

## Tibiofemoral relationship following anatomic triple-bundle anterior cruciate ligament reconstruction

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### Abstract

**Purpose** The purpose of this study was to investigate the tibiofemoral relationship sequentially before and after anatomic triple-bundle (TB) anterior cruciate ligament (ACL) reconstruction in the same patients.

**Methods** Nine patients with complete unilateral ACL rupture participated in this study. Anatomic TB ACL reconstruction was performed using autogenous semitendinosus tendon grafts. Computed tomography images were obtained before surgery as well as 3 weeks and 6 months afterwards. During image acquisition, the patient's knees were fully extended in the supine position. Using three-dimensional computer models, anterior–posterior and medial–lateral displacement of the tibia relative to the femur were evaluated for each period, as were internal–external and varus–valgus rotation, followed by calculation of side-to-side differences in parameters. As the control group, 7 healthy volunteers were evaluated.

**Results** The tibia was located anteriorly by  $1.4 \pm 0.9$  mm and rotated internally by  $2.1 \pm 1.7^\circ$  before surgery, while the tibia was located posteriorly by  $2.0 \pm 1.2$  mm and rotated externally by  $3.4 \pm 3.5^\circ$  3 weeks after surgery. Six months after surgery, there was no significant difference between the patient and control groups.

**Conclusions** The anteriorly located and internally rotated tibia in ACL-deficient knees was over-constrained (posterior displacement and external rotation) 3 weeks after anatomic TB ACL reconstruction, but returned to the normal position 6 months afterwards. Therefore, anatomic tunnel placement, appropriate initial tension, and moderate rehabilitation can be the key for return to the normal tibiofemoral relationship after ACL reconstruction.

**Level of evidence** Therapeutic study, Level IV.

**Keywords** ACL reconstruction · Anatomic triple-bundle · Tibiofemoral relationship · Tension · Graft

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### Introduction

Abnormal tibiofemoral relationships alter the stress distributions in knee cartilages, predisposing the knee to degenerative changes including osteoarthritis [3, 12, 21, 22]. Previous studies demonstrated a difference in the tibiofemoral relationship between anterior cruciate ligament (ACL)-deficient knees and normal knees [1, 8, 23, 31]. Therefore, ACL rupture is associated with a high risk for development of osteoarthritis [7, 16, 25].

One of the aims of ACL reconstruction is to restore the normal tibiofemoral relationship. However, several studies indicated that an abnormal tibiofemoral relationship remained after single-bundle (SB) ACL reconstruction

[2, 24, 36, 40]. Thanks to recent anatomic studies and improvement of surgical instruments, anatomic double-bundle (DB) ACL reconstruction was developed to mimic the normal ACL fibre arrangement. Some studies reported normal knee kinematics after anatomic DB ACL reconstruction [13, 20, 44]. In addition, good clinical outcomes of this technique were observed in some reports [18, 28]. Thus, anatomic DB ACL reconstruction may prevent the onset of knee osteoarthritis. On the other hand, according to detailed studies on ACL, the ligament could be divided into 3 bundles: anteromedial, intermediate, and posterolateral [33, 35]. Norwood et al. [33] first reported the anatomic locations of attachment sites for the 3 ACL bundles. Biomechanical studies revealed each functional characteristic of 3 ACL bundles, suggesting that intermediate bundle supported anteromedial and posterolateral bundles especially in flexion angles [11, 14, 17]. Fujie et al. [11] suggested that the anteromedial bundle is the primary stabilizer to tibial anterior drawer through wide range of motion and the posterolateral bundle is the crucial stabilizer at full extension, while the intermediate bundle is the secondary stabilizer in deep flexion angles. Thus, in order to more closely mimic the fibre arrangement and triangular tibial footprint of the normal ACL, the technique of anatomic triple-bundle (TB) ACL reconstruction with 1 bifurcated anterior graft through 2 separate anterior tibial tunnels was introduced, according to the operative procedure reported by Shino et al. [38]. Tanaka et al. [39] noted that the morphology of the transplanted grafts resembled that of the natural ACL at second-look arthroscopy after anatomic TB ACL reconstruction. Mae et al. [29] reported better immediate postoperative anterior knee stability of TB technique compared with DB technique, indicating that TB technique could stabilize the knee more efficiently.

