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Original Article

Evaluation of the intraoperative kinematics during double-bundle anterior cruciate ligament reconstruction using a navigation system

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A B S T R A C T

Background/objective: There is controversy regarding the biomechanical function of the anteromedial (AM) and posterolateral (PL) bundles in isolated tibiofemoral rotation during double-bundle anterior cruciate ligament (ACL) reconstruction. This study aimed to evaluate the biomechanical function of the AM and PL bundles of the ACL using a computer navigation system.

Methods: This study involved 15 patients who underwent double-bundle ACL reconstruction. Anteroposterior and isolated rotational knee laxity were measured with a navigation system. The measurements were performed four times, namely, before fixation, after temporary PL bundle fixation, after AM bundle fixation, and after double-bundle reconstruction. With knee flexion ranging from 20° to 60°, we continuously measured the anterior tibial displacement under an anterior drawer stress (100 N using a spring balance). The total range of tibial rotation was also measured under an external and internal rotational torque of 3 Nm.

Results: Fixation of either the AM or the PL bundle significantly reduced the anteroposterior displacement at all knee flexion angles. Although the anteroposterior displacement after AM bundle fixation was relatively similar throughout the range of motion (2.4–3.2 mm), the anteroposterior displacement after PL bundle fixation increased continuously with knee flexion (2.2–4.6 mm). With respect to the total range of tibial rotation under external and internal rotational torque, there was no significant difference between AM and PL bundle fixation throughout the range of motion. The total range of tibial rotation was significantly reduced only on double-bundle reconstruction at 20° and 25° knee flexion compared to the pre-reconstruction range ($P = 0.015$ and 0.036, respectively).

Conclusion: The AM and PL bundles function differently for controlling anterior knee laxity throughout the range of motion. The function of the AM and PL bundles was similar for controlling isolated tibiofemoral rotation. Isolated tibiofemoral rotation was significantly controlled only on double-bundle reconstruction at knee flexion angles of 20° and 25°.

Introduction

An emerging body of evidence has shown the importance of anatomic anterior cruciate ligament (ACL) reconstruction[1] for patients with ACL injury. When the knee is flexed, the normal ACL seems to be composed of two distinct functional bundles, namely, the anteromedial (AM) and posterolateral (PL) bundles. These two bundles are considered to have different effects on the knee kinematics in the normal knee. Although the PL bundle becomes tight in the knee extension position and loose in the knee flexion position, the AM bundle is relatively isometric throughout the range of motion. Several biomechanical studies have reported the advantage of anatomic double-bundle reconstruction over conventional single-bundle reconstruction.[2–5] Anatomic double-bundle ACL reconstruction can more closely mimic the normal structure of the ACL. However, there is controversy regarding the biomechanical function of the AM and PL bundles in tibiofemoral rotation. While

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some studies reported that both the AM and PL bundles have similar control over tibial rotation, several studies concluded that the PL bundle has a more important role than the AM bundle in controlling tibial rotation.[6–8]

The use of computer-assisted surgical navigation devices as tools for tunnel placement during ACL reconstruction has been well-validated in previous studies.[9] Computer navigation is also capable of evaluating knee laxity before and after ACL reconstruction.[6,10–16] The present study aimed to evaluate the biomechanical function of the AM and PL bundles using a computer navigation system. We hypothesized that although the functions of the AM and PL bundles were different for controlling anterior knee laxity throughout the range of motion, the function of the AM and PL bundles was similar for controlling isolated tibiofemoral rotation.

Materials and methods

Patients

Fifteen patients (11 males and 4 females) who underwent primary anatomic double-bundle ACL reconstruction with the semitendinosus tendon in our hospital were included in this study. The mean age of patients at the time of surgery was 32.3 years (range, 15–50 years). Exclusion criteria were prior surgery on the involved knee, concomitant knee ligament injury greater than grade 2, severe osteoarthritic changes (joint space narrowing of more than 50% in any compartment), and a body mass index greater than 28. Patients who underwent meniscectomy or meniscal repair were also excluded from this study. The study was reviewed and approved by the ethics committee of our university, and informed consent was obtained from all patients.

