Relationship between anterior cruciate ligament and anterolateral meniscal root bony attachment: High-resolution 3-T MRI analysis

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A R T I C L E   I N F O

A B S T R A C T

Background: The tibial bony attachments of the anterior cruciate ligament (ACL) and the anterolateral meniscal root (ALMR) are very close, and drilling the tibial tunnel in ACL reconstruction may damage the ALMR attachment. This study investigated the relationship between the tibial attachment of the ACL and ALMR using high-resolution 3-T magnetic resonance imaging (MRI).
Methods: Twenty healthy subjects (35.8 ± 13.0 years) had 20 knees scanned using high resolution 3-T MRI. The tibial bony attachments of ACL, ALMR, and the tibia were segmented and three-dimensional models were created. The shape, area, and location of each attachment were evaluated using this model.
Results: The ACL tibial attachment was elliptical in nine knees (45%), C-shaped in nine knees (45%) and triangle in two knees (10%). The mean values of the ACL vs ALMR tibial attachments were as follows: area, 106.2 ± 21.3 vs 56.2 ± 21.3 mm^2; length, 16.8 ± 2.0 vs 11.0 ± 1.8 mm; and width, 6.9 ± 1.3 vs 6.6 ± 1.0 mm. The location of the ACL vs ALMR attachment centres was $46.5 \pm 1.7\%$ vs $56.5 \pm 1.9\%$ in the medial-lateral direction and $36.3 \pm 3.6\%$ vs $36.7 \pm 3.5\%$ in the anterior–posterior direction. The distance between the ACL and ALMR centres was 8.1 ± 1.3 mm.
Conclusions: ACL and ALMR tibial attachments were individually distinguished using high resolution 3-T MRI. The short distance between both centres of the attachments may suggest that ALMR can be damaged when the tibial tunnel is drilled in ACL reconstruction.

1. Introduction

Anatomical reconstruction of the anterior cruciate ligament (ACL) has become a widely accepted option for restoring physiological joint biomechanics in a symptomatic unstable knee, and it is generally accepted that the tibial tunnel should be created on the ACL native footprint [15,28]. However, the ACL tibial footprint overlaps the anterior lateral meniscal root (ALMR) attachment macroscopically, and there is a possibility that drilling the tibial tunnel may damage the ALMR attachment [10,11,14,23,26].

The meniscal root attachment plays a role as an anchor that allows the meniscus to absorb impact in the knee joint. The lateral meniscus supports a larger percentage of load bearing than the medial meniscus and more specifically the anterior horn

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[17,27,30]. Injuries of the meniscal root attachments result in excessive loading and cartilage degeneration of the knee [1,3,18]. Previous studies have shown that injury to the ALMR bony attachment results in increasing contact pressure, and large tibial tunnels created in the centre of the ACL tibial footprint could damage the ALMR attachment and decrease the hoop strength of the lateral meniscus (LM) [19]. The demonstration of nerve fibres and its sensory function have also encouraged the preservation of the ALMR attachment, in addition to prevention of pathological contact pressure and excessive lateral meniscal extrusion (LME) in the knee joint [8,24]. Kodama et al., recently demonstrated that posterolateral location of the tibial tunnel aperture within the ACL footprint increases LME after ACL reconstruction in single- and double-bundle reconstruction procedures [11].

Based on these findings, it is clinically important to understand the three-dimensional (3D) relationship of the attachment sites of these structures. The purpose of this study was therefore, to clarify the morphology of the ACL and ALMR tibial attachment in healthy knees using high-resolution 3-T magnetic resonance imaging (MRI). We hypothesised that: (1) the attachment of ACL and ALMR would be reliably identified; (2) the intact ACL tibial attachment site would be C-shaped, elliptical or triangle; and (3) the ACL footprint and ALMR attachment would be close enough such that tibial tunnel drilling could damage the ALMR attachment.

