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Relationship between thickness of the anteromedial bundle and thickness of the posterolateral bundle in the normal ACL

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Abstract
Purpose Since the development of the anatomic double-bundle anterior cruciate ligament (ACL) reconstruction, many studies have focused on excursion and/or tension of each graft. However, no studies to date have adequately investigated thickness of the graft in anatomic double-bundle ACL reconstruction. To obtain basic knowledge from which an ideal graft thickness can be inferred, thicknesses of the anteromedial bundle (AMB) and posterolateral bundle (PLB) was measured in the normal ACL.
Methods The right knees of 50 cadavers donated for anatomy instruction were studied. Each ACL was separated into the AMB and PLB, and circumferences at the mid-substance and cross-sectional area at the femoral and tibial footprints were measured in each.
Results Cross-sectional areas of the AMB and PLB were 36 ± 10 and 32.1 ± 10.2 mm^2 at the femoral footprint, and 60.9 ± 21.8 and 52.2 ± 17.3 mm^2 at the tibial footprint, respectively. Circumferences at the mid-substance were 14.3 ± 3.3 mm for the ALB and 10.8 ± 3.1 mm for the PLB. A positive correlation was seen between AMB and PLB at each of the three sites.
Conclusion The AMB is thicker than the PLB, showing a constant correlation in the normal ACL. This suggests that the anteromedial graft must be thicker than the posterolateral graft at least in actual operations.

Keywords Anterior cruciate ligament · Anteromedial bundle · Posterolateral bundle · Cross-sectional area · Diameter

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Introduction

The normal anterior cruciate ligament (ACL) is composed mainly of two bundles [9, 22]: the anteromedial bundle (AMB) and the posterolateral bundle (PLB). Several studies have shown that the PLB contributes to rotational stability near the extension position of the knee and that both bundles contribute to anterior stability [4, 10, 14, 22, 23, 34]. The anatomic double-bundle ACL reconstruction has been developed to precisely and independently reconstruct the AMB and PLB [6, 18, 32], and to date has been reported to yield comparatively excellent results [1, 2, 12, 16, 17, 27, 30, 31]. However, some extremely complicated problems are revisited by having to divide the ACL into two functionally different bundles [21, 24]. If the anteromedial graft (AMG) and posterolateral graft (PLG) become functionally independent of that grafts are placed at an anatomic position, excursion of grafts does not exhibit isometry [29]. In addition, either the AMG or the PLG might be the main recipient of external force according to the knee position. These issues may restrict range of motion or lead to graft rupture [21]. To avoid such problems, many recent studies [7, 8, 13, 19, 33] have examined initial tension and flexion angle at the time of graft fixation, and knowledge is slowly being accumulated. However, extremely few reports have studied the thickness of the graft. That is, if division into two bundles is performed at an inappropriate ratio even with sufficient total thickness of grafts, the thickness of either the AMG or the PLG will be insufficient. The risk of failure will thus increase for one of the grafts. A constant standard in the ratio of AMG to PLG thicknesses thus seems necessary.

The purpose of this study was to obtain basic knowledge of the relationship between thicknesses of the AMB and PLB in the normal ACL. Hypothesis of this study was that the AMB is thicker than the PLB, with a constant correlation.

Materials and methods

The donated cadavers for anatomy practice to Kurume University School of Medicine were used in this study. And therefore, the research protocol of the present study was reviewed and approved by the university ethical committee.

Among 55 formalin-fixed cadavers, one with ACL degeneration due to osteoarthritis, one with ACL calcification, and three in which the ACL could not be separated into the AMB and PLB were excluded. The remaining 50 cadavers (32 men, 18 women) were selected as the study materials, examining the right knee in each case. ACLs were almost normal in all 50 knees and were easily separated into the AMB and PLB. Mean age at the time of death was 79 years (median, 80 years; range, 48–103 years).

