Published in final edited form as:

J Biomech. 2011 July 7; 44(10): 1914–1920. doi:10.1016/j.jbiomech.2011.04.030.

The effect of femoral tunnel placement on ACL graft orientation and length during in vivo knee flexion

Ermias S. Abebe¹, Jong-Pil Kim¹, Gangadhar M. Utturkar¹, Dean C. Taylor¹, Charles E. Spritzer², Claude T. Moorman¹, William E. Garrett¹, and Louis E. DeFrate¹

¹Sports Medicine Center, Department of Orthopaedics, Duke University, Durham NC

²Department of Radiology, Duke University, Durham NC

Abstract

Anatomically placed grafts are believed to more closely restore the function of the ACL. This study measured the effect of femoral tunnel placement on graft orientation and length during weight-bearing flexion. Both knees of twelve patients where the graft was placed near the anteroproximal border of the ACL and ten where the graft was placed near the center of the ACL were imaged using MR. These images were used to create 3D models of the reconstructed and intact contralateral knees, including the attachment sites of the native ACL and graft. Next, patients were imaged using biplanar fluoroscopy while performing a quasi-static lunge. The models were registered to the fluoroscopic images to reproduce in vivo knee motion. From the relative motion of the attachment sites on the models, the length and orientation of the graft and native ACL were measured. Grafts placed anteroproximally on the femur were longer and more vertical than the native ACL in both the sagittal and coronal planes, while anatomically placed grafts more closely mimicked ACL motion. In full extension, the grafts placed anteroproximally were $12.3 \pm 5.2^\circ$ (mean and 95%CI) more vertical than the native ACL in the sagittal plane, whereas the grafts placed anatomically were $2.9 \pm 3.7^\circ$ less vertical. Grafts placed anteroproximally were up to 6 ± 2 mm longer than the native ACL, while the anatomically placed grafts were a maximum of 2 ± 2 mm longer. In conclusion, grafts placed anatomically more closely restored native ACL length and orientation. As a result, anatomic grafts are more likely to restore intact knee kinematics.

1. Introduction

The oblique course of the anterior cruciate ligament (ACL) allows it to constrain tibiofemoral motion during complex in vivo loading (Zhang 2003; Scopp 2004). ACL rupture can destabilize the knee, resulting in abnormal joint kinematics (Georgoulis 2003; Logan 2004; Andriacchi 2005; Andriacchi 2006; Defrate 2006; Gao 2010). Although ACL reconstruction results in good short term results, recent postoperative studies suggest that the ability of ACL reconstruction to protect long-term joint health is limited (Fink 2001;

© 2011 Elsevier Ltd. All rights reserved.

Correspondence to: Louis E. DeFrate, Ph.D., Orthopaedic Bioengineering Laboratory, Department of Orthopaedics, Box 3093, Duke University Medical Center, Durham, NC 27710.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Conflict of Interest

Arthrex provided research support to Duke University Medical Center.

Lohmander 2004; Fithian 2005). While many factors likely contribute to the development of osteoarthritis following ACL injury or reconstruction, abnormal kinematics are believed to have an important role in contributing to joint degeneration (Georgoulis 2003; Logan 2004; Tashman 2004; Andriacchi 2005; Li 2006; Tashman 2007; Abebe 2011).

One important variable in restoring normal knee function after ACL reconstruction has been thought to be the placement of the ACL graft (Amis 1998; Ahn 2007; Harner 2008; Steiner 2008; Scanlan 2009; Kopf 2010; Markolf 2010; Abebe 2011). In particular, past studies have investigated the ability of reconstruction techniques to place the graft in its anatomic position on the femur, with anteroproximal placement of the graft being a major concern (Arnold 2001; Kaseta 2008; Steiner 2008; Abebe 2009). Previous cadaver studies suggest that graft placement closer to the anatomical footprint on the femur more closely restores native knee kinematics (Loh 2003; Scopp 2004; Yamamoto 2004).

Although graft placement has been studied extensively (Giron 1999; Arnold 2001; Kaseta 2008; Pearle 2008; Brophy 2009; Steiner 2009), there is a limited understanding of the influence of femoral tunnel placement on in vivo ACL graft function under weight-bearing loading conditions. Given the importance of the ACL in stabilizing knee motion (Sakane 1997; Bull 1999; Georgoulis 2003; Andriacchi 2006; Markolf 2009), there is a need for understanding how femoral tunnel placement affects the ability of a graft to restore the orientation and length of the native ACL.

