attachment site on the femur for an LER would be posterior-distal to the femoral attachment site of the fibular collateral ligament. Different length changes for LER grafts were identified with respect to different femoral attachment sites. Desirable graft fixation locations for treating anterolateral rotatory instability were found posterior-proximal to the femoral fibular collateral ligament attachment.

Clinical Relevance: The present data could be used both in biomechanical studies and in clinical studies as guidelines for planning LER surgical procedures.

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Recent anatomic studies on the anterolateral aspect of the knee have created renewed interest in lateral extra-articular reconstruction (LER) of knees that have a torn anterior cruciate ligament (ACL)¹⁻⁵. Historically, the LER procedures were tried but were abandoned because of clinical failures⁶. However, an LER theoretically has appeal, as it is peripheral to the center of rotation of the knee and therefore has a lever arm to constrain excess rotatory laxity. The combined LER and intra-articular ACL reconstruction might

therefore be able to better control excessive internal rotation of knees and reduce intra-articular forces on ACL grafts. However, there are few data on the biomechanical behavior of these extra-articular reconstructions, especially with respect to isometry^{3,4,7-11}. Information on this behavior is clinically relevant, enabling proper placement of the graft.

In the in vitro setting, different femoral attachment sites were believed to result in isometric or desirable patterns in length changes^{3,7-11}. These different results in the cadaveric experiments

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may be explained by the variety of methods used. Tibiofemoral biomechanics are highly dependent on the muscle-loading conditions of the knee. Length changes between points are highly sensitive to minor shifts in position around the rotational axis of the femur¹². Even the most advanced in vitro experiments are limited by the difficulty in simulating the complex physiological loading conditions that occur during weight-bearing flexion of the knee¹³. Therefore, care should be taken when translating the in vitro biomechanical measurements during variable loading conditions to the results that would be seen in the knee during in vivo weight-bearing motion. Previously, we measured the theoretical length changes of the anterolateral ligament and 2 nonanatomic LERs during in vivo weight-bearing flexion^{14,15}. The anterolateral ligament was a nonisometric structure that showed a consistent length increase, up to 50%, from 0° to 90° of knee flexion. The nonanatomic LER showed length changes up to 15%. These results are promising and demonstrate the potential benefits of adding an LER to the intra-articular ACL reconstruction to better restore knee laxity and intra-articular graft forces. However, the most isometric point in vivo and most desirable

length changes in vivo remain unknown and could improve current surgical techniques.

Therefore, the purpose of this study was to determine the in vivo isometry between various femoral attachment sites and 2 tibial attachment sites: Gerdy's tubercle and the anterolateral ligament attachment. This isometry was determined in healthy subjects during a dynamic sit-to-stand weight-bearing motion.

Materials and Methods

Patient Selection

This study was approved by our institutional review board. Written consent was obtained from all subjects prior to participation in this study. In 18 subjects, healthy knees with no history of injury or surgery involving the lower extremity (12 male and 6 female subjects; mean age [and standard deviation], 35.4 ± 10.9 years; mean height, 175 ± 9 cm; mean weight, 83.3 ± 18.0 kg; and mean body mass index [BMI], 27 ± 3.5 kg/m²) were analyzed in the study. These subjects were included in our previous study on changes in the length of the anterolateral ligament¹⁵.

Imaging Procedures

The magnetic resonance imaging (MRI) and dual fluoroscopic imaging techniques for the measurement of ligament kinematics have been described in

Fig. 1

Fig. 2

Fig. 1 Lateral view of a 3D femoral model showing the distribution of the femoral attachment sites (dots). Various femoral attachment sites were connected to either Gerdy's tubercle or the tibial attachment site of the anterolateral ligament (midway between Gerdy's tubercle and the fibular head).

