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Evaluating rotational kinematics of the knee in ACL reconstructed patients using 3.0 Tesla magnetic resonance imaging

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Abstract

Introduction: Injury to the anterior cruciate ligament (ACL) is common. While prior studies have shown that surgical reconstruction of the ACL can restore anterior–posterior kinematics, ACL-injured and reconstructed knees have been shown to have significant differences in tibial rotation when compared to uninjured knees. Our laboratory has developed an MR compatible rotational loading device to objectively quantify rotational stability of the knee following ACL injuries and reconstructions. Previous work from our group demonstrated a significant increase in total tibial rotation following ACL injuries. The current study is a prospective study on the same cohort of patients who have now undergone ACL reconstruction. We hypothesize that ACL reconstructed knees will have less tibial rotation relative to the pre-operative ACL deficient condition. We also hypothesize that ACL reconstructed knees will have greater rotational laxity when compared to healthy contralateral knees.

Methods: *Patients.* Six of the ACL injured patients from our initial study who had subsequently undergone ACL reconstruction were evaluated 8.1±2.9 months after surgery. All patients underwent single-bundle ACL reconstruction using anteromedial portal drilling of the femoral tunnel with identical post-operative regimens. *Magnetic Resonance (MR) Imaging.* Patients were placed in a supine position in the MR scanner on a custom-built loading device. Once secured in the scanner bore, an internal/external torque was applied to the foot. The tibiae were semi-automatically segmented with in-house software. Tibial rotation comparisons were made within subjects (i.e. side-to-side comparison between reconstructed and contralateral knees) and differences were explored using paired sample t-tests with significance set at $p=0.05$.

Results: Regarding tibial rotation, in the ACL deficient state, these patients experienced an average of $5.9\pm4.1^\circ$ difference in tibial rotation between their ACL deficient and contralateral knees. However, there was a $-0.2\pm6.1^\circ$ difference in tibial rotation of the ACL reconstructed knee when compared to the contralateral uninjured knee. Regarding tibial translation, ACL deficient patients showed a difference of $0.75\pm1.4\text{mm}$ of anterior tibial translation between injured and healthy knees. After ACL reconstruction, there was a $0.2\pm1.1\text{mm}$ difference in coupled anterior

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†Conflict of interest

The authors of this paper have no conflicts of interest to disclose.

tibial translation of the ACL reconstructed knee compared to the contralateral knee. No significant differences in contact area between the two time points could be discerned.

Discussion: The objective of our study was to assess the rotational laxity present in ACL reconstructed knees using a previously validated MRI-compatible rotational loading device. Our study demonstrated that ACL reconstruction can restore rotational laxity under load. This may speak to the benefit of an anteromedial drilling technique, which allows for a more horizontal and anatomically appropriate graft position.

Keywords

Rotation; Stability; ACL; Kinematics; MRI

1. Introduction

Injury to the anterior cruciate ligament (ACL) is common, with up to 81 in every 100,000 people every year [1]. The ACL has been shown to limit anterior tibial translation, valgus rotation and internal tibial rotation [2,3]. Following injury, many patients proceed to have their ACL surgically reconstructed because of instability and desire to return to sports. Clinical assessment of knee joint stability after ACL surgery has been focused on the measurements of anterior tibial translation [4–6]. While prior studies have shown that surgical reconstruction of the ACL can restore anterior–posterior kinematics [7,8], ACL-injured and reconstructed knees have been shown to have significant differences in tibial rotation when compared to uninjured knees [8–10].

Over the past few years, there has been significant emphasis in restoring rotational laxity following ACL reconstructions. While cadaveric studies have shown improved stability with ACL reconstruction lower along the lateral wall, there is a lack of clinical data to support some of these changes. Currently, there are no reliable methods or tools to assess rotational stability [11–13]. Our laboratory has developed an MR compatible rotational loading device to objectively quantify rotational stability of the knee following ACL injuries and reconstructions. *In vivo* motion of the bony and soft-tissue structures of the knee can be measured using kinematic MRI techniques [11,14]. This technique can be an improvement when compared with other indirect measurements of knee motion, such as skin markers, which can be less accurate at assessing tibial rotation [15]. Our previous study has demonstrated that there is a significant increase in total tibial rotation following ACL injuries. We have also demonstrated gender differences in rotational laxity [10].