A recent patient study from our laboratory quantified femoral tunnel placement in two different patient populations using MR imaging 3D modeling techniques (Abebe 2009). In one group, the graft was placed using a transtibial technique, resulting in placement an average of 9mm from the center of the ACL near its anteroproximal border, and in the other, the graft was placed independently of the tibial tunnel, an average of 3mm from the center of the femoral attachment of the ACL. The objective of this study was to use biplanar fluoroscopic and MR imaging techniques to evaluate the effect of graft placement on the ability of a reconstruction to reproduce native ACL orientation and length in these patients under weight-bearing loading. We hypothesized that the more anatomically positioned grafts will more closely restore the native ACL orientation and length compared to grafts placed anteroproximally on the femur.

2. Materials and Methods

Patient Recruitment and Inclusion Criteria

Institutional Review Board (IRB) approval was obtained prior to initiation of this study. Twenty two patients (16 men and 6 women, 19–49 years old) with unilateral ACL reconstruction were recruited from the clinics of two surgeons at our sports medicine center. Subjects were recruited retrospectively between 6 and 36 months post-reconstruction. All subjects completed the same rehabilitation protocols at the Duke University Sports Medicine within a six month period. Initially, chart reviews were performed to identify potential candidates meeting the recruitment criteria. Those with varus-valgus deformity, osteoarthritis, articular cartilage defects, meniscus injury, or any history of trauma or surgery to either knee were excluded. Because it is difficult to recruit subjects with ACL injury and without mensical tears, patients with minor tears of the meniscus (requiring removal of less than 10% of the meniscus) in the operative knee were included in the study. All patients had stable knees under Lachman and pivot shift examinations. At the time of the study, all patients were doing well and had returned to sports activity without restriction. All patients meeting the recruitment criteria were sorted by operative date, and invited in chronological order to participate.

Twelve (9 men, 3 women; mean age: 32 years; mean follow-up: 20 months) received a procedure performed by one surgeon resulting in anteroproximal placement of the graft on the femur, and 10 (7 men, 3 women; mean age: 30 years; mean follow-up: 18 months) received a procedure from another surgeon resulting in anatomic graft placement (Abebe 2011). Since publication of our previous study on graft placement (Abebe 2009), four additional subjects were recruited into the anteroproximal group, and two additional subjects were recruited into the anatomic placement group. Graft placement in these additional subjects was consistent with that reported previously, with the anatomic placement an average of 3mm from the center of the ACL, and the anteroproximal grafts an average of 9mm from the center of the ACL.

Surgical Techniques

Anteroproximal graft placement—After diagnostic arthroscopy was performed to confirm ACL injury, the tibial tunnel was placed using a Concept Precision guide pin (ConMed Linvatec, Largo, FL). The guide was placed in approximately 57° in the sagittal plane and 65° in the coronal plane (Howell 2001; Simmons 2003; Abebe 2009). The tibial tunnel was centered approximately 7mm anterior to the PCL, and passed through the anterior fibers of the MCL. Each tibial tunnel was reamed with a reamer equal in size to the graft diameter used in the procedure. The tibial tunnel location was aimed to allow placement of a 7mm offset guide at approximately the 1:30 position or the 10:30 position. A cannulated reamer was then passed through the tibial tunnel and over the guide pin to create the femoral socket. Notchplasty, when performed, was limited to the anterior portion of the notch, and did not alter the femoral attachment site. Six patients received hamstring grafts, while six had patellar tendon grafts. Patellar tendon grafts ranged from 9 to 10mm in diameter, and hamstrings grafts ranged from 8 to 9mm in diameter. Five patients had intact menisci, and the remaining seven had tears requiring removal of less than 10% of the meniscus (five lateral and two medial).

Anatomic graft placement—Diagnostic arthroscopy was performed to confirm ACL injury. The location and shape of the ACL footprint was identified through the anteromedial and anterolateral portals. A guidepin was placed through the center of the tibial footprint of the ACL. A graft-size-appropriate cannulated reamer was used to create the tibial tunnel. Using the anteromedial portal, the femoral tunnel was placed by positioning the guide (Retro-Drill, Arthrex, Naples, FL) near the center of the ACL footprint, as estimated visually by the surgeon (Kaseta 2008; Wittstein 2009). A guide-pin was placed from outside the joint through a small incision over the lateral femoral cortex just proximal to the lateral femoral condyle and anterior to the intermuscular septum. The guide pin was drilled through the femur to the tip of the aiming guide (Kaseta 2008; Abebe 2009). The pin was threaded to allow the placement of a cutter of the appropriate size on the guide pin as it entered the joint through the femoral ACL footprint. The cutter cut a socket into the femur to the desired depth. No notchplasty was performed. In the anatomic group, all patients received hamstrings grafts ranging from 7.5 to 9mm in diameter. Four patients had intact menisci, and the remaining six had tears requiring removal of less than 10% of the meniscus (three lateral and three medial).

