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The effects of femoral graft placement on cartilage thickness after anterior cruciate ligament reconstruction

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ABSTRACT

Altered joint motion has been thought to be a contributing factor in the long-term development of osteoarthritis after ACL reconstruction. While many studies have quantified knee kinematics after ACL injury and reconstruction, there is limited in vivo data characterizing the effects of altered knee motion on cartilage thickness distributions. Thus, the objective of this study was to compare cartilage thickness distributions in two groups of patients with ACL reconstruction: one group in which subjects received a non-anatomic reconstruction that resulted in abnormal joint motion and another group in which subjects received an anatomically placed graft that more closely restored normal knee motion. Ten patients with anatomic graft placement (mean follow-up: 20 months) and 12 patients with non-anatomic graft placement (mean follow-up: 18 months) were scanned using high-resolution MR imaging. These images were used to generate 3D mesh models of both knees of each patient. The operative and contralateral knee models were registered to each other and a grid sampling system was used to make site-specific comparisons of cartilage thickness. Patients in the non-anatomic graft placement group demonstrated a significant decrease in cartilage thickness along the medial intercondylar notch in the operative knee relative to the intact knee (8%). In the anatomic graft placement group, no significant changes were observed. These findings suggest that restoring normal knee motion after ACL injury may help to slow the progression of degeneration. Therefore, graft placement may have important implications on the development of osteoarthritis after ACL reconstruction.

1. Introduction

ACL reconstruction is a commonly performed procedure that improves functional outcomes and allows many patients to return to recreational activities (Brophy et al., 2012; Feller and Webster, 2013; Koutras et al., 2013; Kvist, 2004). However, despite encouraging short-term clinical results, the development of post-traumatic osteoarthritis is an important concern in the long-term after ACL reconstruction (Delince and Ghafil, 2012; Lohmander et al., 2007). Specifically, numerous studies with follow-up times beyond 10 years have reported radiographic evidence of degenerative changes in more than half of patients (Holm et al., 2012; Janssen et al., 2013; Salmon et al., 2006). While these changes are generally more severe in subjects with a concurrent meniscal injury, cartilage degeneration remains a problem even in patients with intact menisci at the time of surgery (Kessler et al., 2008; Salmon et al., 2006). Since ACL injury generally afflicts a relatively young population, preventing the development of osteoarthritis in these patients is an important clinical problem (Lohmander et al., 2007; Renstrom et al., 2008).

The precise mechanisms contributing to degenerative changes after ACL reconstruction are not well understood. Although a number of factors potentially contribute to the development of osteoarthritis after ACL injury, altered joint motion is believed to be one important factor (Andriacchi et al., 2004; Chen et al., 2012; Papannagari et al., 2006; Tashman and Araki, 2013; Tochigi et al., 2011). In particular, recent studies have suggested that some ACL reconstruction techniques may not restore normal tibiofemoral joint motions under physiological loading conditions (Abebe et al., 2011b; Gao and Zheng, 2010; Papannagari et al., 2006; Tashman and Araki, 2013).

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These abnormal joint motions are believed to alter normal cartilage contact mechanics (Andriacchi et al., 2004; Hosseini et al., 2012). Abnormal cartilage loading potentially disrupts normal cartilage homeostasis (Griffin and Guilak, 2005; Halloran et al., 2012), which could ultimately influence the initiation and progression of joint degeneration in these patients. Since a number of recent studies have indicated that abnormal knee kinematics persist after ACL reconstruction (Deneweth et al., 2010; Gao and Zheng, 2010; Papannagari et al., 2006; Scanlan et al., 2010; Tashman et al., 2004), understanding the relationship between altered joint motion and changes in cartilage morphology could provide critical information for improving long-term outcomes after ACL reconstruction.

Although many studies have quantified altered kinematics after ACL reconstruction, there is limited data relating these altered knee kinematics to early degenerative changes in cartilage. In particular, there is a lack of in vivo data relating altered knee joint motion to site-specific measurements of cartilage thickness in patients with ACL reconstruction. Thus, the objective of this study was to compare cartilage thickness distributions in two groups of patients with ACL reconstruction (Abebe et al., 2011a, 2009, 2011b): one group in which subjects received a non-anatomic reconstruction that resulted in abnormal joint motion and another group in which subjects received an anatomically placed graft that more closely restored normal knee motion. We hypothesized that the abnormal knee motions that were observed with non-anatomic graft placement would result in an increased loss of cartilage thickness compared to anatomically placed grafts.

2. Materials and methods

2.1. Patient recruitment and inclusion criteria

Twenty-two patients (16 men and 6 women, 19–49 years old) between 6 and 36 months after unilateral ACL reconstruction and with healthy contralateral knees participated in this IRB approved study. Patients were recruited from the clinics of two surgeons at the Duke University Sports Medicine Center and completed the same post-surgery rehabilitation protocol. Study participants were excluded if they exhibited any of the following features: varus–valgus deformity, osteoarthritis, tibiofemoral articular cartilage defects, removal of more than 10% of meniscus in the operated knee, or any other history of trauma or surgery to either knee. All participants had stable knees under Lachman and pivot-shift examinations. At the time of testing, all study participants had returned to sports activity without restriction. All patients meeting these recruitment criteria were sorted by operative date, and invited to participate in a chronological order.