Fig. 2 Lateral view of a 3D femoral model in 90° of flexion. A 4 × 4 grid was applied to the lateral femoral epicondyle. A line extended along the posterior cortex of the distal femoral shaft was used as a landmark for the anterior border of the grid, and the PCOL formed the posterior border. The proximal and distal borders were formed by the proximal condylar cartilage border and the osseous femoral joint line, respectively. Distal to proximal: A to D. Anterior to posterior: 1 to 4. Line x: maximum distance perpendicular to the PCOL to the posterior edge of the lateral condyle. Line y: maximum distance from the proximal condylar cartilage border to the osseous femoral joint line. FCL = fibular collateral ligament.

Fig. 3
Heat map illustrating the isometry distribution (mean maximum percentage length change – minimum percentage length change) over the lateral femoral epicondyle for single point-to-point curves when connected to Gerdy's tubercle (GT) or the tibial attachment site of the anterolateral ligament (ALL) during the dynamic sit-to-stand motion. The circle on the femur represents the most isometric attachment site (a 2.2% length change for Gerdy's tubercle and a 3.3% length change for the tibial attachment site of the ALL).

detail previously^{16,17}. MRI scans of the knee joints were performed in the sagittal plane using a 3-T MRI scanner (MAGNETOM Trio; Siemens Healthcare) with a double-echo water-excitation sequence (thickness, 1 mm; resolution, 512×512 pixels)¹⁸. The images were then imported into solid-modeling software (Rhino; Robert McNeel & Associates) to construct 3-dimensional (3D) surface-mesh models of the tibia, fibula, and femur. The attachment sites of the fibular collateral ligament were identified as previously described and were included in the 3D model¹⁷.

After the MRI-based computer models were constructed, the knee of each subject was simultaneously imaged using 2 fluoroscopes (BV Pulsera; Philips) as the patient performed a sit-to-stand motion (from approximately 90° of flexion to full extension). Next, the fluoroscopic images were imported into solid-modeling software and placed in the imaging planes based on the projection geometry of the fluoroscopes during imaging of the patient. Finally, the 3D MRI-based knee model of each subject was imported into the software, viewed from the directions corresponding to the source of fluoroscopic radiation

Fig. 4
Normalized length changes in percentage of area (C1 [anterior], C2 [middle anterior], C3 [middle posterior], and C4 [posterior]) during the dynamic sit-to-stand motion when connected to Gerdy's tubercle (GT; left) or the tibial attachment site of the anterolateral ligament (ALL; right). The mean maximum flexion angle (MAX) was $88^\circ \pm 10^\circ$. Mean values are shown, with the shaded area indicating the 95% CI.

Fig. 5

Normalized length changes in percentage for healthy knees in the proximal-distal direction (A2 to D2) during the dynamic sit-to-stand motion. The mean maximum flexion angle (MAX) was $88^\circ \pm 10^\circ$. The dashed and solid lines represent the theoretical tibiofemoral grafts connected to Gerdy's tubercle (GT) and the tibial attachment site of the anterolateral ligament (ALL), respectively. Mean values are shown, with the shaded area indicating the 95% CI.

used to acquire the images, and independently manipulated in 6 degrees of freedom in the software until the projections of the model matched the outlines of the fluoroscopic images. When the projections best matched the outlines of the images taken during in vivo knee motion, the positions of the models were considered to be reproductions of the in vivo 3D positions of the knees. This system has errors of <0.1 mm and 0.3° in measuring tibiofemoral joint translations and rotations, respectively¹⁸⁻²⁰.