MRI-based modeling

Each subject's operative and intact knees were imaged using a 3T magnet (Siemens, Trio Tim) at the Center for Advanced Magnetic Resonance Development. Coronal, sagittal, and axial images were acquired with the patient in a supine and relaxed position using a double-echo steady state sequence (DESS, field of view: 15×15cm, matrix: 512×512pixels, slice thickness: 1mm, flip angle: 25°, TR: 17ms, TE: 6ms) and an 8 channel receive-only coil. Total scan time was approximately 27 minutes for each knee.

Next, the contours of each subject's femurs, tibias, ACL attachments on the intact knee, and tunnels on the reconstructed knee were manually traced within each coronal, axial, and sagittal plane image using solid-modeling software (Rhinoceros, Robert McNeel and Associates, Seattle, WA). Orthogonal image sets were used to confirm the position of the ACL and tunnel attachment sites to within 0.3mm (Abebe 2009). From these data, models of each subject's intact and operative knee were created, including the location of the ACL and graft attachment sites (Figure 1).

Fluoroscopic imaging

Next, each subject's knees were centered within the beams of two orthogonally positioned fluoroscopes (Pulsera, Philips, The Netherlands) and individually imaged (Abebe 2011). Subjects stood on a level platform and performed a quasi-static single leg lunge while supporting their body weight within the beams of both fluoroscopes (Figure 1). Patients were instructed to flex from 0 to 90° in increments of 15° while orthogonal images were obtained of their knees (resolution: 1024×1024 pixels). The patients were given verbal feedback by a member of the research staff, who monitored flexion using a handheld goniometer. The subjects held their position for approximately 1s as the fluoroscopes recorded the images.

Measurement of ACL and graft length and orientation

Each pair of orthogonal fluoroscopic images was imported into the solid modeling software and positioned in 3D based on the geometry of the fluoroscopes during testing. Edge detection software was then used to outline the bones on the fluoroscopic images (Abebe 2011). Next, the 3D MR knee models were imported into the solid modeling software. Each tibial and femoral model was manipulated in six degrees-of-freedom until its projection, as viewed from the two orthogonal directions, matched the outlines on the fluoroscopic images. Previous studies have shown that this system can reproduce joint motion to within 0.1mm and 0.3° (DeFrate 2006; Caputo 2009).

The orthogonal images and the 3D knee models were used to reproduce the in vivo length and orientation of each subject's graft and native ACL (Figure 2). Left tibia models were registered to right tibia models using the iterative closest point technique (Abebe 2009), so that the length and orientation of the ACL and graft could be measured relative to the same coordinate system. From these models, coronal and sagittal plane angles (Figure 3) and graft lengths were quantified for both the graft and native ACL for all subjects at the targeted flexion angles between 0° and 90° of flexion. ACL length was defined as the length of the line connecting the geometric centers of the femoral and tibial attachments (DeFrate 2004). The sagittal plane angle was defined as the angle between the plane perpendicular to the long shaft of the tibia and the projection of the ACL on the sagittal plane. The coronal plane angle was defined as the angle between the plane perpendicular to the long shaft of the tibia and the projection of the ACL on the coronal plane.

A three way ANOVA with graft placement (anatomic versus anteroproximal) as a categorical predictor and knee state (intact versus reconstructed) and flexion angle as repeated measures was used with Tukey post-hoc tests to determine differences between means (Statistica, StatSoft, Tulsa, OK). In addition, the respective differences in length and orientation between the native ACL and anatomic and anteroproximal grafts were averaged across all flexion angles and compared using a t-test. Differences were considered statistically significant where $p < 0.05$.

Validation of Bilateral Symmetry in Normal Subjects

In this study, symmetry in the length and orientation of the ACL bilaterally is assumed. Therefore, we conducted a validation study comparing the bilateral differences in orientation and length of the ACL in five male subjects with no history of knee injury (average age 25.5 years). Using the methodology described above, MR-based models of the left and right knee joints and attachment sites of the ACL were created and registered using an iterative closest point technique. From these models, the bilateral differences in coronal and sagittal plane angles and ACL lengths were quantified.

3. Results

Our validation study indicated that the absolute value of the bilateral differences in the ACLs of normal subjects were $2.2 \pm 2.4^\circ$, $2.0 \pm 1.3^\circ$, and $1.0 \pm 0.7\text{mm}$ (mean and 95%CI) in sagittal plane angle, coronal plane angle, and ACL length, respectively.