Surgical technique

Three portals, the anteromedial, anterolateral, and far-anteromedial portals were established. The far-anteromedial portal technique[17] was used for femoral tunnel preparation. The centers of the AM and PL femoral bone tunnels were positioned just behind the resident's ridge[18] at the 10:30 and 9:30 clock positions (both for the right knee), respectively. The femoral targeted points for the bundles were marked with the microfracture awl with the knee at 90° of flexion. A passing pin was positioned on the targeted point and was drilled into the lateral femoral condyle with the knee in more than 110° of flexion. The passing pin was overdrilled with a cannulated reamer. For preparation of the tibial tunnel, two 2.0-mm Kirschner wires were inserted into the tibial footprint of the ACL using the director drill-guide system (Acufex; Smith & Nephew, Mansfield, MA, USA). The Kirschner wire for the AM bundle was inserted to enable the tibial bone tunnel opening of the AM bundle to be positioned as far anterior as possible within the native footprint of the ACL. The Kirschner wire for the PL bundle was inserted 8–9 mm posterior to the wire for the AM bundle. Each wire was overdrilled with a cannulated reamer. The semitendinosus tendon was divided in half. Each tendon was doubled and connected to an appropriate size of EndoButton CL (Acufex; Smith & Nephew, Mansfield, MA, USA) on the femoral side and to the EndoButton tape (Acufex; Smith & Nephew) on the tibial side. After passing the graft composites through the bone tunnels, the proximal side of the graft was fixed with the EndoButton CL. On the tibial side, a mild tension force (30 N) was applied to the distal EndoButton tape of each graft. Finally, the grafts were fixed with two staples each (Meira, Nagoya, Japan) with the knee at 30° of flexion.

Navigation process and biomechanical evaluation

For the kinematic analysis, the OrthoPilot ACL navigation system, an image-free, wireless system (version 3.0, B. Braun Aesculap, Tuttlingen, Germany) and a custom-made tibial rotation device were used. The repeatability of the navigation system is < 1 mm for translation and <1° for rotation.[19] Two transmitters were firmly fixed: one on the femur and one on the tibia via metal pin fixators. On each transmitter, 4 reflective markers were attached, which were recognized by the camera of the navigation system. We then used a pointer to accurately identify bony landmarks, including the tibial tuberosity, the anterior edge of the tibia, and the medial and lateral points of the tibial plateau. Knee kinematics between 0° and 90° of knee flexion were then recorded. The custom-made tibial rotation device enables a quantitative tibial rotational torque to be applied equally and has 3 components: a boot, a rotational torque wrench, and a stock. A patient's ankle is fixed in the boot to prevent it from rotating when a rotational load is applied using the torque wrench.

Intraoperatively, the navigation system records the anteroposterior and isolated rotational laxity of the knee. During ACL reconstruction, the measurements were performed 4 times: before reconstruction, after temporary PL bundle fixation, after AM bundle fixation, and after double-bundle reconstruction. The first measurement was started after the femoral and tibial bone tunnels were prepared. The knee was drained, and for the reference measurement, an examiner passively moved the knee slowly from 0° to 60° of flexion and from 60° to 0° of flexion in the neutral tibial rotation. The navigation system recorded the knee kinematics during the knee motion at a sampling rate of 12 Hz. The antero-posterior position of the tibia relative to the femur was continuously recorded. Then, under an anterior drawer stress of 100 N using a spring balance, the antero-posterior position of the tibia relative to the femur between 0° and 60° of knee flexion was continuously measured in neutral tibial rotation [Fig. 1]. Anterior displacement of the tibia in each angle was measured by the differences of the antero-posterior position of the tibia relative to the femur between in the reference measurement and in 100 N anterior drawer stress. Subsequently, the ankle was fixed in the boot of the custom-made device. Isolated rotational laxity of the knee was evaluated, without anterior drawer stress, by measuring the total range of tibial rotation under external and internal rotational torque of 3 Nm. An examiner passively moved the knee slowly from 0° to 60° of flexion and from 60° to 0° of flexion under an external rotational torque of 3 Nm [Fig. 2]. Then, the examiner moved the knee again under an internal rotational torque of 3 Nm. The total of external and internal tibial rotation in each angle of knee flexion mean isolated rotational laxity of the knee. The measurements were performed before the reconstruction, after temporary PL bundle fixation with one staple, after AM bundle fixation with two staples, and after the double-bundle reconstruction. The staple for temporary PL bundle fixation was temporarily taken off before evaluation of the AM bundle. Before evaluation of the double-bundle, the PL bundle was fixed with two staples. During the kinematic evaluation of the bundles, the knee was moved between 20° and 60° of knee flexion. We did not evaluate the function of the bundles in knee flexion of less than 20° because knee extension with 100 N anterior drawer stress or rotational stress to the tibia may damage the grafts during the surgery. Anteroposterior and isolated rotational laxity of the knee were evaluated by 5-degree increments between 20° and 60° of knee flexion.