However, the time point at which the altered tibiofemoral relationship returns to normal after anatomic ACL reconstruction remains unclear. Few studies have sequentially evaluated changes in the tibiofemoral relationship after ACL reconstruction, although these changes are important for determining rehabilitation programmes or activity levels. The objective of this study was to investigate the tibiofemoral relationship sequentially before and after anatomic TB ACL reconstruction using three-dimensional (3D) computer models in the same patients. It was hypothesized that the tibia was over-constrained (posterior displacement and external rotation) immediately after surgery but then returned to the normal position with graft remodelling.

## Materials and methods

Nine patients with complete unilateral ACL rupture participated in this study. There were 3 males and 6 females.

Their age ranged from 13 to 50 years, with a median of 21 years. No patients had any other ligament injury, while 4 had medial meniscal tears and 5 had lateral meniscal tears. For medial meniscal tears, 3 patients underwent meniscal repair and 1 underwent partial meniscectomy. For lateral meniscal tears, 3 patients underwent meniscal repair and 2 underwent partial meniscectomy. There was no articular cartilage damage more severe than grade II [37].

## Surgical procedure

Anatomic TB ACL reconstruction was performed using autogenous semitendinosus tendon grafts [38]. After cleaning up the ACL remnant around the femoral attachment area, an almost longitudinal linear “resident’s ridge” was visualized on the wall. Using an anterolateral entry aimer (Smith & Nephew Endoscopy, Andover, MA, USA), two 2.4-mm guide pins were inserted from the lateral cortex of the femur to the footprint of the anteromedial and posterolateral ACL bundles behind the ridge and just anterior to the articular cartilage margin [15]. Both pins were then over-drilled with cannulated drill bits of appropriate diameter (5–6 mm) in an outside-in manner. For the tibia, three 2.4-mm guide pins were inserted from the medial cortex of the tibia to the attachment of the anteromedial, intermediate, and posterolateral bundles with a drill guide system (Smith & Nephew Endoscopy, Andover, MA, USA). These pins were then over-drilled with cannulated drill bits of appropriate diameter (anteromedial and intermediate tunnels, 4.5–5.0 mm; posterolateral tunnel, 5–6 mm).

The previously harvested semitendinosus tendon was transected into half and folded. An EndoButton-CL (Smith & Nephew Endoscopy, Andover, MA, USA) of appropriate length chosen on the basis of femoral tunnel length was placed at the loop end of the graft. For the 2 anteriorly located grafts (anteromedial and intermediate grafts), No. 3 polyester sutures were placed at each free end of 1 bifurcated graft with whip stitches. For the posterolateral graft, 1 double-looped graft was made by placing two No. 3 polyester sutures at the free end with whip stitches.

The posterolateral graft was passed through the tibial tunnel to the femoral tunnel and fixed on the lateral femoral cortex by turning the EndoButton. The loop end of the bifurcated anteriorly located graft was passed through the far anteromedial portal to the femoral tunnel, and it was then fixed on the lateral femoral cortex by turning the EndoButton. The free ends of the graft were introduced into the joint and passed through the anteromedial and intermediate tibial tunnels in an inside-out manner. Consequently, the anteriorly located grafts (anteromedial and intermediate grafts) ran from 1 femoral tunnel to 2 tibial tunnels.

Sutures from the posterolateral graft and anteriorly located grafts (anteromedial and intermediate grafts) were then tied to 2 double-spike plates (DSP; Meira Corp., Nagoya, Japan). The tensioning sutures distally connected to the 2 DSPs were tied to the tensioners mounted on a metal shell boot bandaged to the tibia. We then applied 10 N of initial tension to each tensioning suture (total, 20 N) at 20° knee flexion, and the creep of the construct was removed by repeatedly tightening the tensioners connected to the graft sutures for 5 min at the same position. Finally, the DSPs connected to the grafts were fixed to the tibia at the same position, with a total of 20 N of initial tension.

### Rehabilitation programme

After brace immobilization for 1 week, range-of-motion exercise was started. Partial weight bearing was allowed 2 weeks after ACL reconstruction, and full weight bearing was started at 4 weeks. Jogging was allowed 3 months after surgery, and jumping was permitted at 6 months. Resumption of previous sporting activities was then permitted at 7–9 months, depending on the recovery of quadriceps muscle power.