In the sagittal plane angle (Figure 4), there was a statistically significant interaction between flexion angle, knee state, and graft placement ($p=0.005$). Grafts placed anterop proximally on the femur were more vertically oriented than the native ACL from 0 to 60° of flexion ($p<0.01$, Figure 4). No statistically significant differences were detected in the sagittal plane angles of grafts placed anatomically and the native ACL between 0 and 90° ($p>0.10$). A power analysis performed using statistical software (Lenth 2009) indicated that these data have more than 90% power in detecting differences of 7° in sagittal plane angle. At full extension, the grafts placed anterop proximally were $12.3 \pm 5.2^\circ$ (mean and 95% confidence interval) more vertical than native ACL in the sagittal plane ($p=0.001$), whereas the anatomically placed grafts were $2.9 \pm 3.7^\circ$ less vertical than the native ACL ($p=0.6$). Averaged across all flexion angles, the anatomic grafts were $3.3 \pm 1.9^\circ$ less vertical than the native ACL, while anterop proximal grafts were $7.3 \pm 1.8^\circ$ more vertical than the native ACL ($p<0.001$).

In the coronal plane angle (Figure 5), there was a statistically significant interaction between flexion angle, knee state, and graft placement ($p=0.008$). Grafts placed anterop proximally placed were more vertical than the native ACL between 30 and 90° of flexion ($p<0.03$, Figure 5). No statistically significant differences in coronal plane angle were observed between the grafts placed anatomically and the native ACL between 0 and 90° of flexion ($p>0.3$). These data have more than 90% power in detecting differences of 4° in the coronal plane angle. At 60° of flexion, the grafts placed anterop proximally were $5.4 \pm 5.3^\circ$ more vertical than the native ACL ($p<0.001$), while the anatomically placed grafts were $3.4 \pm 4.8^\circ$ less vertical than the native ACL ($p=0.3$). Averaged across all flexion angles, anatomic grafts were $1.9 \pm 1.6^\circ$ less vertical than the native ACL, while the anterop proximal grafts were $3.8 \pm 1.8^\circ$ more vertical than the native ACL ($p<0.001$).

With regard to length (Figure 6), there was a statistically significant interaction between flexion angle, knee state, and graft placement ($p=0.008$). Grafts placed anterop proximally were longer than the native ACL at all flexion angles ($p<0.001$). Grafts placed anatomically were longer than the native ACL at all flexion angles except 15 and 45° ($p<0.01$). Averaged across all flexion angles, the anterop proximally placed grafts were $5.6 \pm 0.6\text{mm}$ longer than the native ACL, which was significantly greater than the difference of $2.1 \pm 0.5\text{mm}$ for the anatomic group ($p<0.001$).

4. Discussion

Achieving anatomic femoral tunnel placement remains a concern in ACL reconstruction (Kaseta 2008; Steiner 2008; Abebe 2009; Kopf 2010; Marchant 2010; Scanlan 2010).

Currently, there are few data available on the influence of femoral tunnel placement on ACL graft length and orientation in patients during in vivo weight-bearing activities. The present study used fluoroscopic and MR imaging to quantify the effect of femoral graft placement on the change in length and orientation of the reconstructed ACL relative to the contralateral native ACL. A validated MR imaging technique (Abebe 2009) indicated that the femoral tunnel placement in the anteroproximal placement group was an average of 9mm from the ACL center, and an average of 3mm from the ACL center in the anatomic group. Therefore, we hypothesized that the anatomic femoral tunnel placement would more closely mimic native ACL length and orientation during in vivo weight-bearing flexion compared to the anteroproximal placement.

Our data demonstrate that the ACL grafts placed anteroproximally on the femur were longer and more vertically oriented in the sagittal and coronal planes compared to the contralateral native ACL under physiological loading conditions. In contrast, grafts placed anatomically on the femur more closely mimicked native ACL length and orientation. Recent studies suggest that in order to restore normal knee function, the ACL reconstruction should recreate the anatomy and force vector of the native ACL (Loh 2003; Scopp 2004; Yamamoto 2004; Li 2006; Brophy 2009). A recent study in the same patients as the present study supports this assumption by demonstrating that anatomically placed grafts more closely restored anterior translation, internal rotation, and medial translation when compared to the grafts placed anteroproximally (Abebe 2011). Abnormal knee function after ACL injury has been thought to predispose the knee to degenerative changes (Tashman 2004; Andriacchi 2005; Andriacchi 2006; Li 2006; Tashman 2007; Van De Velde 2009).

Femoral malpositioning of the ACL graft can potentially result in altered ACL force vectors. Vertical grafts in the sagittal plane have been thought to result in increased anterior translation compared to the native ACL (Li 2006; Brophy 2009). A more vertical sagittal plane orientation, as measured in the anteroproximal placement group in the present study, requires higher ACL graft forces to reproduce the same anterior force component as the native ACL (Li 2006). Therefore, a vertical graft is likely to resist anterior loads less efficiently than the native ACL, as demonstrated by the increased anterior translation observed in these patients (Abebe 2011). Conversely, the oblique sagittal plane placement achieved in the anatomic placement group is more closely reproduces native anteroposterior translation (Abebe 2011).