Statistical analyses

All data are presented as mean, standard deviation (SD), and 95%

Fig. 1. Intraoperative measurement of anterior tibial translation. Under an anterior drawer stress of 100 N, the antero-posterior position of the tibia relative to the femur between 0° and 60° of knee flexion was continuously measured in neutral tibial rotation.

confidence interval (CI). Statistical analysis was performed with SPSS Statistics for Windows Version 22.0 (IBM Corp.; Armonk, New York, USA). One-way analysis of variance with Bonferroni post hoc test was used to compare anterior displacement of the tibia and total range of tibial rotation before reconstruction, after temporary PL bundle fixation, after AM bundle fixation, and after double-bundle reconstruction at different flexion angles. A P value less than 0.05 was considered significant.

Results

Anterior displacement of the tibia

Fixation of either the AM or the PL bundle significantly reduced the anteroposterior displacement at all knee flexion angles (20° to 60° of knee flexion) [Table 1]. Although the anteroposterior displacement after AM bundle fixation was relatively similar throughout the range of motion (2.4–3.2 mm), the anteroposterior displacement after PL bundle fixation increased continuously with knee flexion (2.2–4.6 mm) [Fig. 3].

Total range of tibial rotation

Table 2 and Fig. 4 show the total range of isolated tibiofemoral rotation under external and internal rotational torque. There was no significant difference between the AM bundle fixation and PL bundle fixation throughout the range of motion. Isolated tibiofemoral rotation was significantly controlled only on double-bundle reconstruction at knee flexion angles of 20° and 25° ($P = 0.015$ and 0.036, respectively).

Discussion

Our hypothesis was supported by the results of this study. This study showed that although the functions of the AM and PL bundles were different for controlling anterior knee laxity throughout the range of motion, the function of the AM and PL bundles was similar for controlling isolated tibiofemoral rotation. Isolated tibiofemoral rotation was significantly controlled only on double-bundle reconstruction at knee flexion angles of 20° and 25°.

The major goals of ACL reconstruction are to restore the stability of the knee as well as to prevent damage to the articular cartilage and meniscus.[20] Several studies have demonstrated that sectioning the ACL increased isolated tibiofemoral rotation laxity,[8,21] and also that ACL reconstruction significantly reduced isolated tibiofemoral rotation laxity when compared to the ACL-deficient knee.[13,21–25] These studies used isolated tibiofemoral rotational instability to evaluate rotatory knee laxity. On the other hand, the pivot shift test became a popular test to assess for "rotatory knee laxity".[26] Positive pivot-shift tests have been reported to be associated with subjective clinical symptoms in patients with ACL deficiency. However, Diermann et al. reported that an ACL deficiency does not increase the internal tibial rotation under a simulated pivot shift test.[27] They concluded that the anterior tibial translation should be evaluated rather than the internal tibial rotation when measuring rotational knee laxity using instrumented knee laxity devices under pivot shift mechanisms. Therefore, when using the pivot shift test, recent studies have evaluated knee instability by evaluating the anterior tibial translation rather than the internal tibial rotation. Hoshino et al. developed an electromagnetic measurement system (EMS) to quantitatively measure knee kinematics during the pivot-shift tests.[28] They showed that a significant difference between the ACL injured and intact knees was observed only in the tibial anteroposterior translation and acceleration of the tibial posterior