2. Materials & methods

2.1. Participants

Twenty healthy participants (13 male and seven female; mean age 35.8 ± 13.0 years; mean body mass index 24.2 ± 2.7 kg/m^2) were included in the study. Ethical approval was received from the local ethics committee prior to recruitment and each participant provided written informed consent prior to testing. People with any previous knee surgery or signs of ACL insufficiency on physical examination (Positive Lachman test or positive Pivot-Shift test) were excluded from the study. The healthy knees were scanned using high-resolution 3-T MRI (3 T, Magnetom Skyra; Siemens AG Healthcare, Germany) with a 15-channel phased-array send/receive knee coil (Siemens AG Healthcare), using an established MRI protocol (Table 1) [9]. The tibial attachments of ACL and ALMR were carefully segmented on every image with a thickness of three pixels, using coronal MRI images (Figure 1a) and checked simultaneously with sagittal and axial imaging using a 3D processing software (ScanIP, Simpleware Ltd., Exeter, UK). 3D models were reconstructed from high-resolution segmented data using the 3D reconstruction algorithm. The tibial plateau was also segmented, and the medial and lateral tibial eminences were used as references (Figure 1b).

2.2. Evaluation

The segmented ACL tibial attachment, the ALMR tibial attachment, and the medial and lateral tibial spines were evaluated from the superior surface of the tibia which is perpendicular to the tibial plateau (Figure 2). The shape and area of the tibial attachments, as well as length, width, and location of ACL and ALMR attachments were also measured. The location was assessed using a grid system and expressed as the percentages of the distance from the medial and anterior end of the tibia to the centre of ACL and ALMR, which was standardised by the width and length of the tibia. (Figure 3) Moreover, for clinical relevance, the centre of each attachment was measured from the tip of the medial intercondylar eminence, which is commonly used as a landmark in ACL reconstruction. The intercondylar-eminence width was defined as the distance between the intercondylar eminences in the medial-lateral direction.

2.3. Statistical analysis

Stata 15.0 (College Station, TX, USA) was used for the statistical analysis. In order to examine the reliability of the segmentation of the ACL and AMR attachments, measurements were repeated twice by one observer (T.O., 10-year experienced orthopaedic surgeon) with an interval of four weeks to assess intra-class correlation coefficients, and also by two independent observers (T.O. and M.L., 10-year experienced orthopaedic surgeons) to assess inter-class correlation coefficients. The mean and 95%

Table 1
Parameters for the 3D MRI sequences.

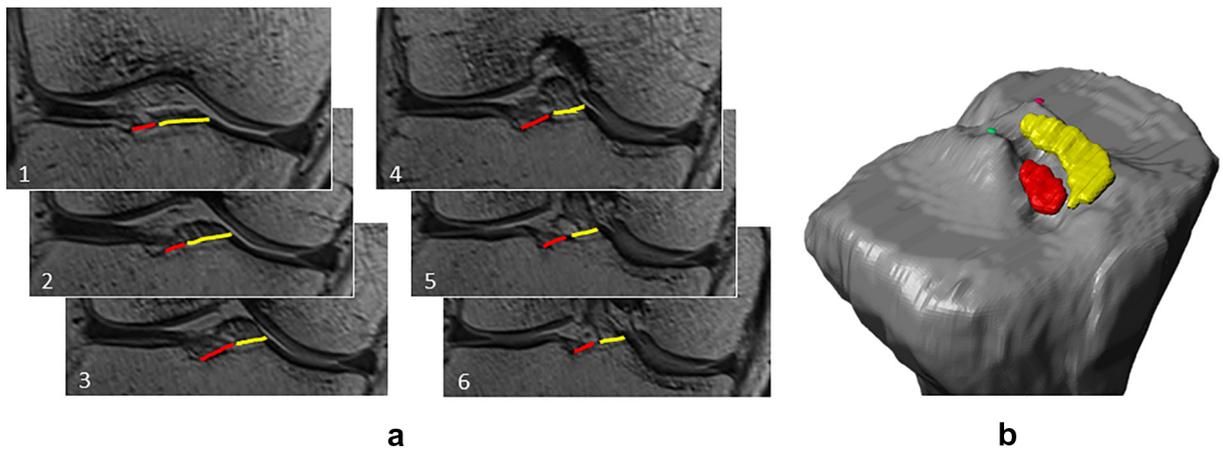|	Proton density sagittal 3D space
Repetition time, ms	1200
Echo time, ms	38.0
Matrix size	320,320
Field of view, mm	160
Slice thickness, mm	0.65
Interslice gap, mm	0
Resolution, mm	0.5 0.5 0.6
Pixel bandwidth, kHz	391
Echo train length	43
No. of signals acquired	1.4
Imaging time, min	9