### Construction of 3D surface bone model

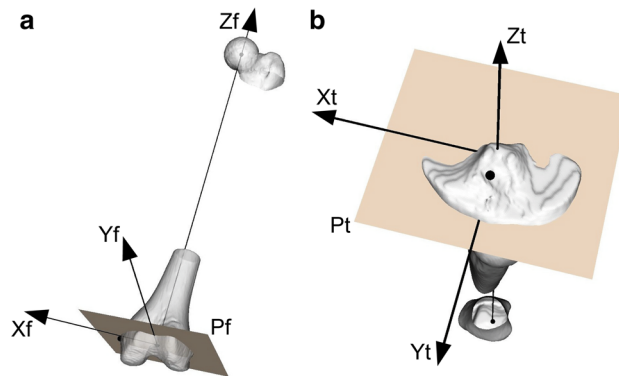
Before surgery, bilateral computed tomography (CT) images of the hip, knee, and ankle joints were obtained using a helical CT scanner (Discovery CT750HD; General Electric, Waukesha, WI, USA). During image acquisition, the patient's knees were fully extended in the supine position with the thighs supported by a holder to keep the patellae upwards. No patients had any loss of range of motion. Follow-up CT imaging of the operated knee was performed at 3 weeks and 6 months after ACL reconstruction, with the leg in the same position. Tube current/voltage for the hips, knees, and ankles was 80 mA/120 kV, 100 mA/120 kV, and 45 mA/120 kV, respectively, and scan length was 9, 22, and 6 cm, respectively. Slice thickness was 1.25 mm.

Data were obtained in the Digital Imaging and Communications in Medicine format and were sent to a workstation (Dell Precision M6500; Dell, Round Rock, TX, USA). The femoral head, distal femur, and proximal/distal tibia were segmented from CT images, and then, 3D surface models were constructed by the marching cubes algorithm [26, 34]. The models were composed of numerous tiny triangles, each containing the positional data for 3 points. The images were viewed using a modified version of Visualization Tool Kit software (Kitware Inc., Clifton Park, NY, USA).

### Data analysis

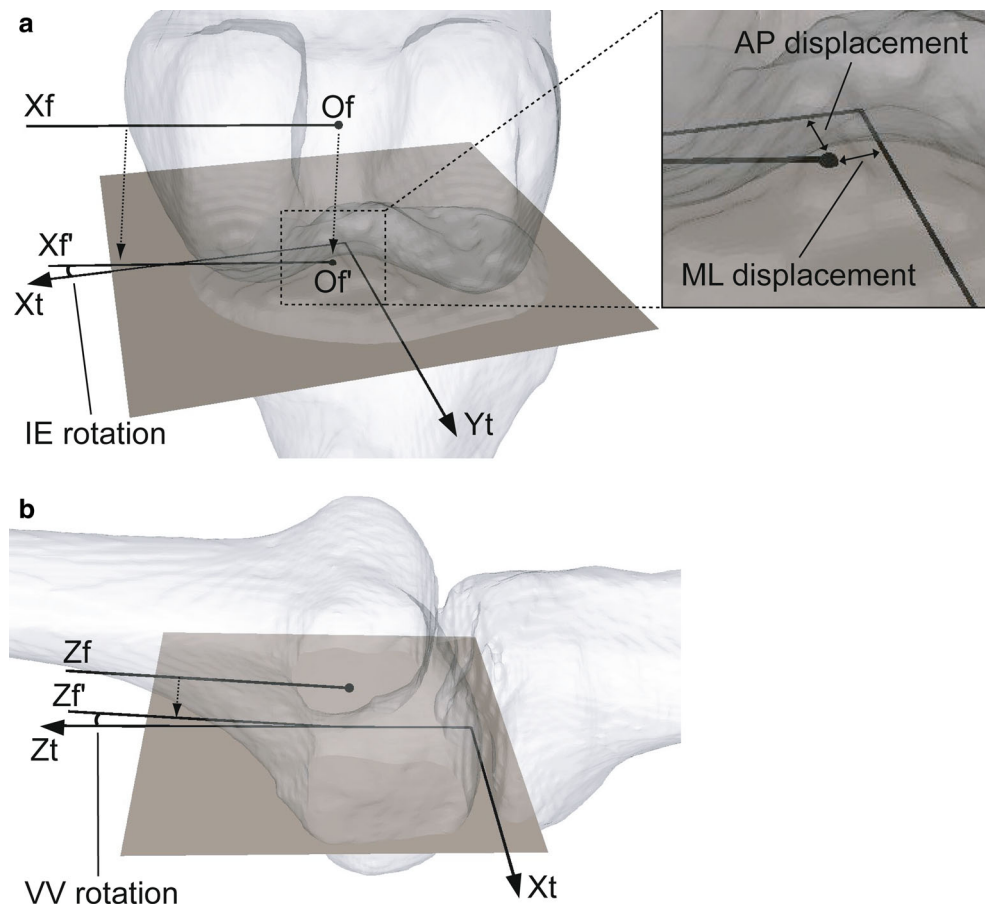
The anatomic femoral coordinate system was based on the centre of the femoral head and the medial/lateral epicondyles. The anatomic tibial coordinate system was based on the centre of the footprint of ACL/posterior cruciate ligament (PCL) and the centre of the ankle. These details are described in Fig. 1. The coordinate systems of ACL-deficient and ACL-reconstructed knees were created by superimposing the mirror images of normal knees.

