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Area of the tibial insertion site of the anterior cruciate ligament as a predictor for graft size

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Abstract
Purpose To determine the distribution of different sizes of the area of the tibial insertion site among the population and to evaluate whether preoperative MRI measurements correlate with intraoperative findings to enable preoperative planning of the required graft size to cover the tibial insertion site sufficiently. The hypothesis was that the area of the tibial insertion site varies among individuals and that there is good agreement between MRI and intraoperative measurements.
Methods Intraoperative measurements of the tibial insertion site were taken on 117 patients. Three measurements were taken in each plane building a grid to cover the tibial insertion site as closely as possible. The mean of the three measurements in each plane was used for determination of the area. Two orthopaedic surgeons, who were blinded to the intraoperative measurements, took magnetic resonance imaging (MRI) measurements of the area of the tibial insertion site at two different time points.
Results The intraoperative measured mean area was 123.8 ± 21.5 mm^2. The mean area was 132.8 ± 15.7 mm^2 (rater 1) and 136.7 ± 15.4 mm^2 (rater 2) when determined using MRI. The size of the area was approximately normally distributed. Inter-rater (0.89; 95 % CI 0.84, 0.92; $p < 0.001$) and intrarater reliability (rater 1: 0.97; 95 % CI 0.95, 0.98; $p < 0.001$; rater 2: 0.95; 95 % CI 0.92, 0.96; $p < 0.001$) demonstrated excellent test–retest reliability. There was good agreement between MRI and intraoperative measurement of tibial insertion site area (ICCs rater 1: 0.80; 95 % CI 0.71, 0.87; $p < 0.001$; rater 2: 0.87; 95 % CI 0.81, 0.91; $p < 0.001$).
Conclusion The tibial insertion site varies in size and shape. Preoperative determination of the area using MRI is repeatable and enables planning of graft choice and size to optimally cover the tibial insertion site.
Level of evidence III.

Keywords Tibial insertion site · Anterior cruciate ligament · ACL · Individualized · Anatomy · Graft size

Introduction

Preoperative planning in anterior cruciate ligament (ACL) surgery is essential. The surgeon has to consider whether single- [6] or double-bundle [9] reconstruction is feasible and what type of graft best fits the anatomical conditions. Studies have already shown that the tibial insertion site varies in shape and size among different individuals [14]. It correlates with the area of the tibia plateau [11] and the femoral bicondylar width [19]. Earlier studies were based on the assumption that a complete footprint restoration is needed to reconstruct a maximum of ACL insertion site area to restore a maximum of the functional envelope of the knee [23, 24].

Intraoperative measurements of the insertion site can be conducted easily using a customized ruler [21]. It was shown that preoperative determination of the length of the tibial insertion site using MRI is possible as well [28]. Furthermore, it could be shown that the size of the graft can be determined preoperatively using MRI measurements [5].

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However, for proper planning, knowledge of the area of the tibial insertion site is much more accurate. Measuring the width and the length of the insertion site enables the surgeon to determine the area of the insertion site using a previously published formula [18]. The required graft to cover the insertion site sufficiently can then be determined based on either preoperative or intraoperative measurements.

Furthermore, it is important to consider that the size of the tibial insertion site varies, and so does the shape. A current study reported that the tibial insertion site is elliptical in 51 %, triangular in 33 % and C-shaped in 16 % [8]. Conduction of multiple measurements in each plane can improve the precision of determination of tibial insertion site's area.

This study is needed because preoperative planning is indispensable to ensure proper covering of the tibial insertion site and to place the graft in the correct position. Choosing graft type and size based on the area of the tibial insertion site is a new approach. It is important to establish an easy and repeatable planning tool that can be used right away in clinical practice.

Therefore, the purposes of this study were to determine the distribution of different sizes of the area of the tibial insertion site among the population and to evaluate whether preoperative MRI measurements correlate with intraoperative findings to enable preoperative planning of the required graft size to cover the tibial insertion site sufficiently.

Materials and methods

One hundred and seventeen patients, who underwent ACL reconstruction between March 2012 and January 2015 at our institution, were enrolled in the study. Patients with prior injuries to the affected knee were excluded. Intraoperative measurements were taken by the senior orthopaedic surgeon using a customized ruler. To take the measurements, the remnant ACL fibres were dissected with a scalpel blade. The measurements of the lengths of the ACL insertion sites were taken in the anterior-posterior direction at 90° knee flexion, as previously described (Fig. 1a) [14]. The measurements of the width of the tibial insertion site were taken in the lateral-medial direction at 90° flexion (Fig. 1b).

