



Contents lists available at ScienceDirect

# Asia-Pacific Journal of Sports Medicine, Arthroscopy, Rehabilitation and Technology

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## Lateral posterior tibial slope does not affect femoral but does affect tibial tunnel widening following anatomic anterior cruciate ligament reconstruction using a Bone–Patellar Tendon–Bone graft



Shuji Taketomi\*, Hiroshi Inui, Ryota Yamagami, Keiu Nakazato, Kohei Kawaguchi, Kenichi Kono, Shin Sameshima, Tomofumi Kage, Sakae Tanaka

Department of Orthopaedic Surgery, Faculty of Medicine, The University of Tokyo, Tokyo, Japan

### ARTICLE INFO

#### Article history:

Received 30 January 2022  
Received in revised form  
17 July 2022  
Accepted 21 September 2022

#### Keywords:

Tunnel widening  
Lateral posterior tibial slope  
Bone–patellar tendon–bone graft  
Anterior cruciate ligament

### ABSTRACT

**Background:** Tunnel widening (TW) after anterior cruciate ligament (ACL) reconstruction has been a research area of interest in ACL reconstruction. In recent years, it has been noted that posterior tibial slope (PTS) affects several types of outcomes after ACL reconstruction including TW. However, the relationships between femoral and tibial TW and between PTS and TW following anatomical ACL reconstruction using a bone–patellar tendon–bone (BTB) graft are often not understood. Therefore, the purpose of this study was to retrospectively clarify the magnitude of femoral and tibial TW and the effect of PTS on TW following anatomical ACL reconstruction using a BTB graft.

**Methods:** A total of 111 patients who underwent isolated ACL reconstructions using BTB grafts were included in this study. Femoral and tibial tunnel aperture areas were measured using three-dimensional computed tomography (3D CT) at 1 week and 1 year postoperatively, and femoral and tibial TW (%) was calculated. Lateral and medial PTS was also measured using 3D CT.

**Results:** As compared with 1 week postoperatively, the mean tibial tunnel aperture areas increased by  $30.6\% \pm 28.5\%$ , and the mean femoral tunnel aperture areas increased by  $28.3\% \pm 27.9\%$  when measured at 1 year postoperatively. Although no significant difference was observed between femoral and tibial TW, a significant positive correlation was noted between femoral and tibial TW ( $r = 0.240$ ,  $p = 0.011$ ). A significant correlation was observed only between lateral PTS and tibial TW ( $r = 0.354$ ,  $p < 0.001$ ). There was no significant correlation between medial PTS and tibial TW, lateral PTS and femoral TW, or medial PTS and femoral TW.

**Conclusion:** Significant positive correlation was observed between femoral and tibial TW. Steeper lateral PTS correlated with greater tibial TW; on the other hand, medial PTS did not correlate with tibial TW. Although lateral PTS affected tibial TW, it did not affect femoral TW.

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## 1. Introduction

Tunnel widening (TW) following anterior cruciate ligament (ACL) reconstruction is a well-known phenomenon.<sup>1</sup> Although most previous studies have reported that TW after ACL reconstruction does not affect the short-term clinical outcome,<sup>2,3</sup> at the very least, TW is a potential problem should a revision procedure be needed.<sup>1,2,4</sup> TW is also considered to be an indication of poor

tunnel-graft healing, and there are concerns that it could lead to laxity in the long term. In recent years, it has been noted that posterior tibial slope (PTS) affects several types of outcomes after ACL reconstruction, such as static anterior tibial translation,<sup>5</sup> graft failure rate,<sup>6</sup> and TW.<sup>7</sup> The influence of lateral PTS is found to be particularly significant. Several studies have found that increased lateral PTS results in greater TW after ACL reconstruction.<sup>7–9</sup>

Recently, ACL reconstruction has focused on the anatomical reconstruction of the ligament to restore the original footprint and normal kinematics of the knee. It has become possible to perform anatomical ACL reconstruction not only with hamstring grafts but also with bone–patellar tendon–bone (BTB) grafts, using the

\* Corresponding author. 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-8655, Japan.  
E-mail address: [takeos-tky@umin.ac.jp](mailto:takeos-tky@umin.ac.jp) (S. Taketomi).

anatomical rectangular tunnel procedure.<sup>10</sup> However, most of the previous papers focused on TW after conventional nonanatomical ACL reconstruction using round tunnel, and there is a lack of studies on TW after anatomical ACL reconstruction. In addition, there are few published papers studying TW after anatomical ACL reconstruction using BTB grafts, and many of these previous studies treated femoral and tibial TW individually as separate events.<sup>7,11–13</sup> Therefore, the correlation between femoral and tibial TW after anatomical ACL reconstruction using BTB grafts has not been fully understood. Even among the papers that studied the relationship between PTS and TW, most examined only the effects on the tibial side of TW,<sup>7–9</sup> and the effects on the femoral side of TW have rarely been investigated.