Figure 1. (a) Tibial attachment of ACL (dotted line) and ALMR (solid line) were segmented on every coronal image. (b) 3D reconstructed model with the ACL attachment (asterisk), ALMR (obelisk), and the medial (arrow) and lateral (arrow head) tibial eminences.

confidence intervals were calculated. The difference in the location, length, and width of ACL and ALMR were evaluated with the paired t-test. The correlations between the intercondylar-eminence width and the area of ACL and ALMR were evaluated using regression analysis. Statistical significance was set at p < 0.05. A prior power analysis for sample size was performed; for an effect size of 0.8, power of 0.9, and an α level of 0.05; a total of 20 individuals were required.

3. Results

The ACL and ALMR attachments were individually identified in all knees. The ACL tibial attachment was elliptical in nine knees (45%), C-shaped in nine knees (45%), and triangular in two knees (10%) (Figure 4). The morphology of the ALMR tibial attachment was elliptical in all knees. The mean values of the ACL and ALMR tibial attachments were as follows: area, 106.2 ± 21.3 mm^2 and 56.2 ± 12.3 mm^2, respectively; length, 16.8 ± 2.0 mm and 11.0 ± 1.8 mm (p < 0.0001), respectively; and width, 6.9 ± 1.3 mm and 6.6 ± 1.0 mm (p = 0.433), respectively (Table 2).
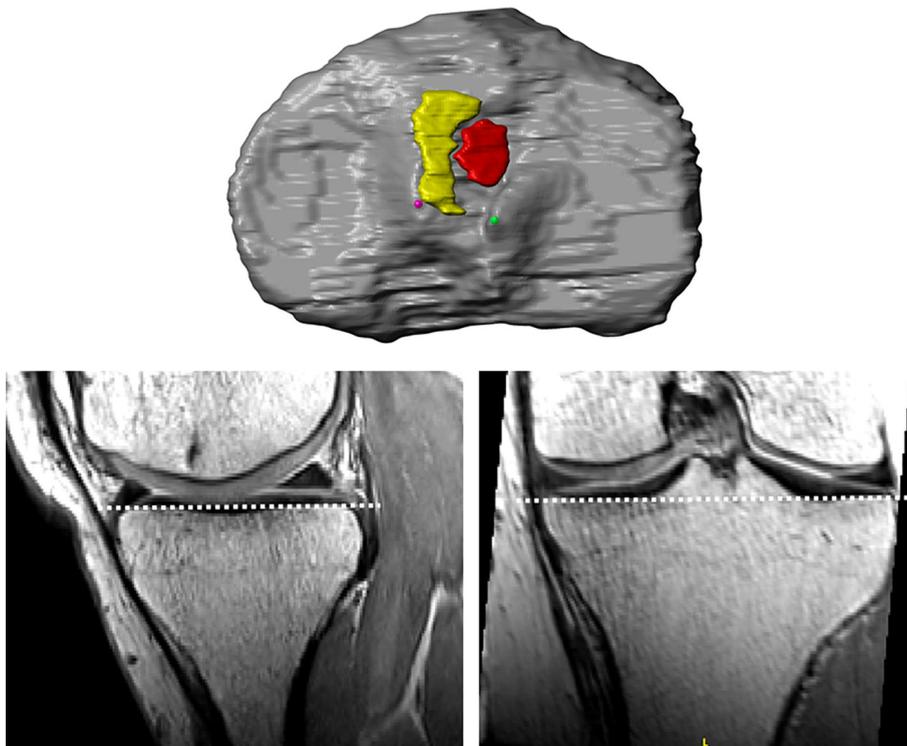