Previous studies have shown that the shape of the tibial insertion site varies [8]. To acknowledge this, three measurements were taken in each plane building a grid to cover the tibial insertion site as closely as possible (Fig. 2). The mean of the three measurements in each plane was used for determination of the area.

Two orthopaedic surgeons, who were blinded to the intraoperative measurements, took MRI measurements of the length and width of the tibial insertion site at two different time points. MRI examination was performed at mean 2.3 ± 4.4 months prior to surgery, using a 1.5 T open-bore magnet (GE Signa, GE Healthcare, USA). Sagittal T2 proton density-weighted sequences were used for taking the measurements of the tibial insertion site length. Coronal T2 proton density-weighted sequences were used for taking the measurements of the tibial insertion site width. At this

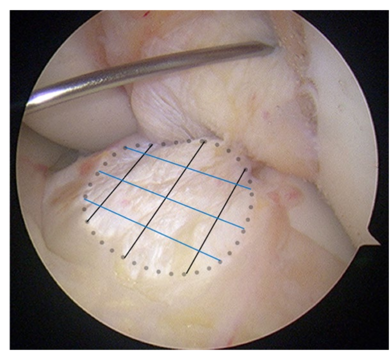
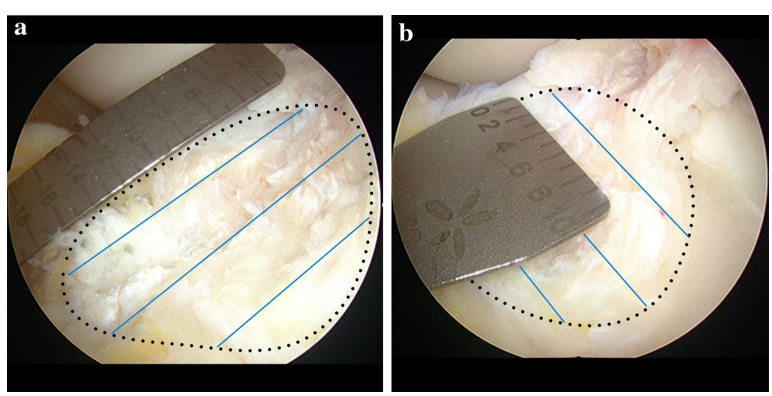


Fig. 2 Remnant of the anterior cruciate ligament was cut at its native insertion site and was reflected to visualize the entire tibial insertion. Three measurements were taken in each plane building a grid to cover the tibial insertion site as closely as possible. The mean of the three measurements in each plane was used for determination of the area

Fig. 1 Arthroscopic intraoperative measurement of the length (**a**) and the width (**b**) of the tibial insertion site of the anterior cruciate ligament. Three measurements were taken in each plane



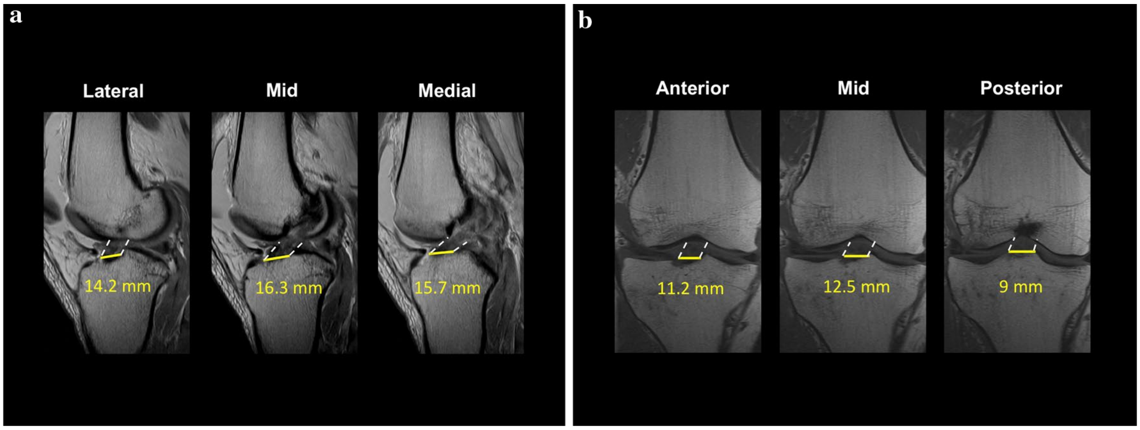


Fig. 3 Measurements of the length (**a**) and the width (**b**) of the tibial insertion site of the anterior cruciate ligament (ACL) on T2 proton density-weighted sequences of a knee MRI. The horizontal yellow lines indicate the tibial ACL insertion site length (**a**) and width (**b**) in the respective image. The mean of the three measurements in each plane was used for determination of the area

point, 23 patients had to be excluded because MRI was performed in an outside hospital and did not meet the required standards.