Anterior–posterior (AP) and medial–lateral (ML) displacement of the tibia relative to the femur were evaluated for each period, as were internal–external (IE) and varus–valgus (VV) rotation of the tibia relative to the femur (Fig. 2), followed by calculation of side-to-side differences in parameters. Positive values indicated anterior/medial displacement and internal/varus rotation of the tibia relative to the femur. The reliability calculations were based on side-to-side differences in 4 parameters measured by the same observer (3 times repeat) and by 3 different observers. The intra- and inter-observer intra-class correlation coefficient (ICC) and standard deviation (SD) are shown in Table 1.



**Fig. 1** Coordinate systems. **a** The femoral coordinate system was based on the centre of the femoral head and the medial/lateral epicondyles. The line between medial and lateral epicondyles was defined as transepicondylar axis (TEA). The midpoint of TEA was defined as the femoral origin (*Of*). The femoral Z-axis (*Zf*) was created between *Of* and the centre of the femoral head. A plane (*Pf*) perpendicular to *Zf* was set at *Of*. The femoral X-axis (*Xf*) was created by projecting TEA to *Pf*. The femoral Y-axis (*Yf*) was created by taking the cross-product of *Zf* and *Xf*. **b** The tibial coordinate system was based on the centre of the footprint of ACL/PCL and the centre of the ankle. The line between the insertion sites of ACL and PCL was defined as anterior–posterior axis (APA). The midpoint of APA was defined as the tibial origin (*Or*). The tibial Z-axis (*Zt*) was created between *Or* and the centre of the ankle. A plane (*Pt*) perpendicular to *Zt* was set at *Or*. The tibial Y-axis (*Yt*) was created by projecting APA to *Pt*. The tibial X-axis (*Xt*) was created by taking the cross-product of *Zt* and *Yt*

**Fig. 2** **a**  $O_f'$  and  $X_f'$  were created by projecting the femoral origin ( $O_f$ ) and X-axis ( $X_f$ ) to the tibial  $XY$  plane. *AP* displacement was defined as the distance between  $O_f'$  and the tibial X-axis ( $X_t$ ). *ML* displacement was defined as the distance between  $O_f'$  and the tibial Y-axis ( $Y_t$ ). *IE* rotation was defined as the angle between  $X_f'$  and  $X_t$ . **b**  $Z_f'$  was created by projecting the femoral Z-axis ( $Z_f$ ) to the tibial  $ZX$  plane. *VV* rotation was defined as the angle between  $Z_f'$  and the tibial Z-axis ( $Z_t$ )



**Table 1** The intra-observer and inter-observer intra-class correlation coefficient (ICC) and standard deviation (SD) for side-to-side differences in 4 parameters

	Intra-observer		Inter-observer	
	ICC	SD	ICC	SD
AP displacement (mm)	0.97	0.1	0.92	0.2
ML displacement (mm)	0.98	0.1	0.87	0.3
IE rotation (deg.)	0.68	0.2	0.52	0.4
VV rotation (deg.)	0.99	0.2	0.98	0.2

*AP* anterior–posterior, *ML* medial–lateral, *IE* internal–external, *VV* varus–valgus, *deg.* degree

**Control group**

As the tibial position relative to the femur was quite influenced by the individual anatomy and size of the knee, the side-to-side difference in each measured parameters was evaluated to minimize these influences. Then, the side-to-side difference of healthy control volunteers was used to compare the tibial position of the ACL-deficient and ACL-reconstructed knees with that of the normal knees.