The current study is a prospective study on the same cohort of patients who have now undergone ACL reconstruction. The objective of this study was to examine knee kinematics, specifically internal tibial rotation and anterior tibial translation, in ACL reconstructed knees with the use of a rotational knee loading device. We hypothesize that ACL reconstructed knees will have less tibial rotation relative to the pre-operative ACL deficient condition. We also hypothesize that ACL reconstructed knees using anteromedial portal drilling single bundle technique will still have greater rotational laxity when compared to healthy contralateral knees.

2. Patients

This study was approved by the institutional review board. Each patient gave informed consent prior to being enrolled in the study. Six of the ACL injured patients from our initial study who had subsequently undergone ACL reconstruction were evaluated 8.1 ± 2.9 months after surgery. All patients had healthy contralateral knees free from osteoarthritis, pain, stiffness or swelling. All patients underwent single-bundle ACL reconstruction using anteromedial portal drilling of the femoral tunnel and hamstring auto-grafts or posterior tibialis allo-grafts. Fixation was achieved using suspensory fixation on the femoral side (Endobutton, Smith and Nephew) and interference fixation (Biointrafix Mitek) on the tibial side. None of the patients had meniscus injuries that require any repair. All patients had the same post-operative protocol with protected weight bearing with crutches and a knee brace for the first 3 weeks. No running or jumping was allowed until 4 months. All patients returned to their previous level of function and were cleared to return to all sports prior to our examination.

3. Methods

Patients were placed in a supine position in the MR scanner on a custom-built loading device that has been previously described. Each subject received bilateral knee magnetic resonance imaging (MRI) at approximately 15° of knee flexion while his lower leg and foot were strapped into an orthopedic walking boot mounted on a rotating plate. While in the boot, the ankle remained in a neutral position. This plate was connected to a weighting system by a microfiber line that ran through a series of pulleys located in the rear of the MR scanner. Once secured in the scanner bore, an internal/external torque (3.35 N m) was applied to the foot by a 2.3 kg water bag via the microfiber line. An axial compressive load (44 N) was also applied to the foot to ensure the leg was properly engaged in the rotational aspect of the set up. Additional padding within the boot and Velcro straps over the foot and leg limited ankle motion. A large strap was placed over the patient's hips to secure the patient and to limit rotation at the hip.

MRI of the knee was performed using a 3 T GE Excite Signa MR Scanner (General Electric, Milwaukee, WI, USA) and an 8-channel phased-array knee coil (Invivo, Orlando, FL, USA). Sagittal 1.5-mm T2 weighted fast spin echo images of both knees were acquired (TR/ TE—4000/50.96, FOV=16 cm, 512×256 matrix, in-plane resolution of 0.3 mm, slice thickness of 1.5 mm, repetition time of 3500 ms and an echo time of 9.7 ms) in the internally and externally rotated positions. Both knees were imaged in a single scanning session.

The tibiae were then semi-automatically segmented with in-house software using B-splines created in MATLAB (MathWorks, Natick, MA, USA). The tibial segmentation of the internally rotated position was registered to the tibial segmentation of the externally rotated position by use of an iterative closest-point shape-matching algorithm. Tibiofemoral rotation was measured by assessing the movement of the femur relative to the fixed tibia. In-house kinematic software generated calculations of the total arc of tibial rotation, defined as the excursion between internal and external rotation. Both parameters were measured while rotational loads were applied.

Tibial rotation comparisons were made within subjects (i.e. side-to-side comparison between reconstructed and contralateral knees) and differences were explored using paired sample t -tests. All statistical analyses were done using SPSS (SPSS Inc. Chicago, IL) with significance level set at $\alpha=0.05$.

