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ORIGINAL RESEARCH

Evaluating the distance between the femoral tunnel centers in anatomic double-bundle anterior cruciate ligament reconstruction using a computer simulation

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Purpose: We aimed to clarify the distance between the anteromedial (AM) bundle and posterolateral (PL) bundle tunnel-aperture centers by simulating the anatomical femoral tunnel placement during double-bundle anterior cruciate ligament reconstruction using 3-D computer-aided design models of the knee, in order to discuss the risk of tunnel overlap. Relationships between the AM to PL center distance, body height, and sex difference were also analyzed.

Patients and methods: The positions of the AM and PL tunnel centers were defined based on previous studies using the quadrant method, and were superimposed anatomically onto the 3-D computer-aided design knee models from 68 intact femurs. The distance between the tunnel centers was measured using the 3-D DICOM software package. The correlation between the AM–PL distance and the subject's body height was assessed, and a cutoff height value for a higher risk of overlap of the AM and PL tunnel apertures was identified.

Results: The distance between the AM and PL centers was 10.2±0.6 mm in males and 9.4±0.5 mm in females ($P<0.01$). The AM–PL center distance demonstrated good correlation with body height in both males ($r=0.66$, $P<0.01$) and females ($r=0.63$, $P<0.01$). When 9 mm was defined as the critical distance between the tunnel centers to preserve a 2 mm bony bridge between the two tunnels, the cutoff value was calculated to be a height of 160 cm in males and 155 cm in females.

Conclusion: When AM and PL tunnels were placed anatomically in simulated double-bundle anterior cruciate ligament reconstruction, the distance between the two tunnel centers showed a strong positive correlation with body height. In cases with relatively short stature, the AM and PL tunnel apertures are considered to be at a higher risk of overlap when surgeons choose the double-bundle technique.

Keywords: anterior cruciate ligament, double-bundle reconstruction, computer simulation, tunnel aperture, distance, height

Introduction

Anterior cruciate ligament (ACL) reconstruction is the standard treatment for ACL injury in athletes who want to return to a highly demanding activity. Recently, anatomic double-bundle ACL reconstruction using hamstring-tendon autografts, which reproduces the main two bundles of ACL fibers, the anteromedial (AM) bundle and posterolateral (PL) bundle,[1–6] has been advocated, because it is more advantageous for restoring rotatory stability than nonanatomic single-bundle reconstruction.[7,8]

An accurate bone-tunnel location is important to achieve successful results after ACL reconstruction.[7,9–11] Stable graft fixation is also essential to obtain secure

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structural properties.[12–14] However, the bony bridge between the femoral AM and PL bundle tunnels can sometimes become thin and weak because of the drill used and tunnel enlargement, and as a result the breakage of the bony bridge may take place and the overlap of these two tunnel apertures can occur in double-bundle ACL reconstruction (Figure 1).[15–17] Especially in cases with a relatively small stature, surgeons might find it difficult to preserve sufficient distance between the AM and PL tunnels when they pursue anatomical tunnel location.[18,19] The diameter of the long axis of the bone tunnel will become larger than that of the drill used because of the drill insertion at an oblique angle, and thus the shape of the intra-articular aperture has been reported to become more of an oval shape than a round one.[15,20,21] An enlarged tunnel aperture in an oval shape reduces the bony bridge between the two tunnels and increases the risk of tunnel overlap, which can thus lead to graft-fixation failure. When two femoral tunnels measuring 6 mm (3 mm radius) in diameter are drilled, in order to secure a 2 mm-wide bony bridge between them, a distance of about 9 mm is needed between the tunnel centers because of the enlarged aperture in the oval shape.[20] Conversely, the tunnel position might be shifted to be a nonanatomic position to avoid any overlap, and then malposition of the tunnels can occur. In order to position two tunnels anatomically and secure a bony bridge between them, basic morphological data about the positional relationship between the AM and PL bundle tunnels would therefore be useful information for surgeons when they reconstruct double bundles of ACL fibers.