Measurement of the ligament

The knee was flexed at 70°–90°, and the muscles, articular capsules, and patellar tendon around the knee were removed using a scalpel. The medial femoral condyle was then resected using an oscillating saw while protecting the ACL with the elevatorium, allowing the whole of the ACL to be observed. The PCL was separated on the tibial side and resected together with the medial femoral condyle. The synovial membrane on the ACL surface, the entirety of which could be observed, was removed with care, and the ACL was separated carefully at the mid-substance of the ligament into the AMB and PLB.

The knee was flexed precisely at 90 degrees using the goniometer and was fixed by 2 Kirshner wires. Superficial fibers at anterior part of the AMB and PLB were carefully traced between the femoral and the tibial insertion, and then, the midpoint of fibers was marked using a marker pen. No. 2 Ethibond suture (Johnson & Johnson, New Brunswick, NJ) was placed around the AMB and PLB at the midpoint of the ligament that was previously marked, and tightened by applying a tension of 0.5 N using a tensionometer (Acufex Microsurgical, Mansfield, MA) (Fig. 1). In this state, the suture was cut from the tip of the tensionometer, and the length of the suture was measured by a unit of 1/10 mm. This measurement was repeated three times, and the mean value was regarded as the circumference.

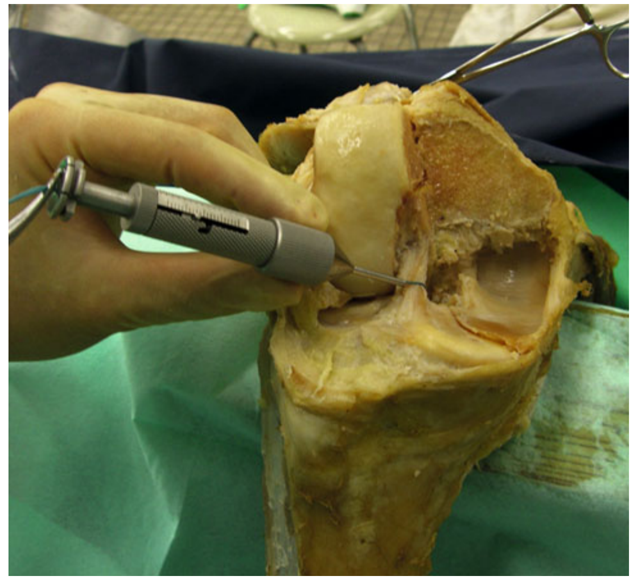

Fig. 1 Measurement of the circumference of the ligament at the mid-substance

The AMB and PLB were then separated from each other at the mid-substance. Each separated bundle of fibers was carefully traced up to the point of attachment to the femur and cut from the bone surface with care. In this state, only the functional fibers that continued from the mid-substance were traced, and the mixture fibers except it excluded as much as possible. The remaining footprint was marked using a marker pen. The tibial side was marked in a similar way. Footprints of the AMB and PLB on the femur and tibia were recorded together with a scale using a digital camera (Pentax, Tokyo, Japan). The images were then input into a computer, and cross-sectional areas (CSAs) of the AMB and PLB at the femoral and tibial footprints were measured using image analysis software “NIH Image J” by a unit of 1/10 mm^2. This value was measured three times, and the mean of those three values was regarded as the CSA.

Statistical analysis

All measurements were made by only one (M.K) of authors. Because of this, the inter-observer reliability of the measurement could not be calculated. However, intra-observer reliability for each of the three measurements was sufficiently high: $R = 0.98$, $R^2 = 0.95$, $P < 0.0001$ at the femoral footprint; $R = 0.86$, $R^2 = 0.74$, $P < 0.0001$ at the mid-substance; and $R = 0.99$, $R^2 = 0.97$, $P < 0.0001$ at the tibial footprint.