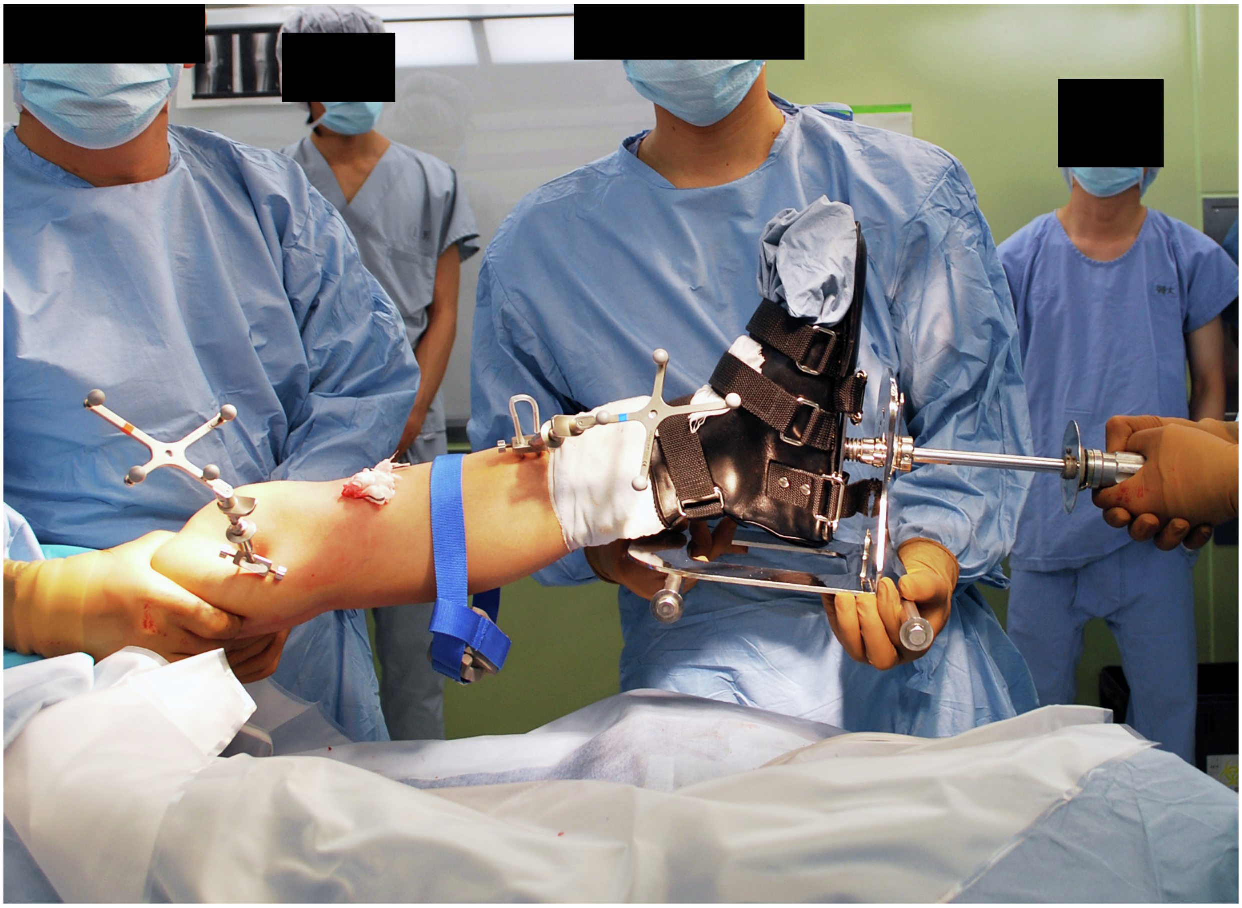

Fig. 2. Intraoperative measurement of isolated tibiofemoral rotation using a navigation system. Isolated rotational laxity of the knee was evaluated, without anterior drawer stress, by measuring the total range of tibial rotation under external and internal rotational torque of 3 Nm.

Table 1
Anterior tibial translation under an anterior drawer stress of 100 N.