The purpose of this study was to clarify the distance between the AM and PL bundle tunnel centers by simulating the femoral tunnel placement on the anatomical ACL footprint in intact knees using a 3-D computer-aided design (CAD) model of the knee, in order to discuss the risk of tunnel overlap. Relationships between the AM–PL distance and body height and sex difference were also analyzed. We hypothesized that the AM–PL distance would positively correlate with body height, while the tunnel distance in females would be significantly shorter than that in males.

Patients and methods

Computed tomography (CT) data from 68 knees without osteoarthritis were surveyed in this study. Thirty-eight males and 30 females with a mean age of 35 years (range 15–59 years) were included. All cases had intact femurs after epiphyseal arrest, while their underlying diseases were vascular disorders (n=20), periarticular fractures of the tibia (n=17) and patella (n=8), ligament injuries (n=12), tumorous diseases of the tibia (n=8), and healthy volunteers (n=3). The 3-D knee models were reconstructed slices ranging from 0.67 to 1 mm in size for the CT dataset with high resolution using the 3-D DICOM software package (Real Intage, Cybernet Systems Co Ltd, Tokyo, Japan). The models were rotated with an accuracy of 0.1° along the three axes to overlap the medial femoral condyle to lateral femoral condyle, just like the lateral view of knee X-rays. The models were divided, and lateral half cross sections were obtained. The tunnel position within the femoral intercondylar notch was defined by the quadrant method.[22] According to this method, footprints of the AM and PL bundles of the ACL were superimposed onto the knee-surface model as tunnel apertures based on the anatomical information obtained from a previous cadaveric study (Figure 2A).[23] It was verified in all cases that both of the AM and PL tunnel apertures were

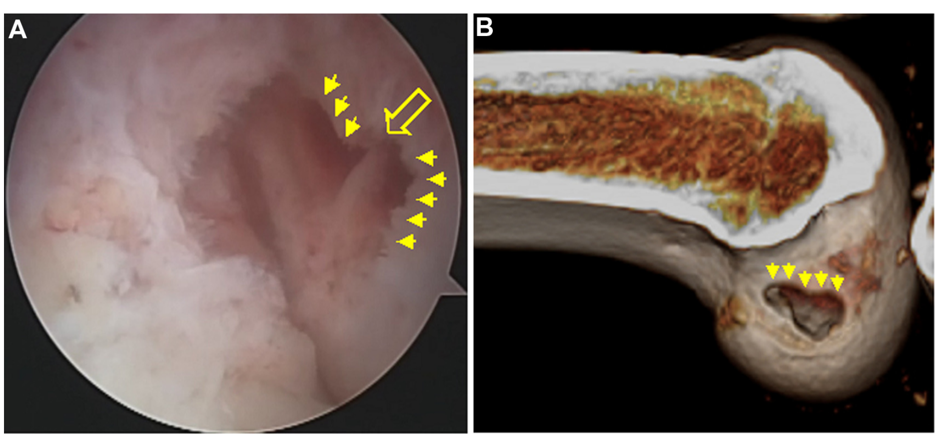

Figure 1 An overlap of two tunnel apertures.
Notes: (**A**) This arthroscopic view of the left knee shows the breakage of the bony bridge (large midair arrow) between two femoral tunnel apertures (group of small arrows). (**B**) A 3-D computed tomography computer-aided design model of the same knee is shown. An overlap of the two tunnel apertures (group of small arrows) has thus occurred.