Tibial and Femoral Attachment Sites

To determine the in vivo lengths of theoretical LERs during motion, various femoral attachment sites and 2 tibial attachment sites—the center of Gerdy's tubercle and the anterolateral ligament attachment (midway between Gerdy's tubercle and the anterior margin of the fibular head)—were used^{21,22}. To account for the geometric variations between knees, all 3D knee models were scaled using the anteroposterior borders of the lateral femoral condyle to the

mean anteroposterior length (66.1 mm). Next, the right femoral models were mirrored to the left models with respect to the sagittal plane. Thereafter, the scaled and mirrored 3D models were aligned to find the best-fit position with respect to the lateral femoral condyle using a surface-to-surface registration method²³. This process resulted in a mean average error of 0.9 ± 0.3 mm between models. An average femoral model was constructed from the scaled, mirrored, and aligned 3D models. The average model was then used to construct a transepicondylar axis (connecting the medial and lateral femoral epicondyles)²⁴. The direction of the transepicondylar axis of the average 3D femoral model was used to project 156 femoral attachment points to the individual scaled, mirrored, and aligned 3D models. The region of interest for the femoral points was determined by the data from previously published in vitro studies^{4,7,9,10}. Approximately the posterior half of the lateral femoral epicondyle was used to project the points to the 3D model with 2.5 mm of spacing (Fig. 1). Once the femoral attachment points were determined on each femoral model,

Fig. 6

Desirable changes in graft length (tightness in extension and lower flexion angles, and not limiting the range of motion in deeper flexion) could be found in the posterior-proximal area of the lateral femoral epicondyle. Similar patterns in graft-length change were found with respect to the most isometric zone (areas C3-4 and D3-4 when connected to Gerdy's tubercle [GT; left] as well as C2-3 and D2-3 for the tibial attachment site of the anterolateral ligament [ALL; right]). The mean maximum flexion angle (MAX) was $88^\circ \pm 10^\circ$. Mean values are shown, with the shaded area indicating the 95% CI.

the scaled and mirrored 3D models with the projected attachment points were restored to the original coordinates for the measurement of individual graft lengths.

Length-Change Measurements

The length changes for each theoretical graft were measured as a function of knee flexion. The direct line connecting the femoral and tibial attachment points was projected on the osseous surfaces to create a curved line to avoid penetration of the connecting line through bone (a wrapping path). An optimization procedure was implemented to determine the projection angle to find the shortest 3D wrapping path at each flexion angle of the knee. This technique has been described in previous studies for measurement of ligament kinematics^{12,16,17}. The length of the projected line (curved around the osseous surfaces) was measured as the length of the ligament. For each subject, the length-change data were normalized to percentage change by using the reference length of each tibiofemoral graft from the relaxed, non-weight-bearing MRI position (MR): $(\text{length} - \text{length MR}) / \text{length MR} \times 100\%$.

A heat map was created to provide visual representation of the isometry distribution over the lateral femoral epicondyle by using the mean maximum percentage length change minus the mean minimum percentage length change of each theoretical tibiofemoral graft during the sit-to-stand motion.

Quadrant Method

A true lateral view of the femur was established at 90° of flexion. A 4×4 grid was applied to the lateral femoral epicondyle using a line extended along the posterior cortex of the distal femoral shaft and the posterior condylar offset line (PCOL). This technique has been used in other studies and was found to have intraobserver and interobserver reliabilities of 0.899 and 0.882, respectively²⁵. Next, lines perpendicular to the PCOL were drawn to the proximal condylar cartilage border and the osseous femoral joint line, and 3 lines were drawn in between to create an evenly distributed grid (Fig. 2). Similar to the intra-articular quadrant method developed by Bernard et al.²⁶, the current method used 4 distances, including condylar width perpendicular to the PCOL with the extended posterior cortex line as border (distance x), sagittal diameter along the PCOL (distance y), distance from the femoral attachment site to the anterior border along line x (distance Δx), and distance from the femoral attachment site to the proximal border along line y (distance Δy). Distances Δx and Δy were expressed as percentages of x and y.

Results

Isometric Point

The mean maximum observed flexion angle during the dynamic sit-to-stand motion was $88^\circ \pm 10^\circ$.

The most isometric femoral attachment site of the theoretical LER grafts that connected to Gerdy's tubercle was found to be posterior-distal to the femoral fibular collateral ligament attachment site; on average, it was 57% distal and 39% posterior, with a mean length change of 2.2% (95% confidence interval [CI], 1.8% to 2.6%).