Therefore, the purpose of this study was to retrospectively clarify the magnitude of femoral and tibial TW and the effect of PTS on TW following anatomical ACL reconstruction using a BTB graft. We hypothesized that there was a correlation between femoral and tibial TW and steeper lateral PTS increased both femoral and tibial TW following anatomical ACL reconstruction using a BTB graft. If there is a correlation between PTS and TW, it will be possible to predict TW to some extent preoperatively.

## 2. Materials and methods

### 2.1. Patients

A total of 155 consecutive patients underwent ACL reconstruction using a BTB graft at our institute between October 2013 and December 2017. Among these, 111 patients were included in this study. The exclusion criteria were as follows: (1) previous intra-articular ligament reconstruction, (2) previous osteotomy around the knee joint, (3) previous contralateral ACL reconstruction, and/or (4) the presence of posterior cruciate ligament insufficiency, abnormal varus/valgus instability, or concomitant reconstruction of other ligaments. In total, 29 patients were excluded: 11, 4, 8, and 6 owing to the first, second, third, and fourth exclusion criteria, respectively. In addition, 2 patients suffered from reinjury before the end of the 1-year postoperative follow-up period, and 13 patients were lost to follow-up. Our final analysis included 30 females and 81 males with a median age of 29 years (range, 14–58 years). **Table 1** summarizes the basic patient information. Our local institutional review board approved this retrospective study. Patients and their families were informed that data from their cases would be submitted for publication; all included patients provided written informed consent.

### 2.2. Surgical procedure

We harvested autologous BTB grafts from the central portion of the patellar tendon, which were 10-mm wide with bone plugs at either end.<sup>14</sup> The femoral bone plug for a rectangular tunnel was usually 6 × 10 × 15 mm, as described by Shino et al.<sup>10</sup> The femoral insertion site was determined after evaluating bony landmarks (i.e., the lateral intercondylar ridge and the lateral bifurcate ridge).<sup>15</sup> Our

priority in creating the femoral tunnel was to position the femoral tunnel apertures as posteriorly and proximally as possible within the femoral footprint of the ACL.<sup>16</sup> A rectangular socket (6 mm height × 10 mm width × 21 mm depth) was created through a far anteromedial (AM) portal.<sup>17</sup> On the tibial side, a rectangular tunnel (6 × 10 mm) was created using the outside-in technique. Both the femoral and tibial tunnels were drilled using a 6-mm cannulated drill and completed using a rectangular dilator with a diameter of 6 mm × 10 mm (Smith & Nephew Endoscopy, Andover, MA). In creating the tibial tunnels, our priority was to position the tibial tunnel apertures as anteriorly and medially as possible within the tibial footprint of the ACL in reference to the ACL remnant, the medial tibial eminence, the anterior horn of the lateral meniscus, the intermeniscal ligament, and the posterior cruciate ligament.<sup>18,19</sup> EndoButton (Smith & Nephew Endoscopy) was used for femoral fixation. The BTB graft was fixed using a double-spike plate small (Smith & Nephew Endoscopy) and a half-threaded 5.0-mm cancellous screw. This was fixed at full knee extension with 80 N pull using a ligament tensioner (Smith & Nephew Endoscopy).<sup>16</sup>

### 2.3. Postoperative rehabilitation

Identical rehabilitation protocols were applied to all patients. In brief, the knee was not immobilized but was protected for 6 weeks using a functional brace. Immediately after the surgery, active and assisted range-of-motion exercises were commenced. The patients commenced partial weight bearing at 2 days postoperatively and full weight bearing at 1 week postoperatively. Patients were permitted to run at 4 months postoperatively and were allowed to return to previous sporting activities at an average of 8–9 months after the operation.

