The effects of femoral graft placement on in vivo knee kinematics after anterior cruciate ligament reconstruction

E.S. Abebe [a], G.M. Utturkar [a], D.C. Taylor [a], C.E. Spritzer [b], J.P. Kim [a], C.T. Moorman III [a], W.E. Garrett [a], L.E. DeFrate [a,*]

[a] Sports Medicine Center, Department of Orthopaedic Surgery, Box 3093, Duke University Medical Center, Durham, NC 27710, USA
[b] Department of Radiology, Duke University, Box 3093, Duke University Medical Center, Durham, NC 27710, USA

ARTICLE INFO

ABSTRACT

Achieving anatomical graft placement remains a concern in Anterior Cruciate Ligament (ACL) reconstruction. The purpose of this study was to quantify the effect of femoral graft placement on the ability of ACL reconstruction to restore normal knee kinematics under in vivo loading conditions. Two different groups of patients were studied: one in which the femoral tunnel was placed near the anterior and proximal border of the ACL (anteroproximal group, $n=12$) and another where the femoral tunnel was placed near the center of the ACL (anatomic group, $n=10$).

MR imaging and biplanar fluoroscopy were used to measure in vivo kinematics in these patients during a quasi-static lunge. Patients with anteroproximal graft placement had up to 3.4 mm more anterior tibial translation, 1.1 mm more medial tibial translation and 3.7° more internal tibial rotation compared to the contralateral side. Patients with anatomic graft placement had motion that more closely replicated that of the intact knee, with anterior tibial translation within 0.8 mm, medial tibial translation within 0.5 mm, and internal tibial rotation within 1°.

Grafts placed anteroproximally on the femur likely provide insufficient restraint to these motions due to a more vertical orientation. Anatomical femoral placement of the graft is more likely to reproduce normal ACL orientation, resulting in a more stable knee. Therefore, achieving anatomical graft placement on the femur is crucial to restoring normal knee function and may decrease the rates of joint degeneration after ACL reconstruction.

© 2010 Elsevier Ltd. All rights reserved.

1. Introduction

Rupture of the Anterior Cruciate Ligament (ACL) has been shown to alter native tibiofemoral motion (Zhang et al., 2003; Andriacchi et al., 2006; Barrance et al., 2006; DeFrate et al., 2006; Gao and Zheng, 2010). Specifically, past in vivo kinematic studies have shown ACL deficiency increases anterior translation, medial translation, and internal rotation of the tibia under various loading conditions (Georgoulis et al., 2003; Andriacchi and Dyrby, 2005; Andriacchi et al., 2006; DeFrate et al., 2006). These altered kinematics are thought to contribute to the degenerative changes observed after ACL injury (Georgoulis et al., 2003; Andriacchi and Dyrby, 2005; Andriacchi et al., 2006; Barrance et al., 2006; Li et al., 2006a). Despite advances in ACL reconstruction techniques, the development of osteoarthritis after surgery remains a concern (Fink et al., 2001; Salmon et al., 2006; Oiestad et al., 2009), with some studies questioning the ability of reconstruction to prevent degeneration compared to patients who forego surgery (Lohmander et al., 2004; von Porat et al., 2004; Fithian et al., 2005).

The inability of ACL reconstructions to restore normal knee motion has been thought to be an important factor contributing to the associated joint degeneration after ACL reconstruction (Logan et al., 2004; Tashman et al., 2004; Papannagari et al., 2006). Anatomically placed grafts are believed to more closely reproduce native ACL function and knee kinematics (Arnold et al., 2001; Heming et al., 2007; Brophy and Pearle, 2009). However, recent studies have suggested that non-anatomic placement of the graft might be a frequent problem during ACL reconstruction (Heming et al., 2007; Abebe et al., 2009; Kopf et al., 2010; Scanlan et al., 2010b). Specifically, some transtibial techniques, in which the femoral tunnel is placed through the tibial tunnel, might be prone to anterior and proximal placement of the graft on the femur (Kohn et al., 1998; Arnold et al., 2001; Gavriilidis et al., 2008; Harner et al., 2008; Kaseta et al., 2008; Abebe et al., 2009; Dargel et al., 2009). Given the critical role the ACL plays in stabilizing tibiofemoral motion (Zhang et al., 2003; Andriacchi et al., 2006; DeFrate et al., 2006; Gao and Zheng, 2010), understanding the effect of femoral graft placement on in vivo knee kinematics is critical to improving surgical treatments following ACL injury.

---

* Corresponding author at: Orthopaedic Bioengineering Laboratory, Department of Orthopaedic Surgery, Box 3093, Duke University Medical Center Durham, NC 27710, USA.
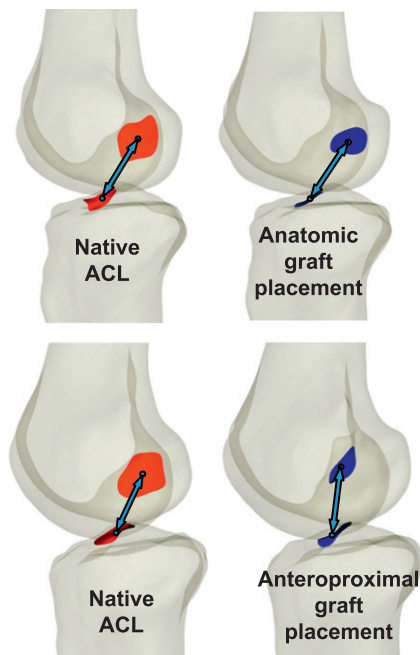E-mail address: lou.defrate@duke.edu (L.E. DeFrate).