Figure 2. The view from the top of the tibia, which is perpendicular to the tibial plateau defined by the white dotted lines.
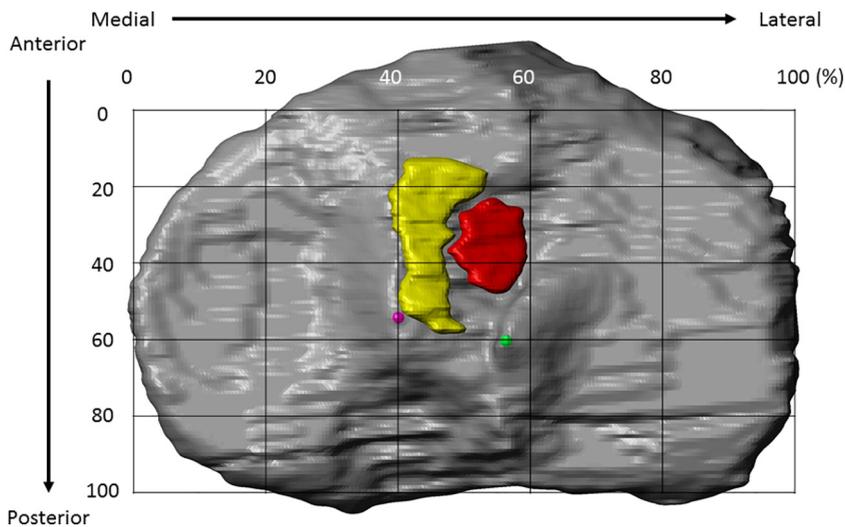
Figure 3. Measurement of the locations using a grid method. Anterior–posterior and medial-lateral axes were established using anatomical coordinates. The locations of the ACL (asterisk) and ALMR (obelisk) tibial attachments were expressed as a percentage of the corresponding maximum dimensions.

The centre of the ACL and ALMR attachments was located 46.5 ± 1.7% and 56.5 ± 1.9%, respectively (p < 0.0001), from the medial edge of the tibial plateau, and 36.3 ± 3.6% and 36.7 ± 3.5% (p = 0.575), respectively, from the anterior edge of the tibial plateau. In relation to the medial tibial spine, ACL and ALMR centres were 5.2 ± 1.7 mm and 10.4 ± 3.9 mm lateral respectively, and 8.5 ± 2.4 mm and 9.1 ± 2.2 mm anterior respectively. The centre of the ACL was found to be 7.9 ± 1.2 mm medial and 0.2 ± 2.0 mm anterior to the centre of ALMR. The distance between ACL and ALMR centres was 8.1 ± 1.3 mm (Table 2). The intercondylar-eminence width was 12.5 ± 2.1 mm. A positive correlation was observed between the ACL area and the intercondylar-eminence width (r = 0.502, p = 0.024), and between the ALMR area and the intercondylar-eminence width (r = 0.487, p = 0.029) (Figure 5).

The intra-class coefficients for intra-observer reliability were 0.92 and 0.83 for the segmentation of ACL and ALMR attachments, respectively. The inter-class coefficients for inter-observer reliability were 0.94 and 0.86 for the segmentation of ACL and ALMR attachments, respectively.

4. Discussion

It is clinically important to understand the relationship of the attachment sites of these structures. The most important finding of the present study was that the attachments of ACL and ALMR are individually distinguishable, and most of the ACL tibial attachments were elliptical or C-shaped. The anatomy of the ACL and ALMR tibial attachments have been reported by many previous studies; however, no report has focused on the relationship between ACL and ALMR (Table 3). To our knowledge, this is the first study to describe a detailed relationship between the ACL and ALMR attachments.

Siebold et al., investigated the anatomy of the ACL tibial attachment macroscopically after removing the overlying soft tissue between LM and ACL. They indicated that the ACL bony attachment can be divided into a "direct" and "indirect" part macroscopically. The "direct" insertion is the narrow but long "C"-shaped attachment with an area of 31.4 mm², and the "indirect" part is the anteriorly and broader attachment of the fan-like extension fibres with an area of 79.6 mm². Both insertions together form a "duck-foot-like" bony ACL attachment with a combined area of 110.9 mm² [22]. After this study, Oka from the same institute
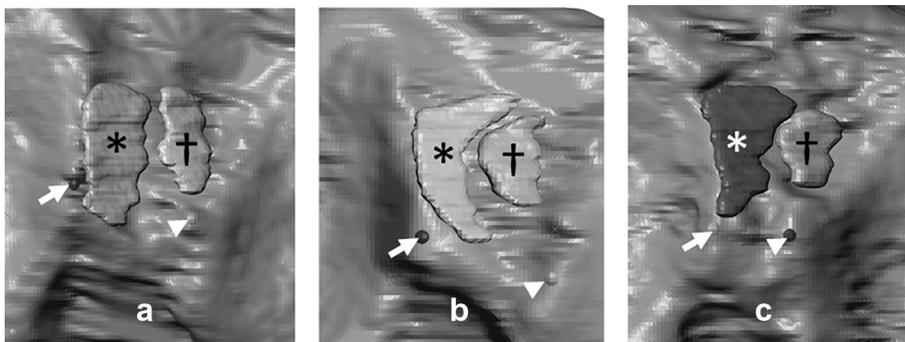