When the LER was connected to the anterolateral ligament attachment, the most isometric femoral attachment site was found to be slightly more proximal-anterior to the point described above; on average, it was 50% distal and 31% posterior, with a mean length change of 3.3% (95% CI, 2.9% to 3.7%) (Fig. 3).

Posterior to the femoral fibular collateral ligament attachment site, a zone in the proximal-distal direction (the blue area on the femoral condyle in Figure 3) demonstrated the lowest percentage change in length during the sit-to-stand motion when connected to Gerdy's tubercle. When connected to the anterolateral ligament attachment, the most isometric zone had a slightly oblique direction from posterior-distal to proximal-anterior.

Femoral and Tibial Attachment Sites

Altering the femoral attachment site in the anterior-posterior direction affected the length changes, irrespective of the tibial attachment site (Fig. 4). The areas located anterior to the most isometric zone resulted in increased graft lengths with increased flexion angles; more posteriorly located areas resulted in decreased length with increased flexion. Moving the femoral attachment site in the proximal-distal direction had a less profound effect on the length changes (Fig. 5).

Moving the tibial attachment site from Gerdy's tubercle to the anterolateral ligament attachment changed the overall

isometric distribution on the lateral femoral epicondyle (Fig. 3). Comparable length changes could be found with respect to the most isometric zone (Fig. 6).

Graft Length Changes

LER grafts that exhibited the least change and a tight (long) graft during early knee flexion (from full extension to 45°) and a slack (short) state during deep knee flexion (from 45° to approximately 90°) were found in the posterior-proximal area: C3-4 and D3-4 for Gerdy's tubercle, and C2-3 and D3-4 (using the quadrant method) for the anterolateral ligament attachment (Fig. 6).

Discussion

The most important finding in this study was that the most isometric location for a theoretical LER graft on the lateral femoral epicondyle was posterior-distal to the femoral fibular collateral ligament attachment site. This was true for both of the tibial attachment sites studied, Gerdy's tubercle and the attachment site of the anterolateral ligament. A graft in this position underwent a length change of approximately 3% during approximately 90° of active knee flexion. A zone, mainly in the proximal-distal direction, was found to show the lowest percentage length change during motion from full extension to approximately 90° of flexion. On the basis of Figure 3, one might conclude that the most isometric femoral attachment site is in the region of the popliteus sulcus, and thus, an LER at this point might interfere with the popliteus tendon. Desirable length changes for LER, in which a tight graft in early knee flexion and a slackened graft in deep flexion were observed, were located in the posterior-proximal area of the lateral femoral epicondyle. Moving the tibial attachment site changed the overall isometry distribution on the lateral femoral epicondyle.

Several cadaveric studies have been published on the isometry of extra-articular reconstructions attached to the lateral femoral condyle^{3,4,7-9,11,27}. The findings of the current study are most consistent with those of the cadaveric studies by Draganich et al.¹⁰ and Ankri et al.²⁸, in which the most isometric point was posterior-distal with a mean length change of 2% to 6% and 4.3%, respectively. Similar to the authors of previous cadaveric studies^{10,28}, we found that the most isometric zone (demonstrating the least overall length change) was posterior to the fibular collateral ligament attachment site and ran mainly in the proximal-distal direction. Sidles et al.⁹ found the most isometric attachment site to be directly posterior to the fibular collateral ligament and the most isometric zone to be more posterior. These differences may be explained not only by the kinematic difference between in vitro and in vivo loading of the knee but also by the different way that their data were normalized ($[\text{maximum length} - \text{minimum length}] / [\text{maximum length} + \text{minimum length}]$); also, the wrapping effect of the tibiofemoral curves was not considered in their study. In the present study, moving the femoral attachment sites in the anterior direction caused changes in which increased flexion resulted in increased length, whereas more posteriorly located points

resulted in decreased length with increased flexion. This phenomenon is in agreement with findings of the most recent cadaveric studies by Imbert et al.³ and Katakura et al.¹¹, which measured the isometric characteristics and graft tension, respectively, of 3 different anterolateral ligament locations on the femur.