Fig. 1. In the anatomic placement group (top), the graft was placed near the center of the native ACL footprint on the femur, while in the anteroproximal placement group (bottom), the graft was centered near the anteroproximal border of the femoral footprint (Abebe et al., 2009), as demonstrated in two subjects.

Hence, the purpose of this study was to quantify the effect of femoral graft placement on the ability of ACL reconstruction to restore normal knee kinematics under in vivo loading conditions. Two different patient populations were studied (Fig. 1): one in which the femoral tunnel was placed near the anterior and proximal border of the ACL using a transtibial technique (anteroproximal group), and another where the femoral tunnel was placed near the center of the ACL using a tibial tunnel independent technique (anatomic group) (Abebe et al., 2009). In the anatomic group, grafts were placed within an average of 3 mm of the center of the ACL, while in the anteroproximal group, grafts were placed an average of 9 mm from the center of the femoral attachment of the ACL, near its anteroproximal border (Abebe et al., 2009). Our hypothesis was that anatomically placed grafts more closely mimic native ACL function and thus, more closely reproduce native tibiofemoral kinematics.

2. Materials and Methods

2.1. Subject recruitment

Twenty two subjects (16 men and 6 women, mean age: 31 years, age range 19–49 years) between 6 and 36 months after unilateral ACL reconstruction participated in this study. Chart reviews were performed to identify potential candidates for this study. Patients were sorted by operative date, and invited in chronological order to participate. Those with osteoarthritis, articular cartilage defects, major tears of the meniscus (requiring removal of more than 10% of the medial or lateral meniscus), or any other history of injury or surgery to either knee were excluded. 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. Those who agreed to participate signed an IRB-approved consent form prior to participation in the study.

Subjects were recruited from the clinics of two surgeons, both of whom had at least 15 years of experience in sports medicine. The surgeons practiced two different single bundle arthroscopic procedures. Previous analysis indicated that one procedure resulted in anatomic femoral graft placement (within an average of 3 mm of the center of the ACL footprint) and the other resulted in anteroproximal femoral graft placement (within an average of 9 mm of the center of the ACL footprint, near its anteroproximal border) (Abebe et al., 2009). Twelve subjects (9 men, 3 women, mean age: 32 years) were in the anteroproximal placement group, and the other ten subjects (7 men, 3 women; mean age: 30 years) were in the anatomic placement group.

2.2. Surgical protocol

2.2.1. 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) aligned at 57° in the sagittal plane and 65° in the coronal plane (Abebe et al., 2009). 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 7 mm offset guide at the 1:30 position or the 10:30 position. A graft size appropriate cannulated reamer was then passed through the tibial tunnel and over the guide pin to create the femoral socket. Limited notchplasty that avoided the articular surface was performed whenever intraoperative assessment showed a risk of impingement. Graft diameter sizes varied from 7 to 9 mm. Five patients had intact menisci, and the remaining seven had tears requiring removal of less than 10% of the meniscus (five lateral tears and two medial tears). Using this technique, the grafts were placed near the anteroproximal border of the ACL footprint, an average of 9 mm from the center of the femoral attachment of the ACL (Abebe et al., 2009).

2.3. Anatomic graft placement

A diagnostic arthroscopy was first performed to confirm ACL injury. The location and shape of the ACL footprint was visualized through the anteromedial and anterolateral portals. A guidepin was placed through the center of the visible 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 centering a guide (Retro-Drill, Arthrex, Naples, FL) on the ACL stump. A guide pin was placed from outside the joint through a small incision over the lateral femoral cortex just anterior to the iliotibial tract. The guide pin was drilled through the femur to the tip of the aiming guide. The pin was threaded to allow placement of a graft size appropriate cutter on the guide pin as it entered the joint through the femoral ACL footprint. The cutter then cut a socket into the femur to the desired depth. Tunnel sizes varied between 7.5 and 8.5 mm depending on harvested graft, and no notchplasty was performed. Four patients had intact menisci, and the remaining six had tears requiring removal of less than 10% of the meniscus (three lateral tears and three medial tears). Using this technique, the grafts were placed an average of 3 mm from the center of the ACL (Abebe et al., 2009).

2.4. Modeling and testing protocol

Both the operative and contralateral intact knee were imaged using a 3T scanner (Trio Tim, Siemens) with the patient in a supine, relaxed position. Sagittal plane images (512 × 512 pixels) with a field of view of 16 × 16 cm, and spacing of 1 mm were generated using a Double-Echo Steady-State sequence (DESS, Flip angle: 25°, TR: 17 ms, TE: 6 ms). From these images, three-dimensional computer models of each subject's femur and tibia were created (Fig. 2) (Abebe et al., 2009).