Additionally, a vertical graft orientation is likely to provide less restraint to other motions in the transverse plane. Previous cadaver studies have shown that more vertical grafts in the coronal plane are biomechanically disadvantageous for controlling rotational stability (Loh 2003; Scopp 2004; Yamamoto 2004). A vertical graft in the coronal plane is also likely to provide insufficient restraint to the increased mediolateral translation observed with ACL deficiency (Defratre 2006). In the present study, as a result of their more vertical grafts, the grafts placed anteroproximally would be expected to be less efficient at constraining internal rotation and medial translation. These results have been confirmed by a kinematic study performed in our laboratory reporting increased internal rotation and medial translation in the anteroproximal graft placement group, while anatomically placed grafts more closely restored normal tibiofemoral motion (Abebe 2011).

In our study, the ACL graft length produced with the anteroproximal graft placement was as high as 6mm longer than the native ACL. In contrast, anatomical placement resulted in graft lengths that were a maximum of 2mm longer than native ACL at all flexion angles. The increased graft lengths observed with anteroproximal graft placement might be a result of the increased anterior translation observed in these patients (Abebe 2011). Previous studies

have also suggested that more vertical grafts might increase anterior knee laxity (Li 2006; Pinczewski 2008; Steiner 2009).

Clinically, patients with more anatomically placed grafts are thought to have better long-term clinical outcomes than patients with more vertical grafts (Harner 2001; Jepsen 2007; Moisala 2007; Pinczewski 2008). For example, a recent study reported that grafts with more posterior placement had higher Lysholm scores compared to patients with more anterior graft placement (Moisala 2007). Another recent study in patients with ACL reconstructions reported an association between a more vertical graft in the coronal plane with a higher degree of radiographic osteoarthritis (Pinczewski 2008). Together, these results might suggest that grafts placed more anatomically more closely restore normal ACL orientation and length and hence, normal knee function. However, additional studies are needed to determine the relationship between 3D graft placement relative to the native ACL footprint and long term outcomes after ACL reconstruction.

There are some limitations with the present study. First, the reconstructions were performed by two different surgeons. However, if the same surgeon were to use two different techniques, the technique with which the surgeon was most familiar would be biased. Therefore, we had two different surgeons perform their preferred technique, which resulted in distinct anteroproximal and anatomic graft placement groups (Abebe 2009). Another limitation is that six patients in the anteroproximal graft placement group received hamstring grafts, and six received patellar tendon grafts, while those that had anatomically placed grafts all received hamstring grafts. This was due to difficulties recruiting subjects that met all of the recruitment criteria and differences in the graft types used by the surgeons. A subgroup analysis was unable to detect differences in the behavior between these two graft types. Future study evaluating the interactions between graft type and graft placement in a larger sample size is warranted. However, regardless of graft type, achieving anatomic graft placement is likely to be important to restoring the orientation and length of the native ACL. Finally, our study only investigated one quasi-static loading condition. Future studies should investigate graft length and orientation under other in vivo loading conditions.

In conclusion, this study investigated the effect of femoral placement on the ability of a reconstruction to reproduce native ACL motion during weight-bearing flexion in patients. The anatomically placed grafts more closely reproduced the orientation of the native ACL compared to grafts placed anteroproximally, which were more vertical than the native ACL. Although both anatomic and anteroproximal grafts were longer than the native ACL, anatomic grafts more closely restored native ACL length. Our findings suggest that, regardless of the technique used to reconstruct the ACL, anatomic graft placement is likely critical to reproducing native ACL force vectors and therefore knee kinematics in 6 degrees-of-freedom (Abebe 2011). Reproducing normal knee function is likely important to reducing the incidence of degenerative changes after ACL injury.

Acknowledgments

This work was supported by the National Institutes of Health (Grant No. R03AR055659) and a grant from the National Football League Charities. Ermias Abebe was supported by a Doris Duke Clinical Research Fellowship. We also gratefully acknowledge the financial support of the Department of Orthopaedics and the Department of Radiology at Duke University Medical Center. We would also like to thank Farshid Guilak, PhD, Holly A. Leddy, PhD, and Steven W. Marshall, PhD for helpful comments regarding this work and Libby Pennington, Kevin A. Taylor, and Daniel M. Brown for technical support.