### 2.4. Computed tomography (CT) evaluation

For all patients, three-dimensional (3D) CT was performed on the reconstructed knee at 1 week and 1 year postoperatively using a helical high-speed Aquilion PRIME, Aquilion precision, or Aquilion ONE (Toshiba Medical Systems Co., Japan) CT machine. To create a 3D reconstruction of the knee, we used the ZIOSTATION software package (Ziosoft Inc., Tokyo, Japan).

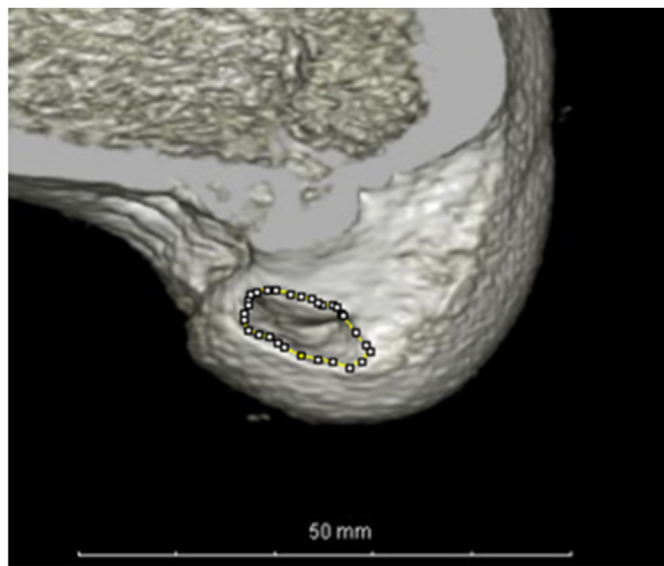
To evaluate femoral TW, the tibia, patella, and medial femoral condyle were removed from the 3D model, because it was necessary to visualize the lateral wall of the intercondylar notch. By superimposing the posterior aspects of the femoral condyles, a true medial view of the femur was established. To ensure accuracy and consistency, all measurements were acquired from the surface of the lateral wall of the intercondylar notch from an orthogonal projection to the angle of the surface being measured. To evaluate the tibial TW, the 3D model of the proximal tibia was realigned to obtain a true proximal-to-distal view. The femoral and tibial tunnel aperture area was measured using ImageJ software (National Institutes of Health, Bethesda, MD, USA), which was calibrated to the scale of the CT image (Figs. 1 and 2).<sup>20</sup> It was previously reported that the method used to measure the tunnel aperture area using ImageJ software had excellent reliability. The intra- and interobserver reliabilities were reported using the intraclass correlation coefficient (0.97 and 0.94, respectively).<sup>11</sup> We used the tunnel aperture area measured at 1 week postoperatively as the baseline measurement, which was then compared with the diameter measured during the 1-year postoperative follow-up. Then, the proportional variation in tibial tunnel aperture area between the two points, defined as TW (%), was determined.

The medial and lateral PTS were measured using CT according to the previously reported method.<sup>7,9,21</sup> To determine the longitudinal axis of the tibia, the central sagittal CT slice with the following

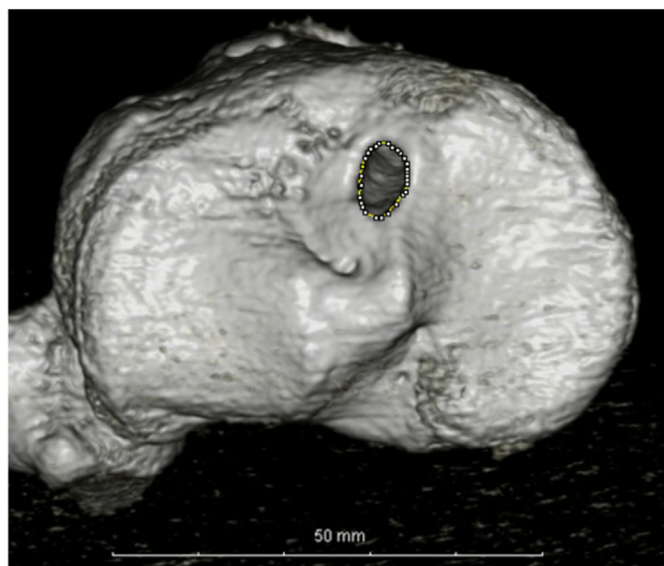
**Table 1**  
Patient information.