Figure 4. Different shape of ACL attachments; a) elliptical, b) C-shaped, and c) triangular.

Table 2
Dimensions of ACL and ALMR tibial attachments.

	ACL	ALMR	p-Value
Area (mm^2)	106.2 ± 21.3	56.2 ± 12.3	<0.0001
Morphology (elliptical/C-shape/triangular)	9/9/2	20/0/0	
Length (mm)	16.8 ± 2.0	11.0 ± 1.8	<0.0001
Width (mm)	6.9 ± 1.3	6.6 ± 1.0	0.433
Location in ML (%)	46.5 ± 1.7	56.5 ± 1.9	< 0.0001
Location in AP (%)	36.3 ± 3.6	36.7 ± 3.5	0.575
Lateral distance from the medial spine (mm)	5.2 ± 1.7	10.4 ± 3.9	0.0001
Anterior distance from the medial spine (mm)	8.5 ± 2.4	9.1 ± 2.2	0.2486
The intercondylar eminences width (mm)	12.5 ± 2.1		
The distance between ACL and ALMR (mm)	8.1 ± 1.3		

evaluated the tibial attachment histologically, and they concluded that the macroscopically "C-shaped" direct insertion might be the cross section of the mid-substance of the ligament just above the insertion. The ACL arises from tibial duck-foot-like direct insertion forming a "C" shape, and surrounds the anterior horn of the lateral meniscus [16].

Previous studies have examined the relationship between the ACL and ALMR. A macroscopic anatomical study showed that 63.2% of ALMR overlaps 40.7% of the tibial attachment of the ACL [13], and a recent study using scanning electron microscopy (SEM) showed that the mean percentage of the ACL fibres overlapping the ALMR attachment, in the coronal and sagittal planes, was 41.0 and 53.9% [23], respectively. In the present MRI study, some fibres from the ACL seem to attach to the ALMR. However, in terms of the bony attachment, a recent histological study shows that there was a clear border between ACL and LM [12]. Siebold et al., also showed ALMR does not blend into the ACL [22]. Therefore, it is important to show the relationship between bony attachment of the ACL and ALMR without including the fibres between ACL and ALMR. Some anatomical studies showed the area which would include the fibres attaching to the ALMR, which is the reason why the area of the ACL is smaller than that of the previous study.

The location of ACL and ALMR was also mentioned previously. Kusano et al., showed that the ALMR attaches deeply beneath the posterior part of the ACL footprint, and Siebold et al. showed that the ALMR inserts completely posterior to the anterior "C"-shaped part of the ACL attachment [12,22]. Watson et al., found that the average distance between the ACL and ALMR centres was 8.4 mm [26], and Ziegler et al. reported that the ACL centre was an average of 7.5 mm medial to the centre of the ALMR [29]. Similar to these studies, in the present study, the ALMR attachment was surrounded by the ACL and the average distance between ACL and ALMR centres was 8.1 mm. Moreover, the present study shows that the average widths of ACL and ALMR were similar (6.9 mm vs 6.6 mm, respectively).