References

- Abebe ES, Moorman CT 3rd, Dziedzic TS, Spritzer CE, Cothran RL, Taylor DC, Garrett WE Jr, DeFrate LE. Femoral tunnel placement during anterior cruciate ligament reconstruction: an in vivo

- imaging analysis comparing transtibial and 2-incision tibial tunnel-independent techniques. *Am J Sports Med.* 2009; 37(10):1904–1911. [PubMed: 19687514]
- Abebe ES, Utturkar GM, Taylor DC, Spritzer CE, Kim JP, Moorman CT 3rd, Garrett WE, Defrate LE. The effects of femoral graft placement on in vivo knee kinematics after anterior cruciate ligament reconstruction. *J Biomech.* 2011; 44(5):924–929. [PubMed: 21227425]
- Ahn JH, Lee SH, Yoo JC, Ha HC. Measurement of the graft angles for the anterior cruciate ligament reconstruction with transtibial technique using postoperative magnetic resonance imaging in comparative study. *Knee Surg Sports Traumatol Arthrosc.* 2007; 15(11):1293–1300. [PubMed: 17721777]
- Amis AA, Jakob RP. Anterior cruciate ligament graft positioning, tensioning and twisting. *Knee Surg Sports Traumatol Arthrosc.* 1998; 6 Suppl 1:S2–S12. [PubMed: 9608456]
- Andriacchi TP, Briant PL, Bevill SL, Koo S. Rotational changes at the knee after ACL injury cause cartilage thinning. *Clin Orthop Relat Res.* 2006; 442:39–44. [PubMed: 16394737]
- Andriacchi TP, Dyrby CO. Interactions between kinematics and loading during walking for the normal and ACL deficient knee. *J Biomech.* 2005; 38(2):293–298. [PubMed: 15598456]
- Arnold MP, Kooloos J, van Kampen A. Single-incision technique misses the anatomical femoral anterior cruciate ligament insertion: a cadaver study. *Knee Surg Sports Traumatol Arthrosc.* 2001; 9(4):194–199. [PubMed: 11522073]
- Brophy RH, Pearle AD. Single-bundle anterior cruciate ligament reconstruction: a comparison of conventional, central, and horizontal single-bundle virtual graft positions. *Am J Sports Med.* 2009; 37(7):1317–1323. [PubMed: 19329787]
- Bull AM, Andersen HN, Basso O, Targett J, Amis AA. Incidence and mechanism of the pivot shift. An in vitro study. *Clin Orthop Relat Res.* 1999; (363):219–231. [PubMed: 10379326]
- Caputo AM, Lee JY, Spritzer CE, Easley ME, DeOrio JK, Nunley JA 2nd, DeFrate LE. In vivo kinematics of the tibiotalar joint after lateral ankle instability. *Am J Sports Med.* 2009; 37(11):2241–2248. [PubMed: 19622791]
- DeFrate LE, Gill TJ, Li G. In vivo function of the posterior cruciate ligament during weightbearing knee flexion. *Am J Sports Med.* 2004; 32(8):1923–1928. [PubMed: 15572322]
- 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; 34(8):1240–1246. [PubMed: 16636348]
- Fink C, Hoser C, Hackl W, Navarro RA, Benedetto KP. Long-term outcome of operative or nonoperative treatment of anterior cruciate ligament rupture--is sports activity a determining variable? *Int J Sports Med.* 2001; 22(4):304–309. [PubMed: 11414676]
- Fithian DC, Paxton EW, Stone ML, Luetzow WF, Csintalan RP, Phelan D, Daniel DM. Prospective trial of a treatment algorithm for the management of the anterior cruciate ligament-injured knee. *Am J Sports Med.* 2005; 33(3):335–346. [PubMed: 15716249]
- Gao B, Zheng NN. Alterations in three-dimensional joint kinematics of anterior cruciate ligament-deficient and -reconstructed knees during walking. *Clin Biomech (Bristol, Avon).* 2010; 25(3):222–229.
- Georgoulis AD, Papadonikolakis A, Papageorgiou CD, Mitsou A, Stergiou N. Three-dimensional tibiofemoral kinematics of the anterior cruciate ligament-deficient and reconstructed knee during walking. *Am J Sports Med.* 2003; 31(1):75–79. [PubMed: 12531761]
- Giron F, Buzzi R, Aglietti P. Femoral tunnel position in anterior cruciate ligament reconstruction using three techniques. A cadaver study. *Arthroscopy.* 1999; 15(7):750–756. [PubMed: 10524823]
- Harner CD, Giffin JR, Duntzman RC, Annunziata CC, Friedman MJ. Evaluation and treatment of recurrent instability after anterior cruciate ligament reconstruction. *Instr Course Lect.* 2001; 50:463–474. [PubMed: 11372347]
- Harner CD, Honkamp NJ, Ranawat AS. Anteromedial portal technique for creating the anterior cruciate ligament femoral tunnel. *Arthroscopy.* 2008; 24(1):113–115. [PubMed: 18188873]
- Howell SM, Gittins ME, Gottlieb JE, Traina SM, Zoellner TM. The relationship between the angle of the tibial tunnel in the coronal plane and loss of flexion and anterior laxity after anterior cruciate ligament reconstruction. *Am J Sports Med.* 2001; 29(5):567–574. [PubMed: 11573914]