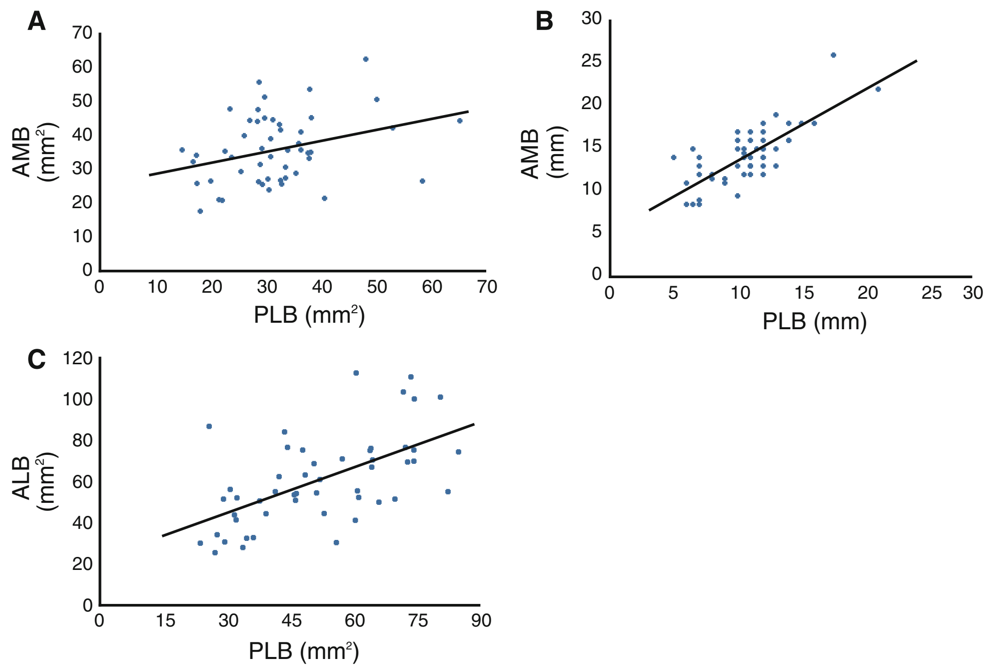

Fig. 2 **a** The correlation between CSA of the AMB and that of the PLB at the femoral footprint, **b** The correlation between circumference of the AMB and that of the PLB at the mid-substance, **c** The correlation between CSA of the AMB and that of the PLB at the tibial footprint

The correlation between measured data for the AMB and PLB at the three sites was analyzed using Pearson's correlation coefficient. A regression line was then obtained using the measured data for the PLB as an independent variable and those for the AMB as a dependent variable. A confidence level of 95% ($P < 0.05$) was chosen for statistical significance. Data are presented as mean value ±SD.

All statistical processing was conducted using JMP version 5.0 software (SAS Institute, Cary, NC).

Results

At the femoral footprint, mean (±standard deviation (SD)) CSA was 36.0 ± 10.0 mm^2 for the AMB and 32.1 ± 10.2 mm^2 for the PLB. Mean CSA ratio (AMB/PLB) was 1.1. At this site, a low positive correlation ($r = 0.31$, $R^2 = 0.10$, $P = 0.0276$) with CSA was observed between the AMB and the PLB at the 3% level (Fig. 2a). At the mid-substance, mean circumference was 14.3 ± 3.3 mm for the AMB and 10.8 ± 3.1 mm for the PLB; the circumference ratio (AMB/PLB) was 1.3. At this site, a high positive correlation ($r = 0.76$, $R^2 = 0.57$, $P < 0.0001$) with circumference was observed between the AMB and the PLB at the 0.01% level (Fig. 2b). At the tibial footprint, mean CSA was 60.9 ± 21.8 mm^2 for the AMB and 52.2 ± 17.3 mm^2 for the PLB; mean CSA ratio (AMB/PLB) was 1.2. At this site, a positive correlation ($r = 0.59$, $R^2 = 0.35$, $P < 0.0001$) with CSA was observed between the AMB and the PLB at the 0.01% level (Fig. 2c). The linear regression formula using CSA or circumference of the PLB as an independent variable, X, and those of the AMB as a dependent variable, Y, was $Y = 0.31X + 26.15$ at the femoral footprint, $Y = 0.82X + 5.50$ at the mid-substance, and $Y = 0.74X + 22.09$ at the tibial footprint.

Discussion

The present study obtained an important finding, although thickness of the AMB and PLB was only measured in the normal ACL at three sites (femoral footprint, mid-substance, and tibial footprint). This finding was that the AMB is thicker than the PLB with a constant correlation in the normal ACL. The AMG must thus be thicker than the PLG at least when the harvested tendon was divided into two grafts, and marked imbalances in the division of grafts must be avoided.