Number of patients	111
Gender (female/male)	30/81
Age (years)	29 (14–58)
Body height (cm)	169.2 ± 7.4
Body mass index (kg/m <sup>2</sup> )	23.7 ± 3.8
Tegner activity scale	7 (3–10)

Data are given as mean ± standard deviation or median (range).



**Fig. 1.** Measurements of the femoral tunnel aperture area on 3D CT. A snapshot of the lateral half of the femur (along with an appropriate scale bar) was downloaded onto a computer. The area of the femoral tunnel aperture was manually traced, and the area was analyzed using ImageJ software (National Institute of Health, Bethesda, MD, USA) calibrated to the scale of the computed tomography image.



**Fig. 2.** Measurements of the tibial tunnel aperture area on 3D CT. A true proximal-to-distal view of the proximal tibia (along with an appropriate scale bar) was downloaded onto a computer. The area of the tibial tunnel aperture was manually traced and analyzed using ImageJ software (National Institutes of Health, Bethesda, MD, USA) calibrated to the scale of the computed tomography image.

criteria was used: (1) the anterior and posterior proximal tibial cortices be seen in concave shape and (2) intercondylar eminence and its PCL attachment. A circle was fitted to the proximal tibia, tangential to the cortices, and a second circle was fitted distally with its center placed on the border of the first circle. The line connecting the center of these two circles was known as the longitudinal axis (Fig. 3A). The mid-sagittal images of the medial and lateral tibiofemoral compartments were selected using a coronal view. The medial and lateral PTS were determined by the angle between the axis perpendicular to the longitudinal axis and the line

connecting the most proximal anterior and posterior subchondral bone points of the medial and lateral tibiofemoral compartments (Fig. 3B). A prior study also reported that the interrater intraclass correlation coefficient of PTS measurements using this method was 0.803, which was highly reliable.<sup>9</sup> Two investigators (K.N. and S.T.) conducted the CT measurements.

### 2.5. Statistical analysis

Statistical analysis was performed using BellCurve for Excel (SSRI Co., Ltd., Tokyo, Japan). Femoral and tibial TW were compared using Student's t-test, and the correlation coefficient between the tibial slope and TW was calculated. The correlation coefficient between femoral TW and tibial TW was also calculated. Statistical significance was set at  $p < 0.05$ .

## 3. Results

As compared with 1 week postoperatively, the mean tibial tunnel aperture areas increased by  $30.6\% \pm 28.5\%$ , and the mean femoral tunnel aperture areas increased by  $28.3\% \pm 27.9\%$  when measured at 1 year postoperatively. Although no significant difference was observed between femoral and tibial TW, a significant positive correlation was noted between femoral and tibial TW ( $r = 0.240$ ,  $p = 0.011$ ; Fig. 4).

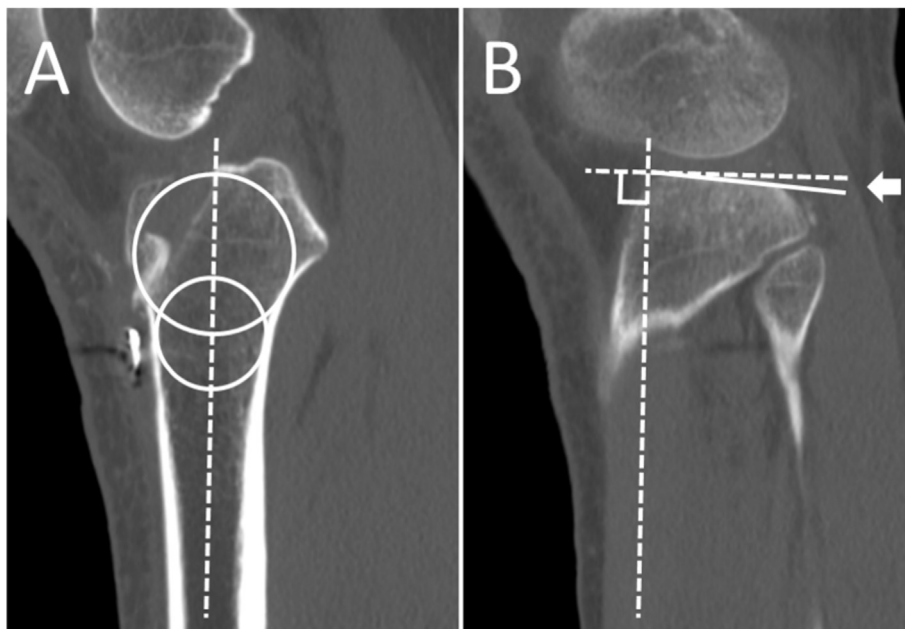
The mean medial PTS was  $6.1 \pm 2.4^\circ$ , and the mean lateral PTS was  $6.3 \pm 2.8^\circ$ . A significant correlation was observed only between lateral PTS and tibial TW ( $r = 0.354$ ,  $p < 0.001$ ; Fig. 5). There was no significant correlation between the medial PTS and tibial TW, lateral PTS and femoral TW, or medial PTS and femoral TW ( $p = 0.21$ ,  $0.59$ , and  $0.42$ , respectively).