Knee flexion angle (degree)	Anterior tibial translation (mm)			
	Before reconstruction	After temporary PL bundle fixation	After AM bundle fixation	After double-bundle reconstruction
20	7.2 ± 3.1 (5.5–8.9)[a]	2.2 ± 0.8 (1.8–2.6)	2.4 ± 0.9 (1.9–3.0)	1.4 ± 0.5 (1.2–1.7)
25	8.4 ± 3.2 (6.6–10.2)[a]	2.4 ± 0.7 (2.0–2.8)	2.6 ± 0.8 (2.1–3.0)	1.6 ± 0.5 (1.3–1.9)
30	9.2 ± 3.3 (7.3–11.0)[a]	2.8 ± 0.7 (2.4–3.2)	2.7 ± 0.8 (2.2–3.1)	1.7 ± 0.6 (1.3–2.0)
35	9.6 ± 3.3 (7.7–11.3)[a]	3.3 ± 0.8 (2.8–3.7)	2.9 ± 0.8 (2.4–3.3)	1.8 ± 0.6 (1.4–2.1)
40	9.7 ± 3.3 (7.9–11.6)[a]	3.7 ± 0.9 (3.2–4.2)[b]	3.0 ± 0.9 (2.5–3.5)	1.8 ± 0.7 (1.5–2.2)
45	9.5 ± 3.2 (7.8–11.3)[a]	4.1 ± 0.9 (3.5–4.6)[b]	3.1 ± 0.9 (2.6–3.6)	2.0 ± 0.8 (1.5–2.4)
50	9.2 ± 3.0 (7.6–10.9)[a]	4.4 ± 1.0 (3.8–4.9)[b]	3.2 ± 0.8 (2.8–3.6)	2.0 ± 0.8 (1.6–2.4)
55	8.6 ± 2.7 (7.1–10.1)[a]	4.6 ± 1.1 (4.0–5.2)[b]	3.2 ± 0.8 (2.8–3.6)	2.0 ± 0.8 (1.6–2.5)
60	8.1 ± 2.4 (6.7–9.4)[a]	4.5 ± 1.0 (4.0–5.1)[b]	3.2 ± 0.8 (2.7–3.6)	2.1 ± 0.8 (1.6–2.5)

Data are shown as mean ± standard deviation (SD) and 95% confidence interval (CI).
[a] A significant difference was found between before reconstruction and the other three fixation group ($P < 0.01$).
[b] A significant difference was found between after temporary PL bundle fixation and after double-bundle reconstruction ($P < 0.05$).

translation during the pivot shift test. In contrast, tibiofemoral rotational angle did not show significant difference between the ACL deficient and intact knees. Therefore, it may be inadequate to recognize the pivot shift test as the test for "rotatory knee laxity".

Controversy exists regarding the biomechanical function of the PL bundle in isolated tibiofemoral rotation. Ferretti et al. reported that fixation of the AM bundle significantly reduced the internal rotation at 15°, 30°, 45°, and 60°, and the external rotation at 0°, 30°, 60°, and 90°.[22] They also showed that the addition of the PL bundle to the AM bundle did not significantly reduce the internal and external rotation of the tibia at the measured degrees of flexion. On the other hand, some studies demonstrated that PL bundle fixation improved isolated tibial rotatory laxity better than AM bundle fixation.[6,7] Ishibashi et al. showed that the PL bundle had a more important role in controlling isolated rotation of the tibia than the AM bundle.[6] Lee et al. concluded that the femoral tunnel position of the PL bundle markedly correlated with isolated rotatory laxity.[7] They reported that low femoral tunnel position and low clock-face position of the PL bundle were related to better isolated rotational stability. In addition, the same authors reported in another study that the double-bundle ACL reconstruction improved isolated rotatory laxity better than the single-bundle ACL reconstruction at 30° and 60° of knee flexion.[25] These studies used the same navigation system (OrthoPilot) as we did in our study.