The implanted graft undergoes remodeling and changes into new ligamentous tissue [3], but the mechanical strength will never exceed that of the normal ligament [5]. The graft thus becomes enlarged and thickened to reinforce overall material strength. To obtain a final structural strength equal to that of the normal ACL, the graft must be as thick as possible because the remodeling process [20] cannot be controlled. However, obtaining an appropriate thickness of graft is not always easy. If the graft is divided in an inappropriate ratio, the thickness of either the AMG or the PLG will be insufficient even if the total thickness of grafts appears adequate. Although the appropriate ratio for thicknesses of the AMG and PLG should logically reflect the situation in the normal ACL, basic data on this issue have been lacking to date.

Many previous studies [11, 15, 25, 26, 28] have addressed the shape and/or CSA of the AMB and PLB at the femoral and tibial footprints. Harner et al. [10] measured CSA of the AMB and PLB using the knees of 10 fresh frozen cadavers. They reported that mean CSAs of the AMB and PLB at the femoral footprint were 47 ± 13 and 49 ± 13 mm^2, respectively, compared with 56 ± 21 and 53 ± 21 mm^2 at the tibial footprint, respectively. Mean cross-sectional ratio (AMB/PLB) was 1.0 on the femoral side and 1.1 on the tibial side. Takahashi et al. [25], using 32 donated cadavers, reported that mean CSAs of the AMB and PLB on the femoral side were 66.9 ± 2.3 and 66.4 ± 2.3 mm^2, respectively, compared with 67.0 ± 18.4 and 52.4 ± 17.6 mm^2 on the tibial side. Mean CSA ratio (AMB/PLB) was 1.0 on the femoral side and 1.3 on the tibial side. Cross-sectional ratios of AMB and PLB in the present study were almost the same as those in the above two reports [11, 25]. The method for measurement of the footprint in this study thus appears suitable. However, absolute values for CSA differ considerably among investigations. This may be due to the extreme difficulty in identifying the true border of the attached part of the ligament. At the footprint of the ligament to the bone, the fibers spread toward the bottom, and many surrounding fibrous tissues other than the functional fibers properly become mixed in. The area of the femoral and tibial footprint is thus more than 3.5 times larger than at the mid-substance [11, 35]. Separating the functional fibers from other fibrous tissues is difficult. The absolute value of the CSA will thus differ according to whether the AMB and PLB have been separated, and the area that is regarded as the boundary of the attached part. However, with regard to mean CSA ratio (AMB/PLB), i.e., the ratio of values for the AMB and PLB determined by the same investigator, the results of the three reports, including this study, appear to approximate each other.

On the other hand, no studies have measured CSA of the AMB and PLB at the mid-substance of the ligament. As far as we can tell, data for the femoral footprint obtained by Mochizuki et al. [15] may reflect thickness of the mid-substance of the ligament for the reasons described below. Using 10 donated cadavers, they carefully removed various fibers that were mixed from the surrounding or fibers of the periligamentous membrane and identified a femoral footprint composed only of functional fibers continuous from the mid-substance of the ligament. As a result, the cross-sectional ratio was considered to approximate that of the mid-substance where only functional fibers are aggregated in a compact manner. They reported that mean long and short diameters at the femoral footprints of the AMB and PLB were 9.2 ± 0.7 × 4.7 ± 0.6 mm and 6.0 ± 0.8 × 4.7 ± 0.6 mm, respectively; the mean circumference ratio (AMB/PLB) was 1.3. In the present study, circumference ratios of both the AMB and the PLB at the mid-substance were completely the same as those at the femoral footprint reported by Mochizuki et al. [15] although absolute values of both AMB and PLB were approximately one-third. The circumference ratio of AMB and PLB (AMB/PLB) can thus be interpreted to approximate 1.3 at all levels when only true functional fibers are traced. This means that the AMB is thicker than the PLB when only functional fibers are traced.