4. Results

The ACL reconstructed group comprised of two men and four women. Average age of all patients was 35.4 ± 10.5 years. Average Tegner activity score prior to injury was 6.5 ± 0.8 pre-operatively and 3.7 ± 1.1 post-operatively. All patients were able to return to their previous level of activity.

On average, there was a $-0.2 \pm 6.1^\circ$ difference in tibial rotation of the ACL reconstructed knee when compared to the contralateral uninjured knee (Fig. 1). In the ACL deficient state, these patients experienced an average of $5.9 \pm 4.1^\circ$ difference in tibial rotation between their ACL deficient and contralateral knees. There was significant difference between the preoperative tibial rotation and postoperative tibial rotation.

On average, there was a 0.2 ± 1.1 mm difference in coupled anterior tibial translation (ATT) of the ACL reconstructed knee compared to the contralateral knee as the knee was taken through the rotational arc (Fig. 2). A similar side-to-side comparison of these same patients when they were ACL deficient showed a difference of 0.75 ± 1.4 mm of ATT between injured and healthy knees. We did not demonstrate any differences in coupled ATT.

In the ACL deficient knees, our patients demonstrated an average of 130.3 ± 83 mm² of contact area in the medial compartment of the ACL deficient tibiofemoral joint when the knee was in external rotation (Table 2). The healthy contralateral side showed 171.2 ± 64 mm² of contact area. The lateral compartment of the ACL deficient knee in external rotation showed 132.6 ± 69.6 mm² of contact area when compared to 179.9 ± 58.6 mm² in the contralateral knee (Table 3). There were no significant side-to-side differences. There were less side-to-side differences in the medial and lateral compartments after ACL reconstruction.

Regarding the contact centroids, in the ACL deficient state, the medial centroid translated medially compared to the contralateral leg by an average of 0.68 ± 8.9 mm (Table 1). After reconstruction, the medial centroid of the injured knee translated just laterally, -0.18 ± 3.1 mm, when compared to the contralateral leg. Similarly, the lateral centroid of the injured knee translated laterally from ACL deficient to ACL reconstructed time point. Furthermore, both medial and lateral centroids of the injured knee translated anteriorly when compared to the contralateral knee.

5. Discussion

The objective of our study was to assess the rotational laxity present in ACL reconstructed knees using a previously validated MRI-compatible rotational loading device [10]. Rotational and axial loads used in this study were based on prior rotational laxity studies, which limited the rotational force to less than 5 N m per patient comfort [24]. Additional

cadaveric studies have also used similar loads for applying internal and external torque [25]. Reproducibility of our technique has been established in our prior study with a standard error of measurement (SEM) of 1.1° and an intraclass correlation coefficient (ICC) of 0.91 [10]. We hypothesized that ACL reconstruction would decrease rotational and anterior–posterior laxity of the knee compared to its ACL deficient state. We also anticipated a change in the tibiofemoral cartilage contact area between the ACL deficient and reconstructed knees. Our study demonstrated that ACL reconstruction can restore rotational laxity under load. There were no significant differences in contact area and centroids following ACL reconstruction.

Biomechanically, the ACL confers anterior and rotational stability to the knee joint [2,3]. While previous studies have shown that ACL reconstruction restores anterior–posterior laxity [7,8], others have found that ACL reconstructed knees still have persistent rotational laxity, as indicated by a positive pivot-shift test [16]. In addition, Stergiou et al. found that ACL reconstruction failed to correct excessive tibial rotation present in ACL deficient patients. They also proposed that a more horizontally oriented graft could restore knee rotational kinematics and prevent future knee pathology [17]. Subsequently, numerous investigators have analyzed ACL graft placement's relation to knee kinematics [18–21].

For our study, all ACL reconstructions had an anteromedial drilling of the femoral tunnel which produces a more horizontally oriented ACL graft. We found a significant difference of $5.9 \pm 4.1^{\circ}$ ($p < 0.05$) in rotational arc during passive rotation between the injured and contralateral knee at the ACL deficient time point. This difference decreased to $-0.2 \pm 6.1^{\circ}$ ($p > 0.05$) following ACL reconstruction.