- Jepsen CF, Lundberg-Jensen AK, Faunoe P. Does the position of the femoral tunnel affect the laxity or clinical outcome of the anterior cruciate ligament-reconstructed knee? A clinical, prospective, randomized, double-blind study. *Arthroscopy*. 2007; 23(12):1326–1333. [PubMed: 18063177]
- Kaseta MK, DeFrate LE, Charnock BL, Sullivan RT, Garrett WE Jr. Reconstruction technique affects femoral tunnel placement in ACL reconstruction. *Clin Orthop Relat Res*. 2008; 466(6):1467–1474. [PubMed: 18404292]
- Kopf S, Forsythe B, Wong AK, Tashman S, Anderst W, Irrgang JJ, Fu FH. Nonanatomic tunnel position in traditional transtibial single-bundle anterior cruciate ligament reconstruction evaluated by three-dimensional computed tomography. *J Bone Joint Surg Am*. 2010; 92(6):1427–1431. [PubMed: 20516318]
- Lenth RV. Java applets for power and sample size [Computer software]. 2009 from <http://www.stat.uiowa.edu/~rlenth/Power/>.
- Li G, Moses JM, Papannagari R, Pathare NP, DeFrate LE, Gill TJ. Anterior cruciate ligament deficiency alters the in vivo motion of the tibiofemoral cartilage contact points in both the anteroposterior and mediolateral directions. *J Bone Joint Surg Am*. 2006; 88(8):1826–1834. [PubMed: 16882908]
- Li G, Papannagari R, DeFrate LE, Yoo JD, Park SE, Gill TJ. Comparison of the ACL and ACL graft forces before and after ACL reconstruction: an in-vitro robotic investigation. *Acta Orthop*. 2006; 77(2):267–274. [PubMed: 16752289]
- Logan MC, Williams A, Lavelle J, Gedroyc W, Freeman M. Tibiofemoral kinematics following successful anterior cruciate ligament reconstruction using dynamic multiple resonance imaging. *Am J Sports Med*. 2004; 32(4):984–992. [PubMed: 15150047]
- Loh JC, Fukuda Y, Tsuda E, Steadman RJ, Fu FH, Woo SL. Knee stability and graft function following anterior cruciate ligament reconstruction: Comparison between 11 o'clock and 10 o'clock femoral tunnel placement. 2002 Richard O'Connor Award paper. *Arthroscopy*. 2003; 19(3):297–304. [PubMed: 12627155]
- Lohmander LS, Ostergren M, Englund M, Roos H. High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury. *Arthritis Rheum*. 2004; 50(10):3145–3152. [PubMed: 15476248]
- Marchant BG, Noyes FR, Barber-Westin SD, Fleckenstein C. Prevalence of nonanatomical graft placement in a series of failed anterior cruciate ligament reconstructions. *Am J Sports Med*. 2010; 38(10):1987–1996. [PubMed: 20702859]
- Markolf KL, Jackson SR, McAllister DR. A comparison of 11 o'clock versus oblique femoral tunnels in the anterior cruciate ligament-reconstructed knee: knee kinematics during a simulated pivot test. *Am J Sports Med*. 2010; 38(5):912–917. [PubMed: 20308433]
- Markolf KL, Park S, Jackson SR, McAllister DR. Anterior-posterior and rotatory stability of single and double-bundle anterior cruciate ligament reconstructions. *J Bone Joint Surg Am*. 2009; 91(1):107–118. [PubMed: 19122085]
- Moisala AS, Jarvela T, Harilainen A, Sandelin J, Kannus P, Jarvinen M. The effect of graft placement on the clinical outcome of the anterior cruciate ligament reconstruction: a prospective study. *Knee Surg Sports Traumatol Arthrosc*. 2007; 15(7):879–887. [PubMed: 17370064]
- Pearle AD, Shannon FJ, Granchi C, Wickiewicz TL, Warren RF. Comparison of 3-dimensional obliquity and anisometric characteristics of anterior cruciate ligament graft positions using surgical navigation. *Am J Sports Med*. 2008; 36(8):1534–1541. [PubMed: 18390491]
- Pinczewski LA, Salmon LJ, Jackson WF, von Bormann RB, Haslam PG, Tashiro S. Radiological landmarks for placement of the tunnels in single-bundle reconstruction of the anterior cruciate ligament. *J Bone Joint Surg Br*. 2008; 90(2):172–179. [PubMed: 18256083]
- Sakane M, Fox RJ, Woo SL, Livesay GA, Li G, Fu FH. In situ forces in the anterior cruciate ligament and its bundles in response to anterior tibial loads. *J Orthop Res*. 1997; 15(2):285–293. [PubMed: 9167633]
- Scanlan SF, Blazek K, Chaudhari AM, Safran MR, Andriacchi TP. Graft orientation influences the knee flexion moment during walking in patients with anterior cruciate ligament reconstruction. *Am J Sports Med*. 2009; 37(11):2173–2178. [PubMed: 19729363]