The clinical relevance of these findings is that drilling a large circular tibial tunnel in the centre of the ACL attachment is likely to damage the ALMR attachment. Watson et al., showed in a cadaveric study that iatrogenic injury to the ALMR occurred in 4 of 6 specimens with 10-mm-diameter reamed tunnels, although the guide-pin was placed directly in the calculated centre of the ACL footprint. The iatrogenic area on the ALMR attachment was 20.5 mm^2 (28.8%) and 16.2 mm^2 (25.9%) when using 40 and 60-degree aiming devices, respectively [26]. LaPrade et al., showed that 11-mm-diameter reaming decreased 38% of the attachment area of ALMR compared with the intact state (p = 0.003). They also showed that the mean ultimate failure strength of the native ALMR was 610 N, which was significantly higher (p = 0.015) than that of ALMR with an 11-mm-diameter-reamed ACL reconstruction tunnel (506 N), demonstrating that this damage does weaken the ALMR attachment [14].
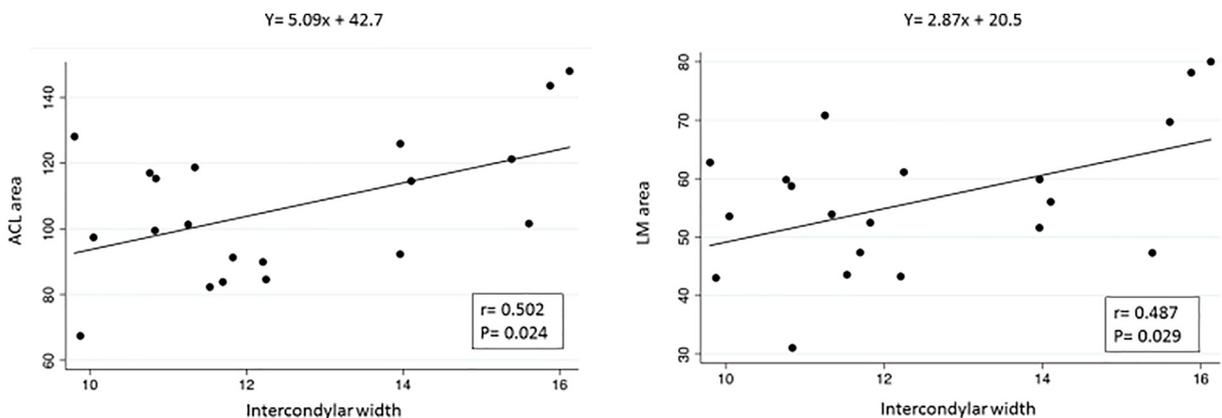

Figure 5. Correlation between the intercondylar width and the ACL/ALMR tibial attachment. The ACL/ALMR tibial attachment was positively correlated with the intercondylar width.

Table 3
Dimensions of ACL and ALMR tibial attachment in previous studies.
Data are shown as mean ± SD (range).

	Study design	ACL			ALMR			ACL-ALMR distance (mm)
		Area (mm^2)	Length (mm)	Width (mm)	Area (mm^2)	Length (mm)	Width (mm)	
Present study	3-T MRI study	106.2 ± 21.3	16.8 ± 2.0	6.9 ± 1.3	56.2 ± 12.3	11.0 ± 1.8	6.6 ± 1.0	8.1 ± 1.3
Cuomo (2006) [4]	Macroscopic cadaveric study		17.0 ± 2.0	9.0 ± 2.0				
Colombet (2006) [2]	Macroscopic cadaveric study		17.6 ± 2.1	12.7 ± 2.8				
Edwards (2007) [5]	Macroscopic cadaveric study		18.0 ± 2.0	9.0 ± 2.0				
Siebold (2008) [21]	Macroscopic cadaveric study	114.0 ± 36	14.0 ± 2.0	10.0 ± 2.0				
Ziegler (2011) [29]	Macroscopic cadaveric study							7.5 ± 0.5 (6.5–8.4)
Ferretti (2012) [6]	Macroscopic cadaveric study	206.2 ± 10.3	18.1 ± 2.8 (13.7–22.1)	10.7 ± 1.9 (7.4–13.1)				
Pujol (2013) [20]	Macroscopic cadaveric study	117.9 (90–130)	13.4 (10–17)	11.1 (9–12)				
LaPrade (2014) [13]	Macroscopic cadaveric study	218.4 ± 51.8 (185.5–251.4)			140.7 ± 30.0 (121.6–159.8)			5.0 ± 1.8 (3.8–6.1)
Watson (2014) [26]	Macroscopic cadaveric study	208.3 (190.7–232.3)			72.1 (59.7–84.6)			8.5 (7.9–9.0)
Siebold (2015) [22]	Macroscopic cadaveric study	110.9 ± 14.7 (80.1–133.1)	12.6 ± 2.3 (7.7–16.3)	3.3		11.8 ± 1.8 (8.4–15.5)		
Tashiro (2017) [25]	3-T MRI study	182.7 ± 41.1						