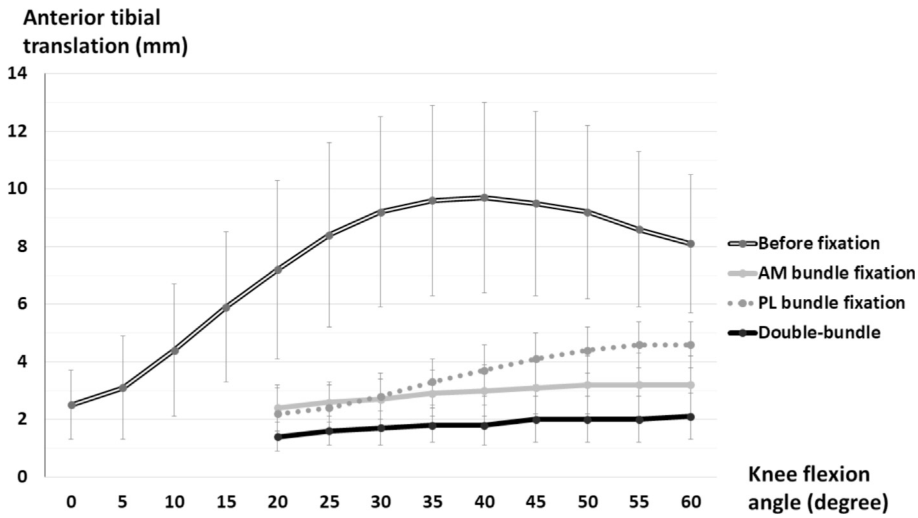

Fig. 3. Anterior tibial translation under an anterior drawer stress of 100 N before reconstruction, after temporary posterolateral bundle fixation, after anteromedial bundle fixation, and after double-bundle reconstruction. AMB, anteromedial bundle; PLB, posterolateral bundle.

Table 2
Total range of isolated tibiofemoral rotation under external and internal rotational torque of 3 Nm.

Knee flexion angle (degree)	Total range of isolated tibiofemoral rotation (degree)			
	Before reconstruction	After temporary PL bundle fixation	After AM bundle fixation	After double-bundle reconstruction
20	21.3 ± 7.7 (17.0–25.5)	16.0 ± 7.0 (12.2–19.9)	16.1 ± 6.3 (12.7–19.6)	13.3 ± 6.8 (9.5–17.0)[a]
25	22.3 ± 7.3 (18.2–26.4)	17.6 ± 6.9 (13.7–21.4)	17.4 ± 6.3 (13.9–20.9)	15.2 ± 6.6 (11.6–18.9)[b]
30	22.2 ± 7.4 (18.1–26.2)	18.6 ± 6.8 (14.8–22.4)	18.3 ± 6.4 (14.7–21.8)	16.5 ± 6.4 (13.0–20.1)
35	21.9 ± 7.0 (18.0–25.8)	19.2 ± 6.6 (15.6–22.8)	18.7 ± 6.3 (15.2–22.2)	17.5 ± 6.0 (14.2–20.9)
40	21.2 ± 6.6 (17.6–24.9)	19.1 ± 6.2 (15.7–22.6)	18.6 ± 6.0 (15.3–22.0)	17.9 ± 5.8 (14.7–21.1)
45	20.3 ± 6.1 (16.9–23.7)	18.7 ± 5.7 (15.5–21.9)	18.1 ± 5.6 (15.0–21.2)	17.8 ± 5.4 (14.8–20.8)
50	19.1 ± 5.5 (16.1–22.2)	17.8 ± 5.2 (14.9–20.7)	17.4 ± 5.0 (14.6–20.2)	17.2 ± 5.1 (14.4–20.1)
55	17.9 ± 4.9 (15.1–20.6)	16.8 ± 4.8 (14.1–19.4)	16.2 ± 4.6 (13.7–18.8)	16.3 ± 4.7 (13.7–19.0)
60	16.5 ± 4.4 (14.1–18.9)	15.6 ± 4.2 (13.2–17.9)	15.0 ± 4.1 (12.7–17.3)	15.1 ± 4.3 (12.7–17.5)

Data are shown as mean ± standard deviation (SD) and 95% confidence interval (CI).
[a] A significant difference was found between before reconstruction and after double-bundle reconstruction ($P = 0.015$).
[b] A significant difference was found between before reconstruction and after double-bundle reconstruction ($P = 0.036$).

