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The effect of graft fixation sequence on force distribution in double-bundle anterior cruciate ligament reconstruction

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Abstract

Purpose—This paper investigated the effect of graft fixation sequence on knee joint biomechanics after a double-bundle ACL reconstruction.

Method—Two independently published biomechanical studies that investigated the biomechanics of double-bundle ACL reconstructions using similar robotic testing systems were compared. In each study, ten human cadaveric knees were tested under three different conditions: intact, ACL deficient, and ACL reconstructed using a double-bundle technique with the anteromedial (AM) graft fixed at 60° of flexion and the posterolateral (PL) graft fixed at full extension. In one study (Study A), the AM graft was fixed first; while in another study (Study B), the PL graft was fixed first. Knee kinematics, in situ forces of the ACL and the ACL grafts were measured under two loading conditions: an anterior tibial load of 134 N and a combined tibial torques (10 N·m valgus and 5 N·m internal tibial torques) in both studies.

Result—When AM graft was fixed first, the in situ force of the AM graft was lower than the native AM bundle at all flexion angles. The in situ force in the PL graft, however, was higher than the native PL bundle at all flexion angles. When the PL graft was fixed first, the in situ force of the AM graft was higher than the native AM bundle, while the in situ forces of the PL graft were lower than the native PL bundle at all flexion angles. Both studies demonstrated that the double-bundle ACL reconstructions can closely restore the normal knee joint kinematics.

Conclusion—Even though the grafts were fixed using similar initial tensions and at same flexion angles, the sequence of fixing the two grafts in a double-bundle ACL reconstruction could

alter the in situ forces in the grafts and affect the knee kinematics. These data imply that in clinical application of a double-bundle ACL reconstruction, the sequence of graft fixation should be an important surgical parameter.

Keywords

Anterior cruciate ligament (ACL); Double-bundle reconstruction; Graft fixation; Sequence; Force distribution

Introduction

It is widely accepted that the ACL is composed of the anteromedial (AM) and the posterolateral (PL) bundles [3,12,15,49]. Anatomical double-bundle ACL reconstruction techniques are introduced to reproduce the function of the two ACL bundles [6,7,10,13,16,19,31,33,35,44]. It is believed that the replication of the AM and PL bundles of the ACL could better control anteroposterior and rotational laxity than traditional single-bundle procedures [1,23,28,40–42].

Since the double-bundle ACL reconstruction has been introduced in 1980s [27,48], its superiority over the most widely practiced single-bundle ACL reconstruction has been debated [1,23,28,40–42]. While adding the second bundle to the reconstruction procedure may recreate a two bundle graft, several critical parameters, such as the anatomy of the footprints of the bundles, the tunnel positions, the flexion angles for graft fixation, and the initial tension for graft fixation, have been extensively discussed [9,11,16,25,26,36,37,40,43–47]. These variables were shown to affect the in situ forces of the graft bundles and the knee kinematics [3,14,15,18,21,22,24,32,38,39]. However, few studies have discussed the effect of fixation sequences of the two graft bundles on the biomechanics of the knee after a double-bundle ACL reconstruction.

This paper analyzed the data of two independently published in vitro biomechanical studies of the knee before and after similar double-bundle ACL reconstructions [25,34]. These two studies fixed the graft bundles at same flexion angles and using similar initial graft tensions, but the sequences of fixation of the two graft bundles were different. We hypothesized that different graft bundle fixation sequences will affect the in situ graft forces and kinematics of the knee after a double-bundle ACL reconstruction.

Materials and methods

Two studies that used similar robotic testing systems [25,34] to investigate the in situ forces of the graft bundles and kinematics of the knee after double-bundle ACL reconstructions were analyzed. These two studies were chosen because they used similar testing protocol and similar ACL reconstruction techniques.

Cadaveric specimen and the robotic testing system

Each study used ten fresh-frozen human cadaveric knees. After thawing the specimens at room temperature for 24 h, the femur and tibia were truncated approximately 20 to 25 cm from the joint line, with all soft tissues around the knee kept intact. The tibia was then fixed to a 6 degree of freedom (6 DOF) load cell that was attached to the end of the robotic arm and the femur to a distal pedestal that was rigidly fixed to the ground. Both studies obtained the kinematic responses of each knee under three conditions (ACL intact, ACL deficient, and ACL reconstructed) at selected flexion angles (0°, 15°, 30°, 60°, and 90°) under similar loading conditions: (1) an anterior tibial load of 134 N (in both studies), (2) combined torques of 10 N m valgus and 5 N m internal tibial torques (0°, 30° in Study A and 15°, 30°

in Study B). The force in the native AM and PL bundle and respective grafts were measured under each of the loading conditions at all selected flexion angles.