In a case report, Furumatsu et al., confirmed damage to the anterior attachment of the LM after primary ACL reconstruction on second-look arthroscopy [7]. Therefore, when a surgeon reams a large diameter tibial tunnel, to minimise the damage on ALRM, it is preferable to create the tunnel as close to medial side of the footprint as possible, without damaging the medial articular cartilage. In addition, changing the shape of tunnel to an oval or elliptical shape, whilst technically more difficult, is another possible option to avoid this damage.

The meniscal root attachments serve as anchors that preserve hoop stresses, and allow the meniscus to absorb the impact on the knee joint. Injuries of the meniscal root attachments result in decreased hoop strength of the meniscus, excessive loading, and cartilage degeneration of the knee. Prince showed that the peak force in the lateral compartment was significantly increased at 0 degrees of knee flexion after a tear in the peripheral one-third of the meniscus, and after meniscectomy in the cadaveric study. Moreover, the peak pressure in the non-traumatised medial compartment was significantly increased after partial lateral meniscectomy [19]. Kodama et al., have described the relationship between the location of the tibial tunnel and the decreased hoop strength of LM which was shown as LME. They showed that a posterolateral location of the tibial tunnel aperture within the footprint of the native ACL increases LME. They concluded that if this location was less than five millimetres from their lateral reference point, LME would be increased. However, in that study, 17 of 26 cases underwent double-bundle reconstruction [11]. The mechanical impairment of the meniscus caused by extrusion can alter the weight-bearing capacities of the tibiofemoral compartments and contribute to progression of knee osteoarthritis by damaging the articular cartilage.

There are some limitations to this study. Firstly, it was difficult to obtain healthy young knee specimens with an intact ACL. Therefore, high-resolution 3-T MRI was used for the analysis and high inter-class reproducibility was shown. Secondly, we did not evaluate the accuracy between this method and direct measurement using anatomical dissections. However, the values were similar to those of a previous study which removed the overlying soft tissue between LM and ACL [22]. Thirdly, the clinical relevance of damaging the ALMR is not entirely clear, particularly with disturbance to part of the ALMR, when previous studies examining this damage have usually compromised the entire attachment. Further research in both cadaveric and clinical outcome studies should help in clarifying whether there is a "threshold of damage" that is acceptable, and below which has no impact on meniscal function. This in turn should help better optimise graft size for each individual patient.

The finding of this study has clinical relevance. The knowledge obtained about the ACL insertion and its relationship to the ALMR attachment should help surgeons to avoid damaging the ALMR attachment when creating a tibial tunnel, by carefully selecting the location and size of the tibial tunnel. In addition, we have demonstrated that we can accurately measure the ACL and ALMR attachments using 3-T high-resolution MRI. This method could be applied for the evaluation of patients that undergo ACL reconstruction. The relationship between LME, ALMR attachment loss, and clinical outcomes is still unclear, and further study is needed regarding this.

5. Conclusions

The morphologies of most ACL tibial attachments were elliptical or C-shaped, and that of all ALMRs were elliptical. The short distance between both centres of the attachments demonstrates that the ALMR can be damaged when a tibial tunnel is drilled in

ACL reconstruction, and should be carefully considered when creating a tibial tunnel, with particular reference to the location and size selected for the tunnel, to avoid unnecessary damage that may impact on subsequent lateral meniscal function.

Authors' contributions

Conceptualization: Takeshi Oshima.
Project administration and Supervision: David A. Parker.
Investigation, Formal analysis and Validation: Takeshi Oshima, Samuel Grasso and Murilo Leie.
Writing-original draft: Takeshi Oshima.
Writing-review and editing: Murilo Leie and David A. Parker.

Conflicts of interest

The authors declare that they have no conflict of interest. No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

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Ethical approval

The study design was approved by the Human Research Ethics Committee of Northern Sydney Local Health District (NSLHD reference: RESP/17/110).

Consent to publish

Participant provided written consent for publication of images.

Informed consent

Informed consent was obtained from all individual participants included in the study.

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