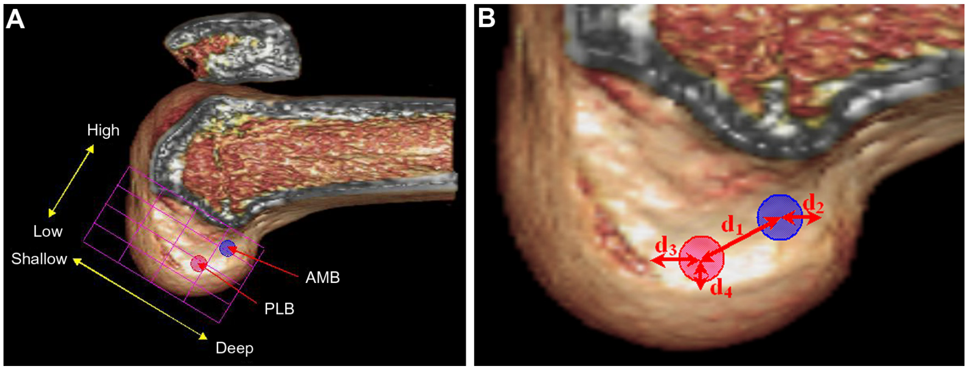

Figure 2 The definition of femoral tunnel position and measurement method.

Notes: (**A**) The position within the lateral femur was defined by the quadrant method.[22] Footprints of the anteromedial bundle (AMB) and posterolateral bundle (PLB) of the anterior cruciate ligament were superimposed onto the surface model of the femoral intercondylar notch based on the percentage from the posterior wall (deep–shallow) and from Blumensaat's line (high–low), according to the footprint location reported in a previous cadaveric study.[23] (**B**) The distances between the AM and PL centers (d_1), the AM center and the posterior bony edge of the intercondylar wall (d_2), the PL center and the anterior border with cartilage (d_3), and the PL center and the inferior border with cartilage (d_4) were measured using the 3-D DICOM software package.

identified behind the resident's ridge and located within ACL footprints in all cases.[23–25] The distances between the AM and PL centers, the AM center and the posterior bony edge of the intercondylar wall, the PL center and the anterior border with cartilage, and the PL center and the inferior border with cartilage were measured in 3-D (Figure 2B). The relationship between the AM–PL distance and the subject's body height was assessed using Pearson's correlation coefficient, and a cutoff height value for a higher risk of excessive adjacency of the AM and PL apertures was identified.

This study was approved by our institutional review board, which permitted use of clinical CT data of the knees obtained in our institution from 2008 to 2009 (Kyushu University, approval 24-108).

Data analysis

Relationships between the AM–PL distance and body height were assessed using Pearson's correlation coefficient. The sensitivity and specificity of body height to clarify whether each patient may have a high risk of intraoperative septal wall breakage due to bone tunnel-aperture adjacency were calculated. A cutoff value for body height was determined using a receiver operating characteristic (ROC) curve. Student's unpaired *t*-test was used for the comparison of anatomical distances in the male and female groups. A two-tailed value of $P\leq0.05$ was considered to be statistically significant.

To examine the reproducibility of this method, the intraclass/interclass correlation coefficients (ICCs) were assessed.[26] The reliability of the measurement values obtained in the CT knee models was high: namely, the intraobserver reliability ICC (1.3) of the data recorded for three measurements in ten knees was 0.99, and the interobserver reliability ICC (2.3) of three different orthopedic observers was 0.95 in this study.

Results

The results of the measurements from the 3-D CT knee models of the intact femurs are presented in Table 1. The distance between the AM and PL centers was 10.2±0.6 mm in males and 9.4±0.5 mm in females ($P<0.01$). The correlation between the AM–PL distance and body height was good in both males ($R=0.66$, $P<0.01$) and females ($R=0.63$, $P<0.01$) (Figure 3). The safe standard distance to secure a bony bridge between the AM and PL centers was set at 9 mm, based on the ovalization of the tunnel aperture. The cutoff value that correlated with a high probability of AM and PL centers within 9.0 mm was calculated to be a height of 160 cm in males and 155 cm in females. Sensitivity was 100% and specificity 92% for these cutoff values.

Discussion

Excessive adjacency of two tunnel apertures should be avoided, because the fracture of the bony bridge could worsen the strength of graft fixation.[27,28] We aimed to survey

Table 1 Measurement results from the 3-D computed tomography knee models of intact femurs

	Distance (mm)		*P*-value
	Male (n=38)	Female (n=30)	
AM–PL	10.2±0.6	9.4±0.5	<0.01
AM–posterior edge	4.9±0.7	4.6±1.0	NS
PL–anterior edge	7.3±1.8	7.1±1.6	NS
PL–inferior edge	3.7±1.0	3.2±0.9	NS

Abbreviations: AM, anteromedial; PL, posterolateral; NS, not significant.