Based on present measurements, a trial calculation of the ideal thickness of both the AMG and the PLG was made using a linear regression formula for the femoral footprint, mid-substance, and tibial footprint. In an actual operation, the CSA of the minimum size through which a graft created using a cylindrical sizing tube with an increment of 0.5 mm in diameter can pass is regarded as the CSA of the graft, by assuming the cross-sectional shape to be a circle. On this

Table 1 Diameter, CSA, and circumference of the AMG derived from the linear regression formula at each measurement site when the diameter of the PLG created in an actual operation was set in 0.5-mm increments

Thickness of the PLG		Thickness of the AMG derived from the linear regression formula at					
		The femoral footprint		The mid-substance		The tibial footprint	
Diameter (mm)	CSA (mm^2)	Diameter (mm)	CSA (mm^2)	Diameter (mm)	Circumference (mm)	Diameter (mm)	CSA (mm^2)
4.5	15.9	6.3	31.1	5.4	17.1	6.6	33.9
5.0	19.6	6.4	32.2	5.9	18.4	6.8	36.6
5.5	23.8	6.5	33.5	6.3	19.7	7.1	39.7
6.0	28.3	6.7	34.9	6.7	21.0	7.4	43.0
6.5	33.2	6.8	36.4	7.1	22.2	7.7	46.6
7.0	38.5	7.0	38.1	7.5	23.5	8.0	50.6
7.5	44.2	7.1	39.8	7.9	24.8	8.4	54.8
8.0	50.3	7.3	41.7	8.3	26.1	8.7	59.3
8.5	56.7	7.5	43.7	8.7	27.4	9.0	64.1
9.0	63.6	7.6	45.9	9.1	28.7	9.4	69.2

basis, the diameter of the ideal AMG derived from the linear regression formula is shown in Table 1, when the diameter of the PLG created during actual surgery is set in 0.5-mm increments. Thus, in our opinion, the most important indicator seems to be the reference value at the mid-substance of the ligament, since the positive correlations observed at both the femoral and the tibial footprints were not particularly strong and many outliers were seen. Accordingly, the diameter of the AMG should ideally exceed that of the PLG by more than 0.9–0.4 mm, if the diameter of the PLG usually used in clinical ranges from 4.5 to 7.0 mm. Other surgeons may trust the data of the femoral footprint or the tibial footprint, but it is desirable for AMG to be thicker than PLG in this situation.

This study had several limitations. First, formalin-fixed cadavers were used. Due to the dehydrating effects of formalin fixation, the measured results may be less than actual conditions, particularly at the mid-substance. However, this condition should apply equally to the AMB and PLB, and thus would not influence the relationship between the AMB and the PLB. Second, the age of donor cadavers was much higher than that of patients who actually undergo ACL reconstruction. However, the cadavers did not belong to a patient group that usually has knee problems requiring total knee arthroplasty or arthroscopy. No individuals showed moderate or more severe degenerative changes, and the ACLs were considered to be almost normal. The present results are thus considered to be sufficiently accurate. Furthermore, some factors that may influence the thickness of the ACL were not sufficiently considered. Width and shape of the intercondylar notch were not measured. Height and weight of the formalin-fixed cadavers could not be measured accurately, and these data had not been recorded during the lifetimes of the donors. Gender and lengths of the femur and tibia were considered, but did not influence the results (data not shown). However, evidence that these factors did, in fact, influence the thickness of the ACL was insufficient. At least for ordinary clinical settings, results of this study can be considered sufficiently reliable.

As clinical relevance, the result of this study shows one opinion on a clinical problem how two grafts prepared from the harvested tendon had better be assigned to AMG and PLG each. Namely, a thicker graft should be used for AMG, and a little thin graft should be used for PLG, but it had better be kept the difference in the diameter within less than about 1 mm, in the anatomic double-bundle ACL reconstruction. This thing may support a traditional way that many surgeons practice by own experience.

Conclusion

The AMB is thicker than the PLB, showing a constant correlation in the normal ACL. This suggests that the AMG must be thicker than the PLG at least when the harvested tendon was divided into two grafts in actual operations. Furthermore, marked imbalances in graft division must be avoided.

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