Next, each patient was asked to stand on a level platform and perform a quasi-static, single leg lunge from 0° to 90° of flexion within the beams of two orthogonally positioned fluoroscopes (Pulsera, Philips, The Netherlands) (Fig. 2). Anteromedial and anterolateral image sets (resolution 1024 × 1024 pixels) were obtained of each knee as the subject flexed in increments of 15°.

The orthogonal image sets were imported into solid modeling software (Rhinoceros 4.0, Robert McNeel and Associates, Seattle, WA) to reproduce the relative position and orientation of the fluoroscopes at the time of testing (Fig. 2). Next, edge detection software written in Mathematica 6.0 (Wolfram Research, Champaign, IL) was used to outline the bone contours of the fluoroscopic images. Each subject's 3D models of the tibia and femur were then imported into the software, allowing for the models to be viewed from the two orthogonal directions corresponding to the views of the fluoroscopes during imaging. Finally, the models were manually manipulated in 6 degrees of freedom until the projections matched the edge-detected outlines on the fluoroscopic images, as described previously (DeFrate et al., 2006; Caputo et al., 2009). In this fashion, the 3D models of each subject were used to reproduce the motion of each subject's knee during the quasi-static lunge. This modeling approach allows for the measurement of tibiofemoral kinematics non-invasively.

2.5. Data analysis

In order to measure the kinematics on both the operative and intact knees using the same coordinate system, all right knee models were mirrored into left knee models and aligned to the contralateral side using an iterative closest point technique (Caputo et al., 2009). The registration of both the reconstructed and contralateral sides allowed identical coordinate systems to be created on both knees simultaneously (DeFrate et al., 2006). First, the long axis of the tibia was created by fitting a cylinder to the shaft of the tibia. Next, a mediolateral axis was drawn perpendicular to the long axis of the tibia, and tangent to the posterior extremes of the tibia. Finally, the anteroposterior axis was drawn perpendicular to the other two axes. On the femur, axes were created along the long axis of the femur and through the transepicondylar line.

Fig. 2. High resolution MR images were segmented to create 3D models of the knee (top left). Next, the patients were imaged using biplanar fluoroscopy while performing a quasi-static lunge (top right). The fluoroscopic images and 3D models were then used to reproduce the motion of each subject's knee during the lunge (bottom).

Using these coordinate systems, we calculated the translation of the midpoint of the transepicondylar line relative to the coordinate system of the tibia (DeFrate et al., 2006). Flexion was defined as the angle between the long axis of the femur and tibia, projected on the sagittal plane of the tibial coordinate system. Internal–external rotation was measured as rotation of the transepicondylar line relative to the medial–lateral axis of the tibia, projected onto the axial plane of the tibial coordinate system.

These coordinate systems were used to measure the in vivo anteroposterior and mediolateral translation, and internal–external rotation of the tibia relative to the femur between $0°$ and $90°$ of flexion. In order to directly compare the ability of a reconstruction to restore each patient's normal knee function, the relative differences between the reconstructed and intact contralateral knees were calculated. A two-tailed t-test was used to determine whether the motion of the reconstructed knees relative to the contralateral knees in both the anatomic and anteroproximal graft placement groups was significantly different from zero. Differences were considered statistically significant where $p < 0.05$.

3. Results

3.1. Anteroposterior tibial translation

Patients with anteroproximal graft placement on the femur had increased anterior tibial translation in the reconstructed knee relative to the contralateral side between $0°$ and $60°$ ($p < 0.03$, Fig. 3). No differences were detected between the reconstructed and contralateral sides in the anatomic placement group at any flexion angle ($p > 0.32$). At $30°$ of flexion, in the anteroproximal placement group there was a maximum of 3.4 ± 1.9 mm (mean and 95% confidence interval) more anterior tibial translation in the reconstructed knee relative to the contralateral knee ($p = 0.003$), while in the anatomic group, anterior translation was 0.3 ± 2.3 mm ($p = 0.75$). In the anatomic group, the mean difference in anterior translation across all flexion angles was -0.1 ± 0.5 mm, with no differences detected between the intact and reconstructed sides ($p = 0.66$). These data have more than 80% power in detecting differences of 0.8 mm in anterior translation relative to the contralateral knee with 95% confidence.