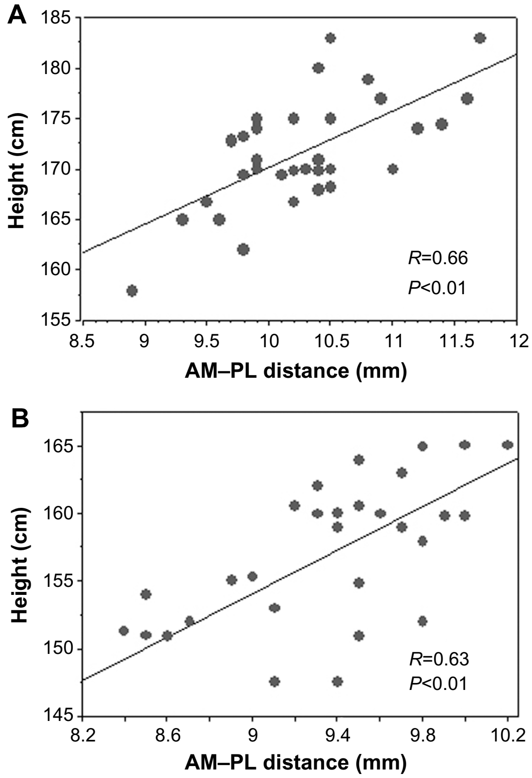

Figure 3 Relationships between anteromedial (AM) and posterolateral (PL) center distances and body height.

Notes: (A) Good correlation (R=0.66) was seen between the two parameters in males ($P<0.01$). (**B**) In addition, in females, good correlation (R=0.63) was seen between the two parameters ($P<0.01$).

the distance between the AM and PL bundle tunnel centers when they were located anatomically in double-bundle ACL reconstruction based on a previous cadaveric study,[23] using a 3-D CAD model of the intact knees, in order to clarify the correlation between the distance of the two femoral tunnels and the height of individuals. Our hypothesis was that small stature would correlate with two very close tunnel centers and the AM–PL tunnel distance in females would be significantly shorter than that in males, and this was affirmed.

An analysis of the AM and PL center geography in the CT CAD models demonstrated that the average distance between the tunnel centers was 10.2 mm in males and 9.4 mm in females. These results would be a guide to determine the tunnel position to be drilled when the bony landmark was vague during the anatomic double-bundle ACL reconstruction. Our results suggest that it would be possible in most cases to preserve the bony bridge between two tunnels with a 6 mm diameter. However, the AM–PL distance in females was significantly shorter than that in males, and the good correlation between the AM–PL distance and body height found in our study suggests that in patients with a short stature (<160 cm for males and 155 cm for females, as confirmed in the ROC curve analysis), the two tunnel centers come closer and there is a higher risk of tunnel overlap. A recent study evaluating the size of the ACL insertion site arthroscopically also reported a weak but significant correlation between the intercondylar notch size and ACL insertion-site size and that women had a smaller insertion site than men,[29] although another study reported no correlation of height or sex with ACL footprint size.[30] This discrepancy might be because the former study estimated the actual ACL insertion-site size and the latter estimated the length of the lateral intercondylar ridge, which is usually a curved line.