- Scanlan SF, Lai J, Andriacchi TP. Side-to-Side Differences in ACL Insertion Anatomy in Healthy Subjects and ACL Reconstructed Patients. *Trans Orthop Res Soc.* 2010
- Scopp JM, Jasper LE, Belkoff SM, Moorman CT 3rd. The effect of oblique femoral tunnel placement on rotational constraint of the knee reconstructed using patellar tendon autografts. *Arthroscopy.* 2004; 20(3):294–299. [PubMed: 15007318]
- Simmons R, Howell SM, Hull ML. Effect of the angle of the femoral and tibial tunnels in the coronal plane and incremental excision of the posterior cruciate ligament on tension of an anterior cruciate ligament graft: an in vitro study. *J Bone Joint Surg Am.* 2003; 85-A(6):1018–1029. [PubMed: 12783997]
- Steiner ME. Independent drilling of tibial and femoral tunnels in anterior cruciate ligament reconstruction. *J Knee Surg.* 2009; 22(2):171–176. [PubMed: 19476185]
- Steiner ME, Murray MM, Rodeo SA. Strategies to improve anterior cruciate ligament healing and graft placement. *Am J Sports Med.* 2008; 36(1):176–189. [PubMed: 18166680]
- Tashman S, Collon D, Anderson K, Kolowich P, Anderst W. Abnormal rotational knee motion during running after anterior cruciate ligament reconstruction. *Am J Sports Med.* 2004; 32(4):975–983. [PubMed: 15150046]
- Tashman S, Kolowich P, Collon D, Anderson K, Anderst W. Dynamic function of the ACL-reconstructed knee during running. *Clin Orthop Relat Res.* 2007; 454:66–73. [PubMed: 17091011]
- Van De Velde SK, Bingham JT, Hosseini A, Kozanek M, DeFrate LE, Gill TJ, Li G. Increased tibiofemoral cartilage contact deformation in patients with anterior cruciate ligament deficiency. *Arthritis Rheum.* 2009; 60(12):3693–3702. [PubMed: 19950260]
- Wittstein J, Kaseta M, Sullivan R, Garrett WE. Incidence of the remnant femoral attachment of the ruptured ACL. *Clin Orthop Relat Res.* 2009; 467(10):2691–2694. [PubMed: 19347414]
- Yamamoto Y, Hsu WH, Woo SL, Van Scyoc AH, Takakura Y, Debski RE. Knee stability and graft function after anterior cruciate ligament reconstruction: a comparison of a lateral and an anatomical femoral tunnel placement. *Am J Sports Med.* 2004; 32(8):1825–1832. [PubMed: 15572308]
- Zhang LQ, Shiavi RG, Limbird TJ, Minorik JM. Six degrees-of-freedom kinematics of ACL deficient knees during locomotion-compensatory mechanism. *Gait Posture.* 2003; 17(1):34–42. [PubMed: 12535724]

Figure 1.

Multi-planar, high resolution MR imaging was used to create 3D models of the knee, including the attachment sites of the ACL and graft (top left). Biplanar fluoroscopy was used to record each subject's knee motion during a single leg lunge (top right). The fluoroscopic images and 3D models were used to reproduce the motion of the each subject's knees during the lunge (bottom left). From these models, the length and orientation of the ACL and graft were measured (bottom right).

Figure 2. Three-dimensional models and fluoroscopic images were used to reproduce the orientation and length of grafts placed anatomicallly (left) and anteroproximally (right) on the femur.

Figure 3.

The sagittal plane angle was defined as the angle between the plane perpendicular to the long axis of the tibia, and the projection of the ACL or graft on the sagittal plane (left). The coronal plane angle was defined as the angle between the plane perpendicular to the long axis of the tibia and the projection of the ACL on the coronal plane (right).

Figure 4.

In the sagittal plane, anteroproximal grafts were more vertical than the native ACL (top left), while the anatomic grafts (top right) more closely restored the sagittal plane orientation of the native ACL. When their respective differences from native were averaged across all flexion angles, anteroproximal grafts were more vertical compared to the anatomic grafts (bottom). (* p < 0.05)

Figure 5.

In the coronal plane, anteroproximal grafts were more vertical than the native ACL (top left), while the anatomic grafts (top right) more closely restored the coronal plane orientation of the native ACL. When their respective differences from native were averaged across all flexion angles, anteroproximal grafts were more vertical compared to the anatomic grafts (bottom). (* $p < 0.05$)

Figure 6.

Both anteroproximal grafts (top left) and anatomic grafts (top right) were longer than the native ACL. When their respective differences from native were averaged across all flexion angles, anteroproximal grafts were longer compared to the anatomic grafts (bottom). (* $p < 0.05$)