As the control group, 7 healthy volunteers (4 men and 3 women) were participated in this study (Table 2). There was no significant difference between the 2 groups except for Tegner activity level. However, effect of low activity was very little in the control group, as we compared the knee laxity of the one knee with that of the other knee in the same volunteers. CT images were obtained in the above-mentioned manner, and 3D surface models were constructed. The position of the tibia relative to the femur was evaluated in the same way as for the patient group, followed by calculation of side-to-side differences (right minus left).

**Clinical stability testing**

Knee laxity was evaluated using the KT-2000 Knee Arthrometer (MEDmetric, San Diego, CA, USA) with manual maximum anterior load before surgery under anaesthesia and 6 months after ACL reconstruction.

We obtained informed consent from all subjects, and the appropriate institutional review board of Osaka University Hospital for human subject research approved the study protocol (ID: 09157-2).

**Table 2** Demographic data of the patient and control groups

	Patient group	Control group	<i>P</i> values
Number	9	7	
Age (years)	25.7 ± 11.3	29.6 ± 7.2	n.s.
Gender (male/female)	3/6	4/3	n.s.
Height (cm)	163.8 ± 7.9	169 ± 7.3	n.s.
Weight (kg)	61.6 ± 9.5	61.4 ± 15.6	n.s.
Tegner activity level	6 (3–7)	4 (3–4)	0.002

Values are expressed as mean ± standard deviation in age, height, and weight. Gender is expressed as number and Tegner activity level as median (range)

Differences of age, height, and weight were evaluated by the Wilcoxon rank sum test and those of gender and Tegner activity level by the Fisher's exact test and the  $\chi^2$  test, respectively

n.s. not significant

### Statistical analysis

All statistical tests were performed with JMP software (version 9.0.2; SAS Institute Inc., Cary, NC, USA). A power analysis, with a power of 0.8 being considered acceptable, showed that a minimum of 7 patients was required for comparison. The Wilcoxon signed rank test was used to detect statistically significant differences within the patient group, and the Wilcoxon rank sum test to

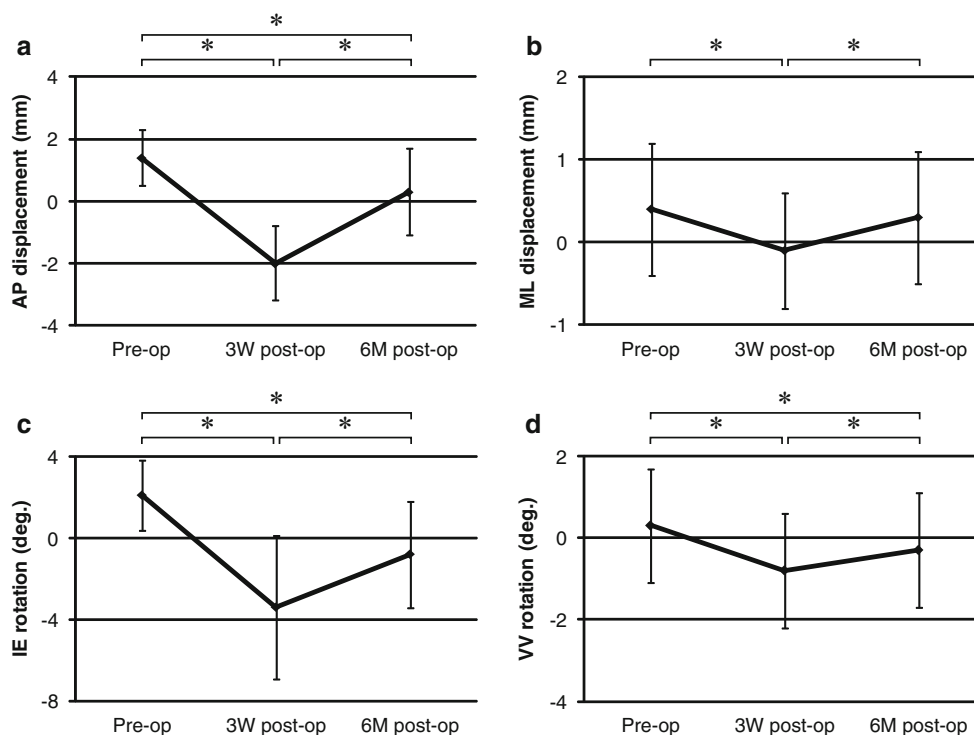
compare the patient and control groups. Differences were considered statistically significant at  $P < 0.05$ .