We set 9 mm as a safe standard distance for the AM and PL tunnel centers, with a diameter of 6 mm to preserve a stable bony bridge between them, based on the AM and PL graft diameter harvested from semitendinosus tendon in our previous study (AM 5.7±0.6, PL 5.5±0.6),[20] another cadaveric study (AM 5.9±0.5, PL 5.6±0.4),[31] and a massive-cohort study (AM 7.1±0.6, PL 5.8±0.6).[32] Clinical comparative studies of single- and double-bundle ACL reconstruction also advocated that the PL tunnel center should be 9 mm apart from the AM center to preserve at least a 2 mm bony bridge.[27,28] In order to preserve a 2 mm width of the bony bridge when the surgeons used drills with a diameter of 6 mm (3 mm radius) and perfectly round holes were made, a distance of at least 8 mm should be secured between the AM and PL tunnel centers. However, the diameter of the long axis of the tunnel aperture does become larger than the drill used during the procedures, because drill insertion at an oblique angle leads to ovalization of the tunnel aperture.[20,33] Our previous study evaluating the postoperative CT findings of 36 cases after double-bundle ACL reconstruction indicated that the ovalization of the tunnel aperture would result in 120%–130% elongation in the diameter when using the transtibial technique and approximately 110% elongation when the transportal technique is used.[20] As much as 120%–130% elongation in the diameter of the tunnel aperture means that when creating two tunnels with a 6 mm diameter, the long axis would be elongated to 7.2–7.8 mm in the transtibial technique, while 110% elongation would remain 6.6 mm in the transportal technique. A cadaveric study with a single-bundle ACL reconstruction also reported that the intra-articular aperture of the femoral tunnel did indeed form an ellipse in all cases, and the percentage of ovalization in the long axis was 121%±8% using the transtibial technique.[33] Therefore, we considered that the two tunnels should be placed at least 9 mm apart from each other in order to avoid any overlap when creating 6 mm-diameter tunnels.

Even if surgeons are very careful to locate the two femoral bone tunnels anatomically, they sometimes encounter a relatively small footprint area, and thus find it difficult to preserve the stable bony bridge between the two intra-articular apertures.[18,19] Based on our results, in cases with relatively short stature (<160 cm for males or 155 cm for females), where the ACL footprint size is supposed to be small, femoral tunnel drilling using tibial tunnel-independent techniques, such as the transportal technique or the outside-in technique, might be considered to avoid the overlap of two tunnels and fixation failure. This is because tibial tunnel-independent techniques tend to make the femoral tunnel apertures less elongated than the transtibial technique, and there is a lower risk of overlap with the two tunnels when double-bundle reconstruction is performed.[20,33] Alternatively, surgeons should select the anatomical single-bundle reconstruction from the beginning in those cases with short stature. A previous study has also reported that a narrow notch (<14 mm) or a shallow notch (<14 mm) are relative contraindications for double-bundle ACL reconstruction,[34] although whether anatomic single-bundle ACL reconstruction competes double-bundle reconstruction in stability needs more discussion.[35,36]

Limitations

One of the limitations associated with this study was that the geographic data on the ACL femoral tunnel positions were not directly obtained from in vivo knees or cadaveric specimens, but from indirect CAD data superimposed based on the ratio obtained from an anatomical study.[22,23] The direct observation of cadavers would be more desirable to assess basic anatomical information, but ethical restrictions and low availability made it difficult to use a sufficient number of cadavers for such fundamental research. However, the key point of this study was not to survey footprint anatomy, but to simulate and evaluate the relationship of the two tunnel apertures when anatomical double-bundle ACL reconstruction is performed. In addition, the positional data based on high resolution 3-D CT data are considered to be as accurate as in vivo knees and cadaveric specimens. Because the quadrant method has been widely used for the postoperative evaluation of tunnel position after ACL reconstruction in recent years,[20,23,37,38] it stands to reason that we used this method for simulating the AM and PL tunnel center.

Conclusion

In the 3-D CAD simulation of double-bundle ACL reconstruction with the location of the femoral tunnels accurately positioned anatomically, the distance between the AM and PL centers was 10.2±0.6 mm in males and 9.4±0.5 mm in females ($P<0.01$), and this distance correlated strongly with the body height. In those cases with relatively short statue, especially in those under 160 cm for males and 155 cm for females, the distance of the AM–PL centers are supposed to be shorter than 9 mm and the risk of bony bridge breakage, due to the overlap of tunnel apertures being higher. In order to avoid any weakening of graft fixation, surgeons should therefore be aware of the patient's body height and be careful when choosing the appropriate surgical technique.

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Disclosure

The authors report no conflicts of interest in this work.

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