3.2. Mediolateral tibial translation

In the anteroproximal placement group, there was increased medial tibial translation in the reconstructed knee relative to the intact knee between $0°$ and $75°$ of flexion ($p < 0.05$, Fig. 4).
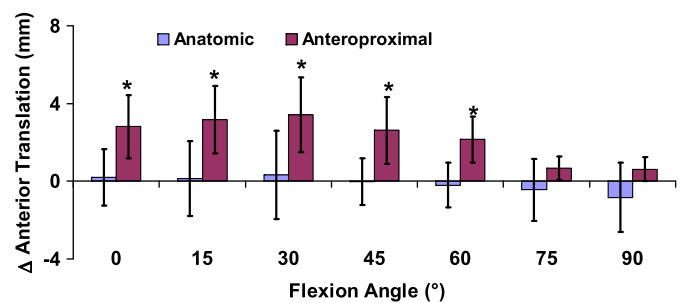

Fig. 3. The increase in anterior tibial translation of the reconstructed knee relative to the contralateral intact knee was measured as a function of flexion (mean and 95% confidence intervals). Zero denotes a knee that exactly mimics the motion of the contralateral side. Patients with grafts placed anteroproximally on the femur had increased anterior tibial translation relative to the contralateral side between $0°$ and $60°$ of flexion, while the anatomically placed grafts more closely restored normal knee motion. ($^*p < 0.05$).
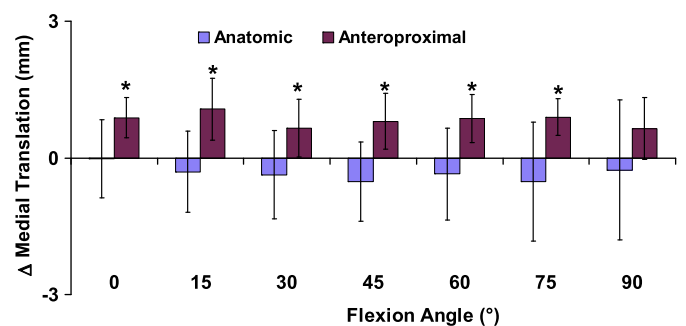

Fig. 4. The increase in medial tibial translation of the reconstructed knee relative to the contralateral intact knee was measured as a function of flexion (mean and 95% confidence intervals). Zero denotes a knee that exactly mimics the motion of the contralateral side. Patients with grafts placed anteroproximally on the femur had significantly increased medial tibial translation relative to the contralateral side between $0°$ and $75°$ of flexion, while the anatomically placed grafts more closely restored normal knee motion. ($^*p < 0.05$).

No differences were detected between the reconstructed and contralateral knees in the anatomic group at any flexion angle ($p > 0.21$). At $15°$ of flexion in the anteroproximal placement group,
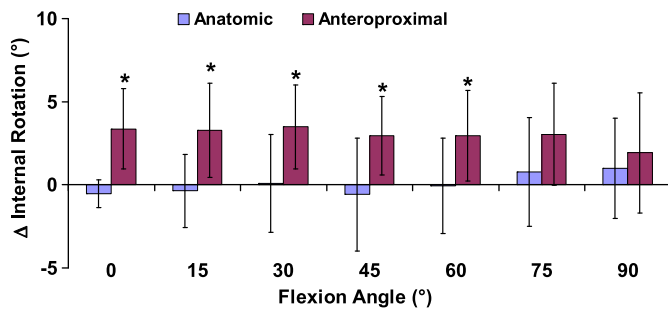
Fig. 5. The increase in internal tibial rotation of the reconstructed knee relative to the contralateral intact knee was measured as a function of flexion (mean and 95% confidence intervals). Zero denotes a knee that exactly mimics the motion of the contralateral side. Patients with grafts placed anteroproximally on the femur had increased internal tibial rotation relative to the contralateral side between 0° and 60° of flexion, while the anatomically placed grafts more closely restored normal knee motion. (*$p < 0.05$).

there was a maximum increase in medial tibial translation of 1.1 ± 0.7 mm in the reconstructed knees relative to the contralateral knees ($p = 0.005$). In the anatomic group at 15° of flexion, there was a slight lateral shift of 0.3 ± 0.9 mm ($p = 0.46$). In the anatomic group across all flexion angles, there was a mean difference in medial translation of -0.3 ± 0.3 mm, with no differences detected between the intact and reconstructed sides ($p = 0.06$). These data have more than 80% power in detecting differences of greater than 0.5 mm with 95% confidence.

3.3. Internal–external tibial rotation

Patients with anteroproximal graft placement had increased internal tibial rotation in the reconstructed knee relative to the contralateral side between 0° and 60° ($p < 0.04$, Fig. 5). No differences were detected between the reconstructed side and contralateral side in the anatomic group at any flexion angle ($p > 0.19$). At 30° of flexion in the anteroproximal group, there was a maximum of $3.5° \pm 2.5°$ more internal rotation in the reconstructed knee relative to the contralateral knee ($p = 0.01$), while in the anatomic group internal rotation was within $0.1° \pm 2.9°$ ($p = 0.95$). In the anatomic group across all flexion angles, there was an average difference in internal rotation of $0.1 \pm 1.0°$, with no difference detected between the intact and reconstructed sides ($p = 0.93$). These data have more than 80% power in detecting differences of greater than 1.5° with 95% confidence.