At the time of the study, 12 subjects (9 men, 3 women; mean age: 32 years; mean follow-up: 20 months) had received a procedure performed by one surgeon resulting in non-anatomic placement of the graft on the femur (Abebe et al., 2011a). 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). These subjects had a graft placed using a transtibial technique, where the femoral tunnel was placed through the tibial tunnel (Abebe et al., 2009; Kaseta et al., 2008). This technique resulted in anteroproximal graft placement on the femur, an average of 9 mm from the center of the original ACL attachment (Abebe et al., 2011a). These subjects had significantly increased anterior translation, medial translation, and internal tibial rotation in their reconstructed knee relative to their normal knee during a quasi-static weight-bearing lunge (Abebe et al., 2011b).

The remaining 10 subjects (7 men, 3 women; mean age: 30 years; mean follow-up: 18 months) had received a procedure from another surgeon resulting in anatomic graft placement (Abebe et al., 2011a). 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). In these subjects, the femoral tunnel was placed independently of the tibial tunnel (RetroDrill, Arthrex, Naples, FL; Abebe et al., 2009; Kaseta et al., 2008). Graft placement was within an average of 3 mm from the center of the ACL (Abebe et al., 2011a). In these subjects, no differences in kinematics were detected between the intact and reconstructed knee during a quasi-static weight-bearing lunge (Abebe et al., 2011b).

2.2. MR imaging

The subjects were seated in a non-weight bearing position for 30 min (Bischof et al., 2010) before the start of the investigation in order to minimize compression of the cartilage prior to imaging. Each subject's operative and intact contralateral knees were imaged at the Center for Advanced Magnetic Resonance Development using a 3 T MR scanner (Trio Trim, Siemens, Germany) while positioned in a supine, relaxed position. Sagittal MR images were acquired using a double-echo steady state sequence (DESS, field of view: 15×15 cm^2, matrix: 512×512 pixels, slice thickness: 1 mm, flip angle: 25°, TR: 17 ms, TE: 6 ms) and an eight-channel knee coil (In Vivo, Orlando, FL; Abebe et al., 2009; Taylor et al., 2011). Total scan time was approximately 9 min for each knee. All MR images were imported into solid modeling software (Rhinoceros, Robert McNeel and Associates) for further processing.

2.3. MR imaging-based 3D modeling and cartilage thickness analysis

For each sagittal MR image slice, the outer margins of the femoral and tibial cortices as well as the surface contours of articular cartilage were outlined (Fig. 1). These traced curves were then used to generate anatomic 3D mesh models of the tibiofemoral joint using solid modeling software (Geomagic Studio, Geomagic Inc., Raleigh, NC; Fig. 1). In order to measure the cartilage thickness on both the operative and intact knee models using the same coordinate system, all operative knee models were mirrored to create two models with the same orientation. Next, the mirrored operative knee models were aligned to the intact knee models using an iterative closest point technique (Caputo et al., 2009). This registration was performed to allow for site-specific comparisons of cartilage thickness. A grid sampling system was then created on both the operative and intact knee models to quantify variations in cartilage thickness by location (Fig. 2). Both the lateral and medial femoral condyles were subdivided into 3×6 grids. Additionally, three points were sampled in the medial aspect of the intercondylar notch because this is a region where elevated cartilage contact strains have been observed in patients with ACL injury (Sutter et al., 2013; Van de Velde et al., 2009). Furthermore, this is also a region where early evidence of degeneration has been observed clinically in patients with ACL deficiency (Fairclough et al., 1990). A total of 18 evenly-spaced points were also sampled on the lateral and medial tibial plateaus. Using mathematical analysis software (Mathematica, Wolfram, Champaign, IL), thickness measurements were calculated by finding the smallest Euclidian distance between the vertex of the articular surface to the cartilage–bone interface of the 3D surface mesh models (Coleman et al., 2013). This thickness information was color encoded on the cartilage surface to generate a thickness map (Fig. 3). These calculations were then followed by averaging thickness at each vertex on the mesh model within a 2.5 mm radius of the grid sampling point for each joint (Coleman et al., 2013). Finally, at each point, the percent change in cartilage thickness was calculated relative to the intact contralateral knee. This MR imaging technique for measuring cartilage thickness has been previously validated in the literature (Van de Velde et al., 2009). Additionally, a recent study from our laboratory indicated that this technique has a coefficient of repeatability of 0.03 mm for measuring tibial, femoral, and patellar cartilage thickness (Coleman et al., 2013), which corresponds to a difference in cartilage thickness of 1% (Coleman et al., 2013; Widmyer et al., 2013).

2.4. Statistical methods

The Yates corrected chi-squared test was used to compare the proportion of males and females between groups and t-tests were used to compare differences between follow-up time and age between groups. A two-way repeated measures analysis of variance (ANOVA) was performed to determine whether knee state (intact versus reconstructed) and location had significant effects on cartilage thickness. The Tukey post-hoc test was used to detect differences between means, as appropriate. Differences were considered statistically significant where $p < 0.05$.

3. Results

No statistically significant differences were observed between groups for proportion of males to females ($p = 0.82$), age ($p = 0.19$), or follow-up time ($p = 0.39$).

In knees with an anatomic reconstruction, there was a statistically significant effect of location on cartilage thickness ($p < 0.001$, Fig. 4). Cartilage in the lateral tibia was thicker than all other regions ($p < 0.001$). No differences in cartilage thickness were observed between the medial femur, lateral femur, medial tibia, and the medial aspect of the intercondylar notch. No statistically significant effects of knee state (intact versus reconstructed, $p = 0.30$) or interactions between knee state and location were observed ($p = 0.27$). In the medial intercondylar notch, there was a mean difference of just 1% in cartilage thickness between intact and reconstructed knees.

In knees with the non-anatomic graft placement, there was a statistically significant interaction between knee state (intact versus reconstructed) and location on cartilage thickness ($p = 0.002$, Fig. 5).