The rate of injury to the extra-articular structures of the knee at the time of the primary ACL tear has been found to be as high as 90%^{29,30}. It is thought that the combination of an intra-articular ACL tear with injury to anterolateral extra-articular structures might be responsible for the severe rotatory instabilities that can be seen in the clinic²⁹⁻³¹. Unaddressed injury to secondary stabilizers may put the knee at risk for persistent postoperative rotatory instability³² and consequently secondary injuries such as meniscal and chondral lesions, increased failure rates, and early cartilage degenerative changes. The combined LER and ACL reconstruction might be able to better restore anterolateral rotatory instability to normal in some patients³³ and improve the tensile strength of the reconstruction, decreasing excessive loads through the ACL graft^{27,34}, potentially protecting the ACL graft during the healing phase³⁵ and subsequently reducing graft failure and recurrence rates^{36,37}.

A minimum degree of isometry reduces the likelihood of unwanted graft behavior, such as graft stretching, failure, and overconstraint of the lateral compartment³⁸. In the normal knee, with increased knee flexion angles, internal tibial rotation also increases³⁹. Thus, a certain degree of isometry is necessary to reduce undesirable graft behavior, but a true isometric reconstruction technique might overconstrain the knee during deeper flexion angles. Therefore, the ideal LER would provide internal rotatory constraint in lower flexion angles, extension, and slacken at increased flexion angles. Hence, the nonisometric behavior of the anterolateral ligament, with its increased length at increased flexion angles makes it unsuitable for reconstruction. This unsuitability was recently confirmed in the study by Schon et al.⁴⁰, in which anterolateral ligament reconstruction overconstrained knee joint kinematics compared with the native knee at all fixation angles.

Functional length of the graft (determined by its proximal and distal fixation) is an important variable in any reconstruction. Stress-strain curves are characterized by a nonlinear toe region and a linear region. Long grafts have a greater elongation under the same load compared with short grafts for both nonlinear and linear regions; decreasing the length of a graft linearly increases its stiffness⁴¹. The fixation sites of the graft in LER determine the effective lengths of the graft and thus play an important role in the kinematic response of the knee.

The femoral attachment site directly affects the effective graft length and length changes that occur during knee motion. Moving the femoral attachment site in the anterior-posterior direction results in considerable length changes during motion, whereas alteration in proximal-distal direction has a less profound effect (Fig. 5). If one wanted to achieve a tight (long) graft in extension and a slack (short) graft in flexion, a femoral

location posterior-proximal to the fibular collateral ligament attachment would be chosen; to achieve a tight graft in increased flexion, a more anterior location would be chosen (Fig. 4). Moving the tibial attachment site changes the effective graft length and changes the isometry distribution. In addition, the tibial attachment site affects the angle of the graft vector. A more anterior tibial attachment site (e.g., Gerdy's tubercle) holds a mechanical advantage over a posterior site (e.g., the anterolateral ligament attachment) for limiting internal rotation.

There are several limitations to this study. Only data from healthy knees during 1 functional activity were used. Future research should also consider knees with a torn ACL and more demanding in vivo functional activities, such as lunging, walking, and running. No pivoting motion was performed in this study and, thus, the effect of rotational moments could not be assessed. Caution should be taken when translating the length changes as observed in this study to actual LER. No reconstruction was performed in the current study. Therefore, no actual restraint due to LER was present. Kinematics, and consequently length changes, could be altered if an LER had been performed. Finally, tunneling grafts deep to the fibular collateral ligament was not considered in this study.

Nevertheless, we believe that the findings of this study offer data that can be used to optimize LER techniques. Future studies should focus on the biomechanical effects of combining LER with ACL reconstruction and should investigate whether the most isometric graft, or a graft that is tight in extension and slack in flexion, would best restore laxity in a knee with a torn ACL.