Double-bundle ACL reconstruction

Both studies performed the double-bundle ACL reconstruction by creating two femoral tunnels, while Study A created two tibial tunnels and Study B used a single tibial tunnel. The two femoral tunnels were positioned using a Kirschner wire at the center of the footprint of each bundle. The tibial tunnels created by Study A were also at the footprint of each bundle and by Study B were 5–7 mm anterior to the tibial insertion site of the posterior cruciate ligament. Both protocols used EndoButton CL (Smith & Nephew Endoscopy, Andover, MA) for femoral fixation, while an Interference screw (Mitek, Raynham, MA) was used for tibial fixation in study A and a spiked washer with screw (Mitek Products, Norwood, Mass) was used in Study B. In both studies, the AM bundle was fixed at 60° of flexion and the PL bundle was fixed at full extension, but the sequence of the fixation was different. The AM bundle was fixed first followed by the PL bundle in study A. On the contrary, the PL bundle was fixed first followed by the AM bundle in study B. The pre-tension protocols were also similar with Study A applying 20 N for each bundle and Study B applying 22 N.

Statistical analysis

In both studies, the in situ forces of the native ACL bundles were compared to those of the corresponding graft bundles. The kinematics of the knee were compared in intact, ACL deficient, and ACL reconstructed conditions. Since the data were compared within each knee specimen, a repeated measured ANOVA was used in both studies for data analysis. In this paper, the in situ forces of the graft bundles and the corresponding kinematics of the reconstructed knees of the two studies were compared to examine the effect of graft fixation sequences of double-bundle ACL reconstructions on knee kinematics and graft forces.

Results

Kinematics and forces under the anterior tibial load

The anterior tibial translations after double-bundle reconstruction in Study A were closely restored to the intact level at all selected flexion angles with a maximum difference of 1.6 ± 2.2 mm at 30° of flexion (n.s.) (Fig. 1a). The anterior tibial translation of the reconstructed knee was larger than the intact knee at all selected flexion angles. In Study B, the anterior tibial translation after double-bundle reconstruction was 1.4 mm higher at full extension and 15° of knee flexion ($P < 0.05$) but 1.7 mm lower at 90° of flexion than the intact knee ($P < 0.05$) (Fig. 1b).

The average entire ACL graft forces of the double-bundle reconstructions were not significantly different from those of the intact ACL at all selected flexion angles in both studies. However, the force distributions between the AM and PL graft bundles of both studies were significantly different from those of the corresponding native ACL bundles. Fixation of the AM graft bundle first then the PL graft bundle resulted in lower AM graft bundle forces (Fig. 2a) and higher PL graft bundle forces (Fig. 2b), while fixation of the PL graft bundle first then the AM graft bundle resulted in lower PL graft bundle forces (Fig. 2a) and higher AM graft bundle forces (Fig. 2b).

Kinematics and forces under the combined rotatory load

In Study A, the anterior tibial translation in response to the combined rotatory load after the double-bundle ACL reconstruction was closely restored to the intact level at 0° and 30° of

flexion (n.s.). In Study B, the coupled anterior tibial translation was 1.1 mm greater at 15° of flexion ($P < 0.05$) and 0.5 mm greater at 30° of flexion.

The double-bundle reconstruction restored internal tibial rotation to intact level at 0° and 30° of flexion in Study A (Fig. 3), but on average, the reconstructed knee had less internal rotation than the intact knee. In Study B, the reconstructed knee restored internal tibial rotation to normal level (n.s. at 15° and 30°). On average, the internal tibial rotations were higher than the native knee after the double-bundle ACL reconstruction at the two flexion angles.

In Study A, the PL graft of the reconstructed knee showed significantly higher forces and the AM graft showed significantly lower forces than those of the native ACL bundles ($P < 0.05$) (Fig. 4). In Study B, there were no significant differences between the in situ forces of the intact AM bundle and the AM graft and between the intact PL bundle and PL graft.