### Results

Within the patient group, compared with the state before surgery, AP and ML displacement significantly decreased 3 weeks after surgery; IE and VV rotation also decreased significantly (Fig. 3). All parameters significantly increased from 3 weeks to 6 months after surgery.

Compared with the control group, AP displacement and IE rotation in the patient group were  $1.4 \pm 0.9$  mm and  $2.1 \pm 1.7^\circ$  and were significantly greater than those in the control group ( $0.1 \pm 1.0$  mm and  $0.1 \pm 2.0^\circ$ ) before surgery (Table 3). Three weeks after surgery, AP displacement and IE rotation in the patient group were  $-2.0 \pm 1.2$  mm and  $-3.4 \pm 3.5^\circ$  and were significantly lesser. ML displacement and VV rotation exhibited no significant difference between the patient and control groups before surgery or 3 weeks after surgery. Then, there was no significant difference between the patient and control groups in AP/ML displacement or IE/VV rotation 6 months after anatomic TB ACL reconstruction.

Side-to-side difference with KT-2000 Knee Arthrometer in response to manual maximum anterior load decreased from



**Fig. 3** Sequential changes of the tibial position in the patient group. **a** AP displacement. **b** ML displacement. **c** IE rotation. **d** VV rotation. Positive values indicate anterior/medial displacement and internal/varus rotation of the tibia. \* $P < 0.05$



**Table 3** Tibial position of the patient and control groups

	AP displacement (mm)	ML displacement (mm)	IE rotation (deg.)	VV rotation (deg.)
Control (R – L)	0.1 ± 1.0	0.3 ± 0.8	0.1 ± 2.0	0.3 ± 0.9
Pre-op	1.4 ± 0.9*	0.4 ± 0.8	2.1 ± 1.7*	0.3 ± 1.4
3 W post-op	–2.0 ± 1.2*	–0.1 ± 0.7	–3.4 ± 3.5*	–0.8 ± 1.4
6 M post-op	0.3 ± 1.4	0.3 ± 0.8	–0.8 ± 2.6	–0.3 ± 1.4

Positive values indicate anterior/medial displacement and internal/varus rotation of the tibia

AP anterior–posterior, ML medial–lateral, IE internal–external, VV varus–valgus, R – L right minus left, pre-op preoperatively, 3 W post-op 3 weeks postoperatively, 6 M post-op 6 months postoperatively, deg. degree

\* Significant difference compared with the control group ( $P < 0.05$ )

$6.8 \pm 2.2$  mm before surgery to  $0.3 \pm 1.6$  mm at 6 months after surgery with a significant difference ( $P = 0.002$ ).

## Discussion

The principal finding of the present study was that the anteriorly located and internally rotated tibia in ACL-deficient knees was over-constrained (posterior displacement and external rotation) 3 weeks after the anatomic TB ACL reconstruction but then returned to the normal position 6 months afterwards. This finding suggested that the anatomic TB ACL reconstruction could restore the normal tibiofemoral relationship. In addition, to our knowledge, this is the first report investigating the tibiofemoral relationship sequentially before and after anatomic ACL reconstruction in the same patients.

The normal ACL runs from the medial wall of the lateral femoral condyle to the anteromedial aspect of the tibial plateau and has a role in maintaining the normal tibiofemoral relationship. Then, in case of ACL rupture, it is easily estimated that the tibia translates anteriorly and rotates internally. This abnormal tibiofemoral relationship initiates the development of degenerative changes. DeFratre et al. [8] reported that the tibia translated anteriorly by 3 mm and rotated internally by  $2^\circ$  in ACL-deficient knees under weight-bearing conditions. Mishima et al. [31] indicated an anterior tibial subluxation of 2.1 mm in such knees under conditions of non-weight bearing. In the present study, the tibia translated anteriorly by 1.4 mm and rotated internally by  $2.1^\circ$  in the absence of weight bearing. Markolf et al. [30] reported that ACL tension was 56 N at full extension without any external force applied, suggesting that the tibiofemoral relationship is influenced by ACL tension at full extension. Thus, even in the absence of weight bearing, the tibia shifts anteriorly and rotates internally in ACL-deficient knees at full extension.