CT images of a small and a large example of TW are shown to facilitate the image of TW (Figs. 6 and 7).

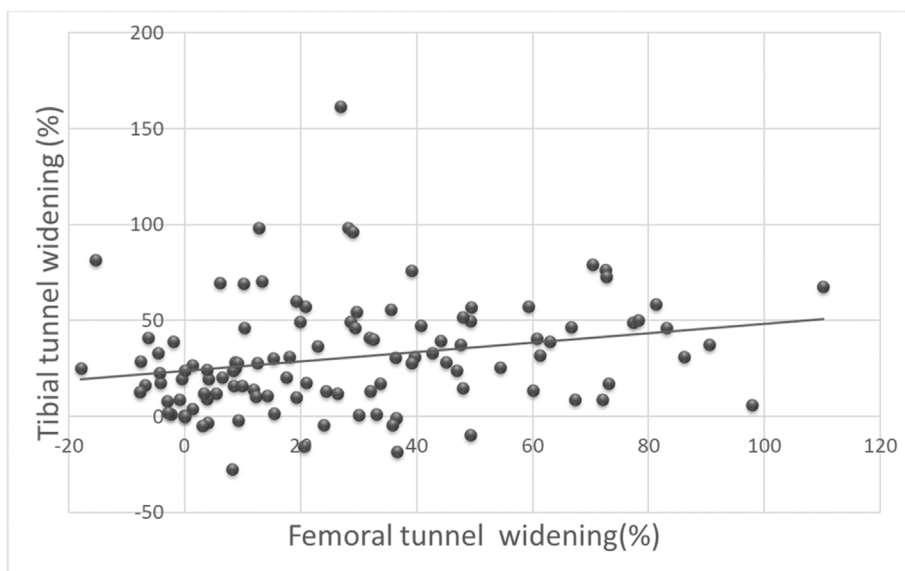
## 4. Discussion

There are two important findings in the current study. A most important finding was that a steeper lateral PTS was correlated with a greater tibial TW; on the other hand, there was no correlation between the medial PTS and tibial TW or PTS and femoral TW (Table 2). Second, a significant positive correlation was observed between femoral and tibial TW.

The results of this study indicated no significant difference in the magnitude between femoral and tibial TW after anatomical rectangular tunnel ACL reconstruction using a BTB graft. There are few reports comparing the magnitude of TW on the femoral and tibial sides after anatomical ACL reconstruction. Lee et al. showed that tibial TW was greater than femoral TW after double-bundle ACL reconstruction using hamstring tendons.<sup>22</sup> Contrary to the results of Lee et al., Araki et al. showed that femoral tunnel volumes tended to be enlarged around the tunnel aperture after double-bundle ACL reconstruction using hamstring tendons compared to tibial tunnels.<sup>23</sup> They did not statistically compare femoral TW with the tibial TW in the literature, although their calculations showed that the femoral side had a greater TW. These findings suggest that whether the femoral or tibial tunnel is more enlarged after ACL reconstruction using the hamstring tendon grafts remains controversial. Uchida et al. studied tibial and femoral TW after anatomical rectangular tunnel ACL reconstruction using BTB grafts by CT images.<sup>13</sup> They showed that the femoral tunnel aperture was significantly enlarged (17.0%), and the tibial tunnel aperture was significantly enlarged (19.6%) 6 months after surgery. They also did not statistically compare femoral TW with tibial TW in the literature, although their calculations demonstrated that femoral and tibial TW were roughly equivalent. This finding is consistent with



**Fig. 3.** Measurements of posterior tibial slope (PTS) on CT images. (A) A circle was fitted to the proximal tibia, tangential to the cortexes. A second circle was fitted distally with its center placed on the border of the first circle. The line connecting the center of these two circles was known as the longitudinal axis. (B) The medial and lateral PTS were determined by the angle between the axis perpendicular to the longitudinal axis and the line connecting the most proximal anterior and posterior subchondral bone points of the medial and lateral tibiofemoral compartments. The arrow indicates the angle of lateral PTS. PTS; posterior tibial slope, CT; computed tomography.