4. Discussion

Achieving anatomic graft placement remains a concern in ACL reconstruction (Bedi and Altchek, 2009; Scanlan et al., 2009; Steiner et al., 2009; Kopf et al., 2010; Scanlan et al., 2010b), with studies often citing anterior and proximal placement on the femur as a problem (Kohn et al., 1998; Arnold et al., 2001; Garofalo et al., 2007; Harner et al., 2008; Kaseta et al., 2008; Abebe et al., 2009). This study used biplanar fluoroscopy and MR imaging to compare the effect of graft placement on the ability of ACL reconstruction to restore normal knee motion during a quasi-static lunge. Two different placement groups were compared: one in which a tibial tunnel independent technique was used to place the graft an average of 3 mm from the center of the ACL, and another in which grafts were placed transtibially near the anteroproximal border of the ACL, an average of 9 mm from the center of the ACL (Abebe et al., 2009).

This study indicates that patients with the anteroproximal placement of the graft on the femur had increased anterior tibial translation, medial tibial translation, and internal tibial rotation compared to

the contralateral native knee during a quasi-static lunge. Similar increases in these motions were observed in the ACL deficient knee (DeFrate et al., 2006). In contrast, knees with anatomic graft placement more closely restored native knee motion under the same loading conditions. These findings suggest that the grafts placed anteroproximally on the femur provide insufficient constraint under these loading conditions, while the anatomically placed grafts more closely replicate native ACL function.

Our findings on the anteroposterior motion of the knee are consistent with previous in vivo studies. Under similar loading conditions, increases in anterior tibial translation as high as 3.5 mm were reported in ACL deficient patients (DeFrate et al., 2006). Others have also documented increased anterior tibial translations in ACL deficient patients during stair climbing (Brandsson et al., 2001) and walking (Georgoulis et al., 2003; Gao and Zheng, 2010). After ACL reconstruction, several studies have reported a decrease in anterior translation with current surgical approaches (Logan et al., 2004; Yoo et al., 2005). In the present study, patients with the anteroproximal graft placement had increases of up to 3.4 mm, while the more anatomically placed grafts restored anterior translation to within 1 mm.

Similarly, our data on medial tibial translation is consistent with previous studies. Other studies have documented increased medial translation, with an increase of up to 1.2 mm in ACL deficient patients under similar in vivo loading conditions (DeFrate et al., 2006), and an increase of up to 1.3 mm in a cadaver model of ACL deficiency (Li et al., 2007). In the current study, patients with anteroproximal graft placement had increases in medial translation as high as 1.1 mm, while the anatomically placed graft restored medial translation to within 0.5 mm.

Lastly, an increase in internal tibial rotation of 2.2° has been reported in ACL deficient patients during a similar activity to that performed in the current study (DeFrate et al., 2006). Increased internal tibial rotation relative to the intact knee has also been observed with ACL deficiency during walking (Georgoulis et al., 2003; Andriacchi et al., 2004, 2006; Gao and Zheng, 2010). For example, Gao and Zheng (2010) reported an increase of 2° to 4° in internal tibial rotation of the deficient knee relative to the intact knee throughout the gait cycle After ACL reconstruction, several studies have reported decreases in internal tibial rotation relative to the deficient knee during walking (Georgoulis et al., 2003; Gao and Zheng, 2010), while other studies have reported an external tibial rotation relative to the intact knee during walking (Scanlan et al., 2010a) or running (Tashman et al., 2004). In the present study, the patients reconstructed with anteroproximally placed grafts on the femur had up to 3.5° more internal rotation, while those with the anatomic femoral graft placement were within 1° of the contralateral side.

The results of this study can be explained in part by the orientation of the graft resulting from the placement of the femoral tunnel. Anterior and proximal graft placement is likely to produce a graft that is more vertical than the native ACL (Arnold et al., 2001; Heming et al., 2007; Harner et al., 2008; Pearle et al., 2008; Abebe et al., 2009). This was confirmed in a study of graft orientation in this same patient population, where anteroproximal femoral graft placement resulted in a more vertically oriented graft in the coronal and sagittal planes than the native ACL during weight-bearing flexion (Abebe et al., 2010).

From a biomechanical perspective, vertically oriented grafts are likely to be less effective at resisting motions in the transverse plane. Previous cadaver studies have indicated that vertical grafts in the sagittal plane require higher forces to resist the same anterior shear force (Li et al., 2006b). Furthermore, more vertical grafts in the coronal plane have been shown to not restore rotational stability as effectively as more horizontal grafts in cadaver models (Loh et al., 2003; Scopp et al., 2004; Yamamoto et al., 2004).

More vertical grafts are also likely to be inefficient in controlling the increased medial translation observed with ACL deficiency (DeFrate et al., 2006; Li et al., 2006a). Thus, it is likely that patients reconstructed with a graft placed anteroproximally on the femur have increased anterior translation, medial translation, and internal rotation due to a graft that does not mimic the orientation of the native ACL. In contrast, those patients with anatomically placed grafts likely have grafts that more closely restore native ACL orientation, resulting in a reconstruction that more closely restores normal knee motion.