In summary, the most isometric attachment site on the femur for an LER would be posterior-distal to the femoral

attachment site of the fibular collateral ligament. Moving the femoral attachment site anteriorly resulted in increased length of theoretical LERs with increased flexion, whereas more posteriorly attachments resulted in decreased length with increased flexion angles. Desirable graft-fixation locations, stabilizing the knee at low flexion angles but not overconstraining the knee at high flexion, were found posterior-proximal to the femoral fibular collateral ligament attachment. ■

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References

- Nitri M, Rasmussen MT, Williams BT, Moulton SG, Cruz RS, Dornan GJ, Goldsmith MT, LaPrade RF. An in vitro robotic assessment of the anterolateral ligament, part 2: anterolateral ligament reconstruction combined with anterior cruciate ligament reconstruction. *Am J Sports Med.* 2016 Feb 1 Mar;44(3):593-601. Epub 2016 Feb 1.
- Spencer L, Burkhart TA, Tran MN, Rezansoff AJ, Deo S, Catherine S, Getgood AM. Biomechanical analysis of simulated clinical testing and reconstruction of the anterolateral ligament of the knee. *Am J Sports Med.* 2015 Sep;43(9):2189-97. Epub 2015 Jun 19.
- Imbert P, Lutz C, Daggett M, Niglis L, Freychet B, Dalmay F, Sonnerly-Cottet B. Isometric characteristics of the anterolateral ligament of the knee: a cadaveric navigation study. *Arthroscopy.* 2016 Oct;32(10):2017-24. Epub 2016 May 4.
- Kittl C, Halewood C, Stephen JM, Gupte CM, Weiler A, Williams A, Amis AA. Length change patterns in the lateral extra-articular structures of the knee and related reconstructions. *Am J Sports Med.* 2015 Feb;43(2):354-62. Epub 2014 Dec 24.
- Rasmussen MT, Nitri M, Williams BT, Moulton SG, Cruz RS, Dornan GJ, Goldsmith MT, LaPrade RF. An in vitro robotic assessment of the anterolateral ligament, part 1: secondary role of the anterolateral ligament in the setting of an anterior cruciate ligament injury. *Am J Sports Med.* 2016 Mar;44(3):585-92. Epub 2015 Dec 18.
- Pearle A, Bergfeld J. Extraarticular reconstruction in the anterior cruciate ligament deficient knee. Chicago: Human Kinetics; 1992.
- Krackow KA, Brooks RL. Optimization of knee ligament position for lateral extraarticular reconstruction. *Am J Sports Med.* 1983 Sep-Oct;11(5):293-302.
- Kurosawa H, Yasuda K, Yamakoshi K, Kamiya A, Kaneda K. An experimental evaluation of isometric placement for extraarticular reconstructions of the anterior cruciate ligament. *Am J Sports Med.* 1991 Jul-Aug;19(4):384-8.
- Sidles JA, Larson RV, Garbini JL, Downey DJ, Matsen FA 3rd. Ligament length relationships in the moving knee. *J Orthop Res.* 1988;6(4):593-610.
- Draganich LF, Hsieh YF, Reider B. Iliotibial band tenodesis: a new strategy for attachment. *Am J Sports Med.* 1995 Mar-Apr;23(2):186-95.
- Katakura M, Koga H, Nakamura K, Sekiya I, Muneta T. Effects of different femoral tunnel positions on tension changes in anterolateral ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc.* 2016 May 25. [Epub ahead of print].
- Park SE, DeFrate LE, Suggs JF, Gill TJ, Rubash HE, Li G. The change in length of the medial and lateral collateral ligaments during in vivo knee flexion. *Knee.* 2005 Oct;12(5):377-82.
- Van de Velde SK, Gill TJ, Li G. Evaluation of kinematics of anterior cruciate ligament-deficient knees with use of advanced imaging techniques, three-dimensional modeling techniques, and robotics. *J Bone Joint Surg Am.* 2009 Feb;91(Suppl 1):108-14. Epub 2009 Feb 21.
- Van de Velde SK, Kernkamp WA, Hosseini A, LaPrade RF, van Arkel ER, Li G. In vivo length changes of the anterolateral ligament and related extra-articular reconstructions. *Am J Sports Med.* 2016 Jun 23 Oct;44(10):2557-62. Epub 2016 Jun 23.
- Kernkamp WA, Van de Velde SK, Hosseini A, Tsai TY, Li JS, van Arkel ER, Li G. In vivo anterolateral ligament length change in the healthy knee during functional activities—a combined magnetic resonance and dual fluoroscopic imaging analysis. *Arthroscopy.* 2017 Jan;33(1):133-9. Epub 2016 Sep 20.
- Kozanek M, Fu EC, Van de Velde SK, Gill TJ, Li G. Posterolateral structures of the knee in posterior cruciate ligament deficiency. *Am J Sports Med.* 2009 Mar;37(3):534-41. Epub 2008 Dec 16.
- Van de Velde SK, DeFrate LE, Gill TJ, Moses JM, Papannagari R, Li G. The effect of anterior cruciate ligament deficiency on the in vivo elongation of the medial and lateral collateral ligaments. *Am J Sports Med.* 2007 Feb;35(2):294-300.