In the current study, 3 weeks after surgery, the tibia was located posteriorly and rotated externally compared with the control group. In the previous biomechanical studies, the excessive graft tension caused posterior displacement

and external rotation of the tibia compared with normal knees [27]. The concept of the TB technique is to more closely mimic the fibre arrangement of the normal ACL [33, 35, 38]. At the second-look arthroscopy after TB technique, Tanaka et al. [39] noted that the morphology of the transplanted grafts was very similar to the natural ACL. On the other hand, Mae et al. [29] indicated that TB technique could stabilize the knee more efficiently than DB technique immediately after surgery. Therefore, the findings of the present study indicated that the grafts were over-tensioned 3 weeks after ACL reconstruction, even though the initial tension was only 20 N. Mae et al. [28] previously reported a side-to-side difference in anterior laxity of  $-3.7$  mm immediately after anatomic DB ACL reconstruction with 20 N of initial tension. Therefore, the over-constrained condition immediately after surgery remained in force for 3 weeks. Some workers recommend accelerated rehabilitation, which encourages full weight bearing 1–2 weeks after surgery [5, 42]. However, we do not recommend such a course of action because the abnormal tibiofemoral relationship was still present 3 weeks after ACL reconstruction.

From 3 weeks to 6 months after ACL reconstruction, the tibia moved anteriorly and medially and showed internal and varus rotation. Previous animal studies suggested that grafts loosened somewhat through the remodelling process until 6 months after surgery [4, 6, 10]. Therefore, graft remodelling through the processes of necrosis, cell ingrowth, revascularization, and ligamentization might result in postoperative changes in the tibiofemoral relationship in this study [41, 43].

Among other studies to evaluate the tibiofemoral relationship in ACL-reconstructed knees, Papannagari et al. [36] and Deneweth et al. [9] reported that an abnormal tibiofemoral relationship was still evident 3–4 months after ACL reconstruction with anterior tibial translation. On the other hand, Kopf et al. [20] indicated that anatomic DB ACL reconstruction restored knee kinematics to normal. In this study, we evaluated the tibiofemoral relationship at 2 time points: 3 weeks and 6 months after anatomic TB ACL reconstruction. As a result, the tibia was over-constrained at 3 weeks but then returned to the normal position

6 months after surgery. The clinical relevance of this study is that anatomic tunnel placement, appropriate initial tension, and moderate rehabilitation can be the key for return to the normal tibiofemoral relationship after ACL reconstruction.

There are some limitations in this study. First, we evaluated the tibiofemoral relationship in only 1 position: full extension. Although evaluation at various flexion angles might have been useful, previous reports showed the most significant difference at full extension between the normal and ACL-deficient knees [8, 36]. Therefore, the tibiofemoral relationship was investigated only at full extension. Second, we used only an operative technique: anatomic TB ACL reconstruction with 20 N of initial tension. We might have to compare the tibiofemoral relationship after TB technique with that after DB technique, while we have performed TB technique since 2004 because of morphological and biomechanical advantages. However, it may not matter which of SB, DB, or TB technique ACL is reconstructed with [19]. We consider that “anatomic reconstruction” including anatomic tunnel placement is the most important matter. In addition, although a different initial tension might have led to different results, excessive tension might have caused graft failure or articular cartilage degeneration. Therefore, we adopted 20 N as the minimally required initial tension. Third, our follow-up period was extended to only 6 months after surgery. According to the previous report [28], there was no significant change of the side-to-side difference in anterior knee laxity from 3 to 24 months after ACL reconstruction. Thus, the normal tibiofemoral relationship in this study was expected to continue beyond 6 months after surgery. However, we have to meticulously follow-up the tibiofemoral relationship and elucidate whether osteoarthritis will develop. Fourth, 1 patient underwent partial medial meniscectomy in this study. Musahl et al. [32] described that anterior tibial translation significantly increased in the ACL-deficient knee after total medial meniscectomy during Lachman examination. Thus, in order to demonstrate the superiority of ACL reconstruction, we should have recruited only the patients without meniscal tears. However, as the tibia was located posteriorly and rotated externally 3 weeks after surgery and returned to the normal position 6 months afterwards, partial meniscectomy had only a small effect on the result of this study. Finally, the sample size is small.

## Conclusions

The anteriorly located and internally rotated tibia in ACL-deficient knees was over-constrained (posterior displacement and external rotation) 3 weeks after anatomic TB ACL

reconstruction, but returned to the normal position 6 months afterwards. Therefore, anatomic tunnel placement, appropriate initial tension, and moderate rehabilitation can be the key for return to the normal tibiofemoral relationship after ACL reconstruction.

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**Conflict of interest** The authors declare that they have no conflict of interest.

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