Many investigators have hypothesized that abnormal tibiofemoral knee motion following injury predisposes the knee to osteoarthritis (Tashman et al., 2004, 2007; Andriacchi and Dyrby, 2005; Andriacchi et al., 2006). Specifically, recent studies have indicated that the abnormal motions observed with ACL deficiency (including increased internal rotation, anterior translation, and medial translation of the tibia) can alter normal cartilage loading (Andriacchi et al., 2006; Li et al., 2006a; Van De Velde et al., 2009). In addition, many recent studies have suggested that the inability to correct abnormal kinematics with ACL reconstruction is an important factor contributing to degenerative changes observed after reconstruction (Logan et al., 2004; Tashman et al., 2004; Papannagari et al., 2006; Scanlan et al., 2010a). This study demonstrated that more anatomically placed grafts more closely restored normal knee motion, while the more vertically oriented grafts in the anteroproximal graft placement group (Abebe et al., 2010) did restrain anterior translation, medial translation, or internal rotation. These findings suggest that achieving anatomic graft placement is an important factor in reproducing normal ACL function and knee motion. Therefore, graft placement might be an important variable in decreasing the incidence of joint degeneration after ACL reconstruction.

There are some limitations with the present study. First, the reconstructions were performed by two different surgeons. While this can potentially introduce bias, it is important to note that using one surgeon to perform both surgeries would bias the technique with which the surgeon was most familiar. For this reason, we chose to retrospectively evaluate patients from two experienced surgeons each using the technique with which they were most comfortable. In the patients with anteroproximal graft placement on the femur, 6 patients received hamstring grafts and 6 had bone-patellar-tendon-bone grafts, while in the anatomic group, hamstring grafts were used for all patients. This difference was a result of difficulties recruiting patients that met all of the inclusion criteria with the same graft types in both groups. Nevertheless, anterior translation, internal rotation, and medial translation were consistently increased in patients with anteroproximal graft placement. In this study, we used the contralateral knee as a control for the motion of the reconstructed knee. Although there may be a degree of asymmetry in the knee motions within subjects, recent studies have suggested that the contralateral knee is a reliable control for kinematic and anatomic studies of cruciate ligament injury and reconstruction (Kozanek, 2008; Jamison et al., 2010; Scanlan et al., 2010a, b). Finally, this study only examined one quasi-static activity. Future studies should consider the effect of graft placement on knee motion during other activities of daily living.

In conclusion, this study compared the effect of graft placement on the ability of ACL reconstruction to restore native knee motion in subjects during weight-bearing flexion. The data showed that the more anatomically placed grafts more closely restored native knee kinematics compared to grafts placed anteroproximally relative to the ACL attachment site on the femur. These findings suggest that, regardless of technique, achieving anatomic femoral placement of the graft is crucial to reproducing native knee kinematics and might help to decrease the incidence of joint degeneration after ACL reconstruction.

References

Abebe, E.S., Kim, J.P., Utturkar, G.M., Spritzer, C.E., Moorman 3rd, C.T., Taylor, D.C., Garrett Jr., W.E., DeFrate, L.E. (2010). In vivo graft deformation in transtibial and tibial tunnel independent ACL reconstruction techniques. Trans. Orthop. Res. Soc.

Abebe, E.S., Moorman 3rd, C.T., Dziedzic, T.S., Spritzer, C.E., Cothran, R.L., Taylor, D.C., Garrett Jr., W.E., DeFrate, L.E., 2009. 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. 37 (10), 1904–1911.

Andriacchi, T.P., Briant, P.L., Bevill, S.L., Koo, S., 2006. Rotational changes at the knee after ACL injury cause cartilage thinning. Clin. Orthop. Relat. Res. 442, 39–44.

Andriacchi, T.P., Dyrby, C.O., 2005. Interactions between kinematics and loading during walking for the normal and ACL deficient knee. J. Biomech. 38 (2), 293–298.

Andriacchi, T.P., Mundermann, A., Smith, R.L., Alexander, E.J., Dyrby, C.O., Koo, S., 2004. A framework for the in vivo pathomechanics of osteoarthritis at the knee. Ann. Biomed. Eng. 32 (3), 447–457.

Arnold, M.P., Kooloos, J., van Kampen, A., 2001. Single-incision technique misses the anatomical femoral anterior cruciate ligament insertion: a cadaver study. Knee Surg. Sports Traumatol. Arthrosc. 9 (4), 194–199.

Barrance, P.J., Williams, G.N., Snyder-Mackler, L., Buchanan, T.S., 2006. Altered knee kinematics in ACL-deficient non-copers: a comparison using dynamic MRI. J. Orthop. Res. 24 (2), 132–140.

Bedi, A., Altchek, D.W., 2009. The "footprint" anterior cruciate ligament technique: an anatomic approach to anterior cruciate ligament reconstruction. Arthroscopy 25 (10), 1128–1138.

Brandsson, S., Karlsson, J., Eriksson, B.I., Karrholm, J., 2001. Kinematics after tear in the anterior cruciate ligament: dynamic bilateral radiosterometric studies in 11 patients. Acta Orthop. Scand. 72 (4), 372–378.

Brophy, R.H., Pearle, A.D., 2009. Single-bundle anterior cruciate ligament reconstruction: a comparison of conventional, central, and horizontal single-bundle virtual graft positions. Am. J. Sports Med. 37 (7), 1317–1323.