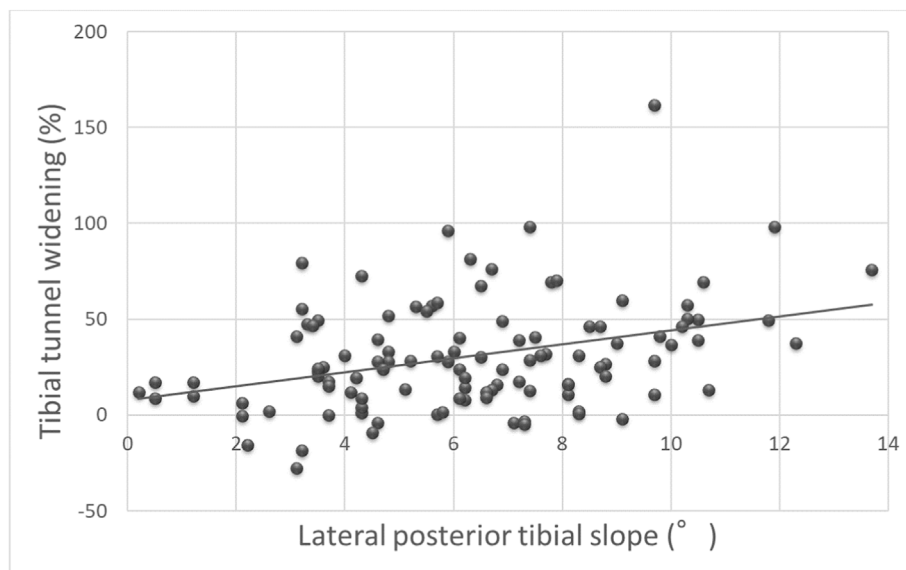
**Fig. 4.** Correlation between femoral and tibial tunnel widening. A significant positive correlation was observed between femoral and tibial tunnel widening ( $r = 0.240$ ,  $p = 0.011$ ).

the results of our study. Compared to our results, lesser femoral and tibial TWs were observed in their study, possibly due to the use of a cancellous screw for femoral fixation in their procedure.

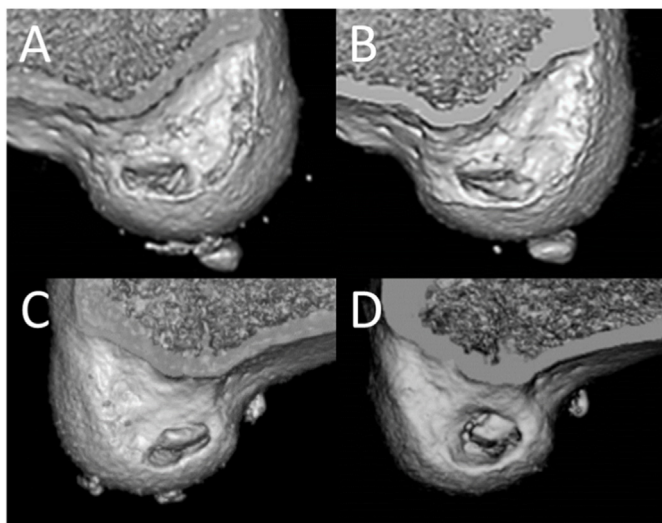
The fact that this study focused on ACL reconstruction using BTB might also have influenced the findings of no significant difference between the magnitude of femoral and tibial TW. In ACL reconstruction using BTB, the bone plugs are typically aligned with the femoral tunnel aperture, which may suppress TW on the femoral side. On the other hand, when the knee is extended and flexed between the femoral and tibial sides, the change in the graft-bending angle is thought to be smaller on the tibial side, which might have a suppressive effect on TW on the tibial side. It is

possible that these two factors offset each other, resulting in no difference between the femoral and tibial TW in this study.