Our results are consistent with prior studies—Abebe et al. used MR imaging and biplanar fluoroscopy to demonstrate that horizontal graft placement, as achieved via anteromedial drilling, resulted in improved anterior translation and rotation compared to more vertically oriented grafts during a quasi-static lunge [18]. However, our findings are contrary to what Yoo et al. found. Using cadaveric knees, they showed that horizontally oriented ACL reconstructions did not restore rotational kinematics to that of ACL intact knees under simulated physiological loads [22]. Furthermore, Hemmerich et al. found no significant rotational differences between the ACL deficient, ACL reconstructed and contralateral knee in patients who had had single bundle ACL reconstructions [23].

Our work demonstrated that as the knee moves through the rotational arc, there is no significant difference in coupled anterior tibial translation when compared to the healthy contralateral knee. This conclusion is in line with prior studies, which have shown that ACL reconstruction can adequately restore anterior–posterior stability of the knee [7,8]. Finally, our results showed no side-to-side difference in articular cartilage contact area as the knee moved through the rotational arc between ACL injured and reconstructed time points. This is consistent with prior work from our lab, which showed no significant difference in contact area or contact location between ACL reconstructed and contralateral knees when the femoral tunnel is drilled through the tibial tunnel [14]. Moreover, it appeared that medial and lateral centroids translated laterally and anteriorly after ACL reconstruction.

Our study had several limitations. First, our sample size was small, even compared to our initial study of ACL deficient patients [10]. We had a few drop outs in the study, which speaks to the challenge of longitudinal follow-up. In this follow-up study, we had an uneven distribution of men and women following ACL reconstruction. Our prior study demonstrated a significant impact of gender on total tibial rotation which we were unable to evaluate in this study due to our small sample size. Our study may have benefited from assessing kinematics and contact area at various flexion angles. We initially chose 15° because of the rotational control of the ACL. However, our MR bore size makes it difficult to reliably achieve higher degrees of flexion. Finally, our rotation device subjects the patient to passive rotation of the knee, which is not a functional movement. Further studies will need to be done to assess how passive rotational laxity impacts functional motion of the knee.

6. Conclusion

Our results suggest that, when compared to the healthy contralateral knee, ACL reconstruction using anteromedial femoral tunnel drilling can restore total rotational laxity under load. ACL reconstruction also is successful in restoring coupled anterior–posterior laxity of the knee. There were no significant side-to-side differences in joint contact area and centroids following ACL reconstructions.

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Fig. 1. Side-to-side difference in tibial rotation between the affected knee and the contralateral knee measured pre- and post-operatively.

Fig. 2. Side-to-side difference in tibial translation between the affected knee and the contralateral knee measured pre- and post-operatively.

Table 1

Difference between injured and contralateral knee in contact centroid translation as the knee moves from external to internal rotation. Positive numbers denote posterior and medial translation.

	Initial (deficient)	Follow up (reconstructed)	<i>p</i>-Value
<i>Medial centroid translation (mm)</i>			
A-P	0.06 ± 3.6	-2.43 ± 3.7	0.16
M-L	0.68 ± 8.9	-0.18 ± 3.1	0.85
<i>Lateral centroid translation (mm)</i>			
A-P	0.44 ± 2.5	-0.27±1.8	0.67
M-L	0.46 ± 3.9	-0.08±1.7	0.79

Table 2

Contact area (mm²) in medial compartment with knee in external rotation.

	Initial	Post-op
Injured	130.3 ± 83	111.2 ± 35.2
Contralateral	171.2 ± 64	143.5 ± 49
<i>p</i> -value	0.07	0.3

Table 3

Contact area (mm²) in lateral compartment with knee in external rotation.

	Initial	Post-op
Injured	153.2 ± 47.4	165.7 ± 66.9
Contralateral	179.8 ± 58.6	151.3 ± 47.5
<i>p</i> -value	0.07	0.6