Caputo, A.M., Lee, J.Y., Spritzer, C.E., Easley, M.E., DeOrio, J.K., Nunley 2nd, J.A., DeFrate, L.E., 2009. In vivo kinematics of the tibiotalar joint after lateral ankle instability. Am. J. Sports Med. 37 (11), 2241–2248.

Dargel, J., Schmidt-Wiethoff, R., Fischer, S., Mader, K., Koebke, J., Schneider, T., 2009. Femoral bone tunnel placement using the transtibial tunnel or the anteromedial portal in ACL reconstruction: a radiographic evaluation. Knee Surg. Sports Traumatol. Arthrosc. 17 (3), 220–227.

DeFrate, L.E., Papannagari, R., Gill, T.J., Moses, J.M., Pathare, N.P., Li, G., 2006. The 6 degrees of freedom kinematics of the knee after anterior cruciate ligament deficiency: an in vivo imaging analysis. Am. J. Sports Med. 34 (8), 1240–1246.

Fink, C., Hoser, C., Hackl, W., Navarro, R.A., Benedetto, K.P., 2001. Long-term outcome of operative or nonoperative treatment of anterior cruciate ligament rupture—is sports activity a determining variable? Int. J. Sports Med. 22 (4), 304–309.

Fithian, D.C., Paxton, E.W., Stone, M.L., Luetzow, W.F., Csintalan, R.P., Phelan, D., Daniel, D.M., 2005. Prospective trial of a treatment algorithm for the management of the anterior cruciate ligament-injured knee. Am. J. Sports Med. 33 (3), 335–346.

Gao, B., Zheng, N.N., 2010. Alterations in three-dimensional joint kinematics of anterior cruciate ligament-deficient and -reconstructed knees during walking. Clin. Biomech. (Bristol, Avon) 25 (3), 222–229.

Garofalo, R., Moretti, B., Kombot, C., Moretti, L., Mouhsine, E., 2007. Femoral tunnel placement in anterior cruciate ligament reconstruction: rationale of the two incision technique. J. Orthop. Surg. 2, 10.

Gavriilidis, I., Motsis, E.K., Pakos, E.E., Georgoulis, A.D., Mitsionis, G., Xenakis, T.A., 2008. Transtibial versus anteromedial portal of the femoral tunnel in ACL reconstruction: a cadaveric study. Knee 15 (5), 364–367.

Georgoulis, A.D., Papadonikolakis, A., Papageorgiou, C.D., Mitsou, A., Stergiou, N., 2003. Three-dimensional tibiofemoral kinematics of the anterior cruciate ligament-deficient and reconstructed knee during walking. Am. J. Sports Med. 31 (1), 75–79.

Harner, C.D., Honkamp, N.J., Ranawat, A.S., 2008. Anteromedial portal technique for creating the anterior cruciate ligament femoral tunnel. Arthroscopy 24 (1), 113–115.

Heming, J.F., Rand, J., Steiner, M.E., 2007. Anatomical limitations of transtibial drilling in anterior cruciate ligament reconstruction. Am. J. Sports Med. 35 (10), 1708–1715.

Jamison, S.T., Flanigan, D.C., Nagaraja, H.N., Chaudhari, A.M., 2010. Side-to-side differences in anterior cruciate ligament volume in healthy control subjects. J. Biomech. 43 (3), 576–578.

Kaseta, M.K., Defrate, L.E., Charnock, B.L., Sullivan, R.T., Garrett Jr., W.E., 2008. Reconstruction technique affects femoral tunnel placement in ACL reconstruction. Clin. Orthop. Relat. Res.

Kohn, D., Busche, T., Carls, J., 1998. Drill hole position in endoscopic anterior cruciate ligament reconstruction. Results of an advanced arthroscopy course. Knee Surg. Sports Traumatol. Arthrosc. 6 (Suppl 1), S13–S15.

Kopf, S., Forsythe, B., Wong, A.K., Tashman, S., Anderst, W., Irrgang, J.J., Fu, F.H., 2010. Nonanatomic tunnel position in traditional transtibial single-bundle anterior cruciate ligament reconstruction evaluated by three-dimensional computed tomography. J. Bone Jt. Surg. Am. 92 (6), 1427–1431.

Kozanek, M., Van de Velde, S.K., Gill, T.J., Li, G., 2008. The contralateral knee joint in cruciate ligament deficiency. Am. J. Sports Med. 36 (11), 2151–2157.

Li, G., Moses, J.M., Papannagari, R., Pathare, N.P., DeFrate, L.E., Gill, T.J., 2006a. Anterior cruciate ligament deficiency alters the in vivo motion of the tibiofemoral cartilage contact points in both the anteroposterior and mediolateral directions. J. Bone Jt. Surg. Am. 88 (8), 1826–1834.

Li, G., Papannagari, R., DeFrate, L.E., Yoo, J.D., Park, S.E., Gill, T.J., 2006b. Comparison of the ACL and ACL graft forces before and after ACL reconstruction: an in-vitro robotic investigation. Acta Orthop. 77 (2), 267–274.

Li, G., Papannagari, R., DeFrate, L.E., Yoo, J.D., Park, S.E., Gill, T.J., 2007. The effects of ACL deficiency on mediolateral translation and varus–valgus rotation. Acta Orthop. 78 (3), 355–360.