To date, there have been few studies on the correlation between femoral and tibial TW. To the best of our knowledge, there has been no report to clarify the correlation between femoral and tibial TW. The results of this study showed that there is a significant correlation between femoral and tibial TW. This may mean that the influence of common femoral and tibial factors or individual factors is greater than the influence of independent factors on the femoral or tibial side, respectively, on TW. Examples of the former include age<sup>24</sup> or bone quality, the intra-articular environment including cytokines,<sup>25</sup> the initial tension on the graft tendon,<sup>12</sup> whereas the



**Fig. 5.** Correlation between lateral posterior slope and tibial tunnel widening. A significant correlation was observed between lateral posterior tibial and tibial tunnel widening ( $r = 0.354$ ,  $p < 0.001$ ).



**Fig. 6.** CT images of femoral tunnel widening (TW). CT images 1 week postoperatively (A) and 1 year postoperatively (B) of a case with small femoral TW. This case was a 38-year-old, male, recreational jogger with a pre- and postoperative Tegner activity scale of 6. He had a good postoperative course and was able to return to his preoperative activity 8 months after surgery. CT images 1 week postoperatively (C) and 1 year postoperatively (D) of a case with large femoral TW. This case was a 20-year-old female dancer with a pre- and postoperative Tegner activity scale of 7. She had a good postoperative course and returned to dancing 6 months after surgery.

latter include the graft-bending angle between the femur or tibia, the windshield wiper effect,<sup>26</sup> and the length of the tendinous portion in the bone tunnel,<sup>11,13</sup> which depends on the position of the bone plug in the tunnel.

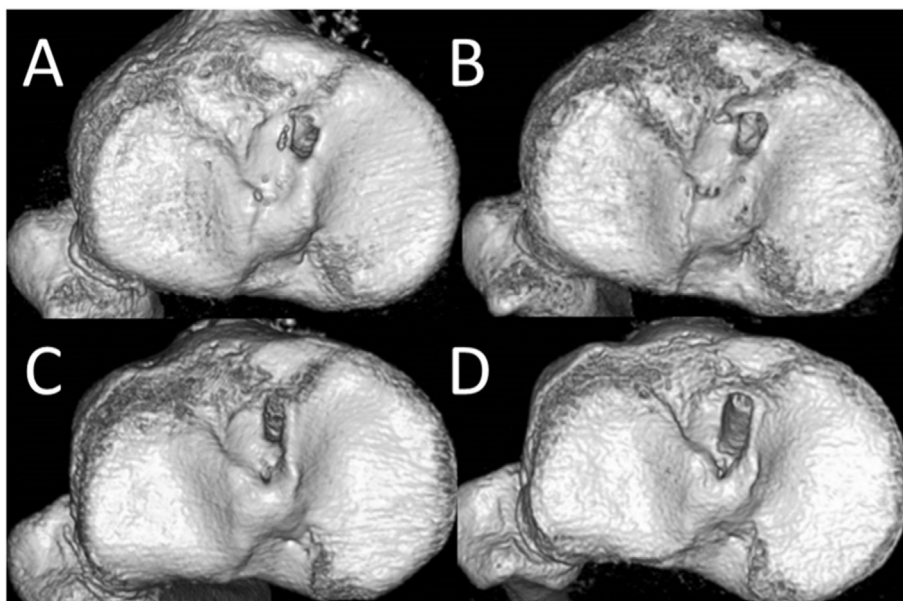
In the present study, although a significant positive correlation was observed between lateral PTS and tibial TW, there was no significant correlation between lateral PTS and femoral TW, contrary to the hypothesis. Similar to the present study, Sabzevari et al. reported a significant positive correlation between lateral PTS and the percentage of tibial TW, and the authors also found that lateral PTS was not significantly correlated with the percentage of femoral TW after primary single-bundle anatomical ACL reconstruction

using a hamstring autograft.<sup>8</sup> However, their study was based on the evaluation of TW only on plain anteroposterior radiographs, which was not a sufficient evaluation because the bone tunnels expand in three dimensions. It has been reported that steeper lateral PTS increases force on the graft,<sup>27</sup> and it could affect both femoral and tibial TW. However, in view of the results of the current study, lateral PTS had a large effect on tibial TW, whereas other factors such as graft bending angle, tunnel location, age, or bone quality had a large effect on femoral TW,<sup>28–30</sup> suggesting that the effect of lateral PTS was relatively small in this study.