18. DeFrate LE, Papannagari R, Gill TJ, Moses JM, Pathare NP, Li G. The 6 degrees of freedom kinematics of the knee after anterior cruciate ligament deficiency: an in vivo imaging analysis. *Am J Sports Med.* 2006 Aug;34(8):1240-6.
19. Li G, Van de Velde SK, Bingham JT. Validation of a non-invasive fluoroscopic imaging technique for the measurement of dynamic knee joint motion. *J Biomech.* 2008;41(7):1616-22. Epub 2008 Apr 3.
20. Li G, Wuerz TH, DeFrate LE. Feasibility of using orthogonal fluoroscopic images to measure in vivo joint kinematics. *J Biomech Eng.* 2004 Apr;126(2):314-8.
21. Claes S, Vereecke E, Maes M, Victor J, Verdonk P, Bellemans J. Anatomy of the anterolateral ligament of the knee. *J Anat.* 2013 Oct;223(4):321-8. Epub 2013 Aug 1.
22. Kennedy MI, Claes S, Fuso FA, Williams BT, Goldsmith MT, Turnbull TL, Wijdicks CA, LaPrade RF. The anterolateral ligament: an anatomic, radiographic, and biomechanical analysis. *Am J Sports Med.* 2015 Jul;43(7):1606-15. Epub 2015 Apr 17.
23. Tsai TY, Dimitriou D, Li G, Kwon YM. Does total hip arthroplasty restore native hip anatomy? Three-dimensional reconstruction analysis. *Int Orthop.* 2014 Aug;38(8):1577-83. Epub 2014 Jun 26.
24. Most E, Axe J, Rubash H, Li G. Sensitivity of the knee joint kinematics calculation to selection of flexion axes. *J Biomech.* 2004 Nov;37(11):1743-8.
25. Johal P, Hassaballa MA, Eldridge JD, Porteous AJ. The posterior condylar offset ratio. *Knee.* 2012 Dec;19(6):843-5. Epub 2012 Jun 7.
26. Bernard M, Hertel P, Homung H, Cierpinski T. Femoral insertion of the ACL. Radiographic quadrant method. *Am J Knee Surg.* 1997 Winter;10(1):14-21; discussion 21-2.
27. Draganich LF, Reider B, Ling M, Samuelson M. An in vitro study of an intra-articular and extraarticular reconstruction in the anterior cruciate ligament deficient knee. *Am J Sports Med.* 1990 May-Jun;18(3):262-6.
28. Ankri M, Khiami F, Rochcongar G, Joubert T, Pillet H, Thoreux P, Rouch P. Isometric point of lateral femoral condyle analysis with in vitro kinematic study in order to position the extra-articular part of an ACL reconstruction. *Comput Methods Biomech Biomed Engin.* 2015 Aug 6:1-2. Epub 2015 Aug 6.
29. Ferretti A, Monaco E, Fabbri M, Maestri B, De Carli A. Prevalence and classification of injuries of anterolateral complex in acute anterior cruciate ligament tears. *Arthroscopy.* 2017 Jan;33(1):147-54. Epub 2016 Jun 21.