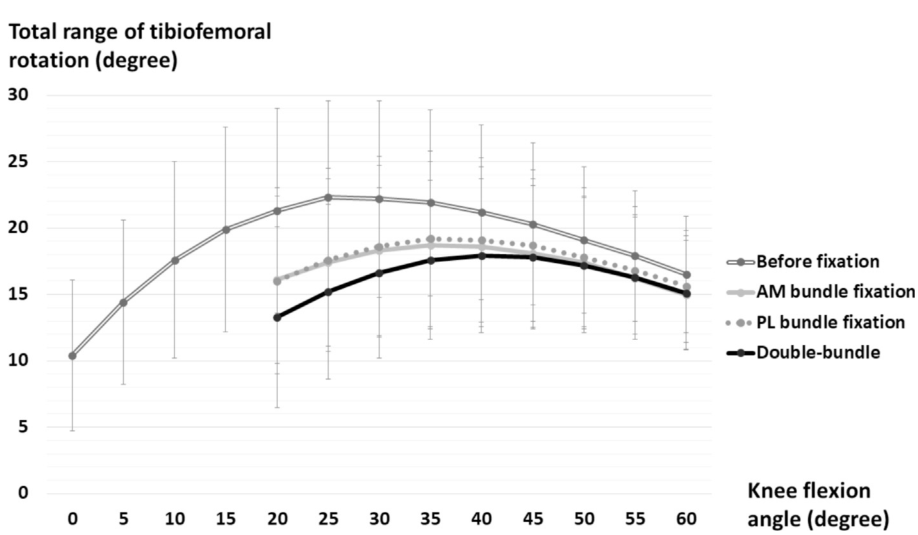

Fig. 4. Total range of isolated tibiofemoral rotation under external and internal rotational torque of 3 Nm before reconstruction, after temporary PL bundle fixation, after AM bundle fixation, and after double-bundle reconstruction. AM, anteromedial; PL, posterolateral.

Although it is difficult to explain why the results of our study were different from those of the above studies, one of the reasons may be that we used the custom-made tibial rotation device for isolated tibial rotation stress. On the other hand, in the above previous studies, manual isolated tibial rotation stress was applied with manual maximum force. Quantitative stress of isolated tibial rotation may be desirable to evaluate accurate biomechanical function of the ACL. It has been claimed that the AM bundle is less able to restrain tibial rotation because of the lack of a moment arm, whereas the more oblique PL bundle is better aligned to restrain tibial rotation because of its greater excursion around the vertical axis in the centre of the joint.[29] However, our study showed that both the AM and PL bundles similarly control isolated tibiofemoral rotation. Moreover, Komzák et al. reported that reconstruction of the AM bundle had a greater effect on reducing internal rotation than reconstruction the PL bundle.[30] The addition of anterolateral ligament reconstruction may be desirable in patients who have massive rotational knee instability.

There are several limitations to this study. Firstly, the surgeon was not blinded to the results of the knee laxity tests, as the results were fed back on the navigation computer display after each test was performed. This could possibly have led to bias. However, we used a spring balance for the anterior drawer stress and the custom-made tibial rotation device for isolated tibial rotation stress. It is hoped that these quantitative measurements of the load could minimize the bias. Secondly, normal (contralateral) knee kinematics were not assessed during the surgery because the use of Kirschner wires to fasten transmitters to the femur and tibia of the uninjured leg was deemed to be overly invasive. Thirdly, we did not evaluate the function of the bundles in knee flexion of less than 20° because knee extension with 100 N anterior drawer stress or rotational stress to the tibia may damage the grafts during the surgery. Finally, the pivot shift test was not performed during the surgery. This is because the transmitters and the Kirschner wires that were fixed in the tibia and femur came in the way of performing the pivot shift test. Moreover, the pivot shift test is performed manually, and thus the loading was not standardized. We believe that a quantitative measurement of the load is essential to evaluate the kinematics of the knee before and after the reconstruction.

Conclusions

This in vivo study demonstrates that the AM and PL bundles function differently for controlling anterior knee laxity throughout the range of motion. The function of the AM and PL bundles was similar for controlling isolated tibiofemoral rotation. Isolated tibiofemoral rotation was significantly controlled only on double-bundle reconstruction at knee flexion angles of 20° and 25°.

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Declaration of competing interest

The authors have no conflicts of interest relevant to this article.

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