In the present study, similar to the results of Sabzevari et al.,<sup>8</sup> only lateral PTS affected tibial TW; on the other hand, the medial PTS did not affect the tibial TW. They explained the reason for this result by the tensile force on the graft in the effect of tibial bony morphology. Previous studies showed that the lateral tibial plateau is more important than the medial plateau in the pivot shift mechanism and therefore the lateral tibial plateau places an increased force on the ACL.<sup>31,32</sup> The differences in the shapes of tibial plateau could explain the difference in their effect on the forces applied to the ACL. The medial tibial plateau has a concave shape and therefore provides more stability, whereas the lateral tibial plateau is convex, with greater potential for motion during activities. In addition, increased lateral PTS can cause increased anterior tibial translation.<sup>33</sup> These factors increase the forces on the graft and motion at the graft–tunnel junction, resulting in TW as reported.<sup>12,34</sup> Because the medial–lateral difference in PTS was very small in this study, it is likely that only lateral PTS affected tibial TW because of the difference in the medial and lateral geometry of the tibia, but it remains a matter of speculation.

On the other hand, Nagai et al.<sup>9</sup> reported that a steeper medial and lateral PTS correlated with greater tibial TW. Although they used the same methods as in this study to measure PTS, they stated that the medial and lateral PTS were 3.7° and 4.9°, respectively, values that were different from the present study. The difference in the results might be attributed to the fact that the two studies were conducted in individuals of different races. This difference in PTS may be the reason why the effect of PTS on tibial TW was only lateral in the present study, whereas it was both medial and lateral in the report by Nagai et al.

The strength of this study is the use of CT to measure TW and



**Fig. 7.** CT images of tibial tunnel widening (TW). CT images 1 week postoperatively (A) and 1 year postoperatively (B) of a case with small tibial TW. This case was a 30-year-old, male, recreational basketball player with a pre- and postoperative Tegner activity scale of 7. He had a good postoperative course and returned to basketball 9 months after surgery. CT images 1 week postoperatively (C) and 1 year postoperatively (D) of a case with large tibial TW. This case was a 39-year-old, male, recreational soccer player with a pre- and postoperative Tegner activity scale of 7. He had a good postoperative course and returned to basketball 8 months after surgery.

**Table 2**  
Correlation between posterior tibial slope and tunnel widening.

	Medial PTS	Lateral PTS
Femoral tunnel widening	No correlation	No correlation
Tibial tunnel widening	No correlation	Correlated

PTS; posterior tibial slope.

PTS. A recent review also concluded that as compared with plain radiography and magnetic resonance imaging, CT is the best method for evaluating TW after ACL reconstruction.<sup>35</sup>

This study has several limitations. First, only the aperture portion was measured to evaluate TW in this study. Some previous papers have measured the aperture portion, and some have measured the midportion of the tunnel. A recent systematic review concluded that no significant difference in TW was found between the aperture and the midportion in patients who underwent ACL reconstruction.<sup>36</sup> Second, in the present study, none of the factors that might affect TW, such as graft-bending angle, position of the bone plug in the tunnel, and tunnel location, were evaluated. Thus, further investigations in larger cohorts using multivariate regression analyses of such factors must be performed in the future. Third, there was a gender bias in the cohort of this study, which might have affected the results. Fourth, CT images were acquired at only two time points (1 week and 1 year postoperatively). Therefore, tibial TW that occurred at any other time point might have been undetected. Finally, the current study did not analyze the effects of TW on clinical outcomes after ACL reconstruction. It has been demonstrated that femoral tunnels enlarge anteriorly and distally (i.e., the direction in which the mechanical traction force of the graft works) rather than concentrically after anatomical ACL reconstruction.<sup>37–39</sup> This finding suggests that the wall supporting the graft moves closer to the direction of the pull, resulting in increased laxity of the knee joint due to TW. To clarify whether these factors influence clinical results after ACL reconstruction, future studies involving a large number of patients are required.

## 5. Conclusions

Although there was no significant difference between femoral and tibial TW after anatomical rectangular tunnel ACL reconstruction using a BTB graft, a significant positive correlation was observed between femoral and tibial TW. A steeper lateral PTS correlated with greater tibial TW; on the other hand, the medial PTS did not correlate with the tibial TW. Although lateral PTS affected tibial TW, it did not affect femoral TW.

## Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

## Declaration of competing interest

Our institutions have received grants from Smith & Nephew outside this work.

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