Logan, M.C., Williams, A., Lavelle, J., Gedroyc, W., Freeman, M., 2004. Tibiofemoral kinematics following successful anterior cruciate ligament reconstruction using dynamic multiple resonance imaging. Am. J. Sports Med. 32 (4), 984–992.

Loh, J.C., Fukuda, Y., Tsuda, E., Steadman, R.J., Fu, F.H., Woo, S.L., 2003. Knee stability and graft function following anterior cruciate ligament reconstruction: Comparison between 11 o'clock and 10 o'clock femoral tunnel placement. Arthroscopy 19 (3), 297–304.

Lohmander, L.S., Ostenberg, A., Englund, M., Roos, H., 2004. High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury. Arthritis Rheum. 50 (10), 3145–3152.

Oiestad, B.E., Engebretsen, L., Storheim, K., Risberg, M.A., 2009. Knee osteoarthritis after anterior cruciate ligament injury: a systematic review. Am. J. Sports Med. 37 (7), 1434–1443.

Papannagari, R., Gill, T.J., Defrate, L.E., Moses, J.M., Petruska, A.J., Li, G., 2006. In vivo kinematics of the knee after anterior cruciate ligament reconstruction: a clinical and functional evaluation. Am. J. Sports Med. 34 (12), 2006–2012.

Pearle, A.D., Shannon, F.J., Granchi, C., Wickiewicz, T.L., Warren, R.F., 2008. Comparison of 3-dimensional obliquity and anisometric characteristics of anterior cruciate ligament graft positions using surgical navigation. Am. J. Sports Med. 36 (8), 1534–1541.

Salmon, L.J., Russell, V.J., Refshauge, K., Kader, D., Connolly, C., Linklater, J., Pinczewski, L.A., 2006. Long-term outcome of endoscopic anterior cruciate ligament reconstruction with patellar tendon autograft: minimum 13-years review. Am. J. Sports Med. 34 (5), 721–732.

Scanlan, S.F., Blazek, K., Chaudhari, A.M., Safran, M.R., Andriacchi, T.P., 2009. Graft orientation influences the knee flexion moment during walking in patients with anterior cruciate ligament reconstruction. Am. J. Sports Med. 37 (11), 2173–2178.

Scanlan, S.F., Chaudhari, A.M., Dyrby, C.O., Andriacchi, T.P., 2010a. Differences in tibial rotation during walking in ACL reconstructed and healthy contralateral knees. J. Biomech. 43 (9), 1817–1822.

Scanlan, S.F., Lai, J. and Andriacchi, T.P. (2010b). Side-to-side differences in ACL insertion anatomy in healthy subjects and ACL reconstructed patients. Trans. Orthop. Res. Soc.

Scopp, J.M., Jasper, L.E., Belkoff, S.M., Moorman 3rd, C.T., 2004. The effect of oblique femoral tunnel placement on rotational constraint of the knee reconstructed using patellar tendon autografts. Arthroscopy 20 (3), 294–299.

Steiner, M.E., Battaglia, T.C., Heming, J.F., Rand, J.D., Festa, A., Baria, M., 2009. Independent drilling outperforms conventional transtibial drilling in anterior cruciate ligament reconstruction. Am. J. Sports Med. 37 (10), 1912–1919.

Tashman, S., Collon, D., Anderson, K., Kolowich, P., Anderst, W., 2004. Abnormal rotational knee motion during running after anterior cruciate ligament reconstruction. Am. J. Sports Med. 32 (4), 975–983.

Tashman, S., Kolowich, P., Collon, D., Anderson, K., Anderst, W., 2007. Dynamic function of the ACL-reconstructed knee during running. Clin. Orthop. Relat. Res. 454, 66–73.

Van De Velde, S.K., Bingham, J.T., Hosseini, A., Kozanek, M., DeFrate, L.E., Gill, T.J., Li, G., 2009. Increased tibiofemoral cartilage contact deformation in patients with anterior cruciate ligament deficiency. Arthritis Rheum. 60 (12), 3693–3702.

von Porat, A., Roos, E.M., Roos, H., 2004. High prevalence of osteoarthritis 14 years after an anterior cruciate ligament tear in male soccer players: A study of radiographic and patient relevant outcomes. Ann. Rheum. Dis. 63 (3), 269–273.

Yamamoto, Y., Hsu, W.H., Woo, S.L., Van Scyoc, A.H., Takakura, Y., Debski, R.E., 2004. 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. 32 (8), 1825–1832.

Yoo, J.D., Papannagari, R., Park, S.E., DeFrate, L.E., Gill, T.J., Li, G., 2005. The effect of anterior cruciate ligament reconstruction on knee joint kinematics under simulated muscle loads. Am. J. Sports Med. 33 (2), 240–246.

Zhang, L.Q., Shiavi, R.G., Limbird, T.J., Minorik, J.M., 2003. Six degrees-of-freedom kinematics of ACL deficient knees during locomotion-compensatory mechanism. Gait Posture 17 (1), 34–42.