30. Terry GC, Norwood LA, Hughston JC, Caldwell KM. How iliotibial tract injuries of the knee combine with acute anterior cruciate ligament tears to influence abnormal anterior tibial displacement. *Am J Sports Med.* 1993 Jan-Feb;21(1):55-60.
31. Monaco E, Ferretti A, Labianca L, Maestri B, Speranza A, Kelly MJ, D'Arrigo C. Navigated knee kinematics after cutting of the ACL and its secondary restraint. *Knee Surg Sports Traumatol Arthrosc.* 2012 May;20(5):870-7. Epub 2011 Aug 30.
32. Kamath GV, Redfern JC, Greis PE, Burks RT. Revision anterior cruciate ligament reconstruction. *Am J Sports Med.* 2011 Jan;39(1):199-217. Epub 2010 Aug 13.
33. Zantop T, Schumacher T, Schanz S, Raschke MJ, Petersen W. Double-bundle reconstruction cannot restore intact knee kinematics in the ACL/LCL-deficient knee. *Arch Orthop Trauma Surg.* 2010 Aug;130(8):1019-26. Epub 2010 Mar 9.
34. Engebretsen L, Lew WD, Lewis JL, Hunter RE. The effect of an iliotibial tenodesis on intraarticular graft forces and knee joint motion. *Am J Sports Med.* 1990 Mar-Apr;18(2):169-76.
35. Dodds AL, Gupte CM, Neyret P, Williams AM, Amis AA. Extra-articular techniques in anterior cruciate ligament reconstruction: a literature review. *J Bone Joint Surg Br.* 2011 Nov;93(11):1440-8. Epub 2011 Nov 8.
36. Ferretti A, Monaco E, Ponzio A, Basiglini L, Iorio R, Caperna L, Contedua F. Combined intra-articular and extra-articular reconstruction in anterior cruciate ligament-deficient knee: 25 years later. *Arthroscopy.* 2016 May 4 Oct;32(10):2039-47. Epub 2016 May 4.
37. Marcacci M, Zaffagnini S, Giordano G, Iacono F, Presti ML. Anterior cruciate ligament reconstruction associated with extra-articular tenodesis: a prospective clinical and radiographic evaluation with 10- to 13-year follow-up. *Am J Sports Med.* 2009 Apr;37(4):707-14. Epub 2009 Feb 3.
38. Amis AA, Zavras TD. Isometricity and graft placement during anterior cruciate ligament reconstruction. *Knee.* 1995;2(1):5-17.
39. Qi W, Hosseini A, Tsai TY, Li JS, Rubash HE, Li G. In vivo kinematics of the knee during weight bearing high flexion. *J Biomech.* 2013 May 31;46(9):1576-82. Epub 2013 Apr 13.
40. Schon JM, Moatshe G, Brady AW, Serra Cruz R, Chahla J, Dornan GJ, Turnbull TL, Engebretsen L, LaPrade RF. Anatomic anterolateral ligament reconstruction of the knee leads to overconstraint at any fixation angle. *Am J Sports Med.* 2016 Jul 12 Oct;44(10):2546-56. Epub 2016 Jul 12.
41. DeFrate LE, van der Ven A, Gill TJ, Li G. The effect of length on the structural properties of an Achilles tendon graft as used in posterior cruciate ligament reconstruction. *Am J Sports Med.* 2004 Jun;32(4):993-7.