Discussion

The most important finding of the present study is that different sequences of graft bundle fixation in double-bundle ACL reconstruction can affect the in situ graft forces and kinematics of the knee. In Study A where the AM graft was fixed first, the in situ forces in the PL grafts were larger than those of the native PL bundle, while AM graft forces were lower than the native AM bundle. In contrast, when the PL graft was fixed first in Study B, the in situ forces in the AM graft were larger than those in the native AM bundle and in the PL graft were lower than those in the native PL bundle. While both studies demonstrated clinically satisfactory kinematic responses, fixing the AM graft first has a trend to cause overly corrected tibial rotation, while fixing the PL graft first has a trend to under correct the tibial rotation and to overly correct the tibial translation at high flexion angles. The effect of graft bundle fixation sequence in a double-bundle ACL reconstruction could not be examined from either Study A or Study B alone.

Numerous studies investigated the surgical techniques of double-bundle ACL reconstruction. The fixation protocols, including the initial graft tension and the knee flexion angle for graft fixation, are extensively studied in order to fix the two grafts efficiently and safely [2,8,25,37,41,42,44,45]. Despite the extensive literature on double-bundle ACL reconstruction, few studies have discussed the effect of graft fixation sequence. Cuomo et al. performed an interesting study where they tensioned one graft at a selected flexion angle (AM graft at 90° and PL graft at 20°) to restore the laxity of the knee under a 90 N anterior drawer force and then flexed the knee to another selected angle to tension the second graft to restore the knee laxity under the same anterior drawer force if any residual laxity existed at that angle [11]. The graft fixed first always carried higher loads than the native ACL bundle. Even though this is not a clinically applicable technique, it does imply that graft fixation sequence can affect the biomechanics of the ACL reconstructed knees.

From a biomechanical point of view, the sequence of graft fixation can cause a redistribution of forces between the grafts, as shown in Fig. 5. When the first graft is fixed tightly, the tibia will be forced to a posterior position. The second graft fixation will cause further posterior tibial translation, thus causing the first fixed graft to slack.

The main reason for advocating a double-bundle ACL reconstruction is to improve the rotational stability [1,17,27,29,44]. The PL graft in an anatomic ACL reconstruction may contribute to an improvement of the pivot-shift test, when compared with the single-bundle reconstruction [20,40]. In Study A, the internal rotation seemed to be over-constrained accompanied by a high tension in the PL graft. In Study B where the tension in the PL graft was lower, larger tibial internal rotations were observed. This indirectly supports the claim

that the PL bundle may be an important restraint to rotational laxity [3,11,47]. However, over-tensioning of a single graft might cause graft failure in a reconstructed knee. Graft failure has been reported in various patient follow-up studies [4,20,30]. There is no guideline on the sequence of graft fixation in current clinical applications. Further investigation is needed to better understand the mechanisms of graft failure. This analysis indicated that any double-bundle ACL reconstruction technique should include the graft fixation sequence in the graft fixation protocol.

This paper is limited to analyzing the graft fixation at full extension and 60° of flexion in the double-bundle ACL reconstruction. Even though the two studies were similar, the graft fixations at the tibial tunnel were not the same. It should be kept in mind that the comparison of the two studies is more on the trend of the data when the grafts were fixed in different sequences. A controlled study design is warranted where various graft fixation angles and graft tensioning strategy, including tensioning the two grafts simultaneously, should be investigated.

Conclusion

This study showed that even when the grafts are fixed using similar initial tensions and at similar flexion angles, the sequence of fixing the two grafts can alter the in situ forces in the grafts. The graft fixed first may carry lower loads, while the graft fixed second carries higher loads, and consequently, the knee kinematics can be affected. This data implies that, in the clinical application of double-bundle ACL reconstructions, the sequence of graft fixation should be an important surgical parameter.

Acknowledgments

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Fig. 1. Kinematic response to 134 N anterior tibial load; **a** Study A, **b** Study B. Represent statistical significance ($P < .05$) in comparison with intact bundle. Error bars represent standard deviation [5], DB Recon, double-bundle reconstruction

Fig. 2.

The differences in the in situ forces between the grafts and native bundles. **a** AM bundle, **b** PL bundle. *AMB* Anteromedial bundle, *PLB* Posterolateral bundle

Fig. 3. Internal tibial rotation in response to combined rotatory loads; **a** Study A, **b** Study B. *Error bars* represent standard deviation [5], DB Recon, double-bundle reconstruction

Fig. 4.

In situ force under combined rotatory loads; **a** Study A, **b** Study B. Represent statistical significance ($P < .05$) in comparison with intact bundle. *Error bars* represent standard deviation [5], *AMB* Anteromedial bundle, *PLB* Posterolateral bundle

Fig. 5.
a AM fixed at 60°; **b** Tighten the AM graft caused posterior tibial translation; **c** Install PL graft at full extension; **d** Tighten PL graft causing posterior tibial translation, thus relaxing the AM graft