The three images demonstrating the largest exposure of the remnant ACL fibres at the tibial insertion site were chosen in each plane. To measure the exact length of the tibial insertion site, the distance between the most anterior and most posterior fibres of the distal ACL was determined in each image [2]. To measure the exact width of the tibial insertion site, the distance between the most medial and most lateral fibres of the distal ACL was determined in each image. The measurements were taken using a straight line parallel to the tibia plateau surface. (Fig. 3a, b). Again, the mean of the three measurements in each plane was used for determination of the area.

A previously described formula [18] for area of an ellipse was adapted on three measurements for each plane to calculate the area of the tibial insertion site: $((\text{length } 1 + \text{length } 2 + \text{length } 3)/3) \times ((\text{width } 1 + \text{width } 2 + \text{width } 3)/3) \times (\eta/4)$.

Institutional review board approval was obtained from the University of Pittsburgh prior to the start of this study (MOD12020619-08/PRO12020619).

Statistical analysis

The data were processed with the statistical software package SPSS (version 20.0, SPSS Inc., Chicago, USA). The distribution of the intraoperative tibial insertion site area measurements was described. Means and standard deviations were calculated. The inter-rater reliability between MRI raters 1 and 2 as well as the particular intrarater reliability was determined based on intraclass correlation coefficient (ICC). ICC was also performed between the MRI raters and intraoperative measurements. Pearson correlation was used to determine correlation between demographic data (age, weight, height, BMI, sex) and intraoperative measurements. Linear regression modelling was used to

Table 1 Demographic data of the study population

	Mean ± SD	Range
Age (years)	24.4 ± 9.1	14.3–53.8
Height (cm)	174.3 ± 10.1	155.0–201.0
Weight (kg)	77.0 ± 16.9	47.6–118.8
BMI (kg/m^2)	25.1 ± 4.0	16.4–39.8
Males (%)	58	

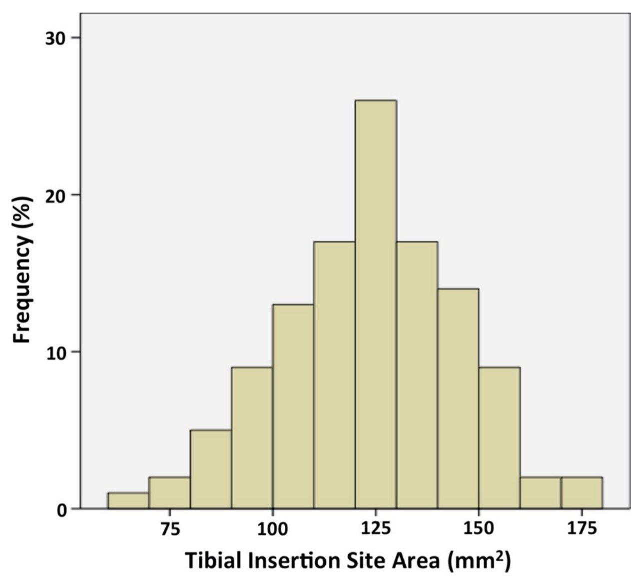


Fig. 4 Distribution of the area of the tibial insertion site of all patients initially enrolled in this study based on intraoperative measurements

Table 2 Measurements of the tibial insertion site of the anterior cruciate ligament

	Mean length (mm)		Mean width (mm)		Area (mm^2)	
	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD	Range
MRI rater 1	16.6 ± 1.3	13.1–19.2	10.2 ± 1.0	7.3–12.5	132.8 ± 15.7	75.1–188.5
MRI rater 2	16.7 ± 1.3	12.5–19.1	10.4 ± 0.9	7.3–12.3	136.7 ± 15.4	71.7–184.5
Intraoperative	16.3 ± 1.6	11.0–20.0	9.7 ± 1.4	6.0–12.0	123.8 ± 21.5	61.3–172.8

estimate prediction models for the area of the tibial insertion site. Bland–Altman plots were created to detect the agreement between MRI and intraoperative measurements. Significant values were set at 0.05. Data description included means with 95 % confidence intervals. Prior to the study, a sample size calculation was performed showing a sample size of 62 patients sufficient to reach an alpha of 0.05 and a power of 80 %. Diagrams were created with the software package Excel (version 14.2.4, Microsoft® Excel®, Redmond, USA).

Results

Table 1 shows the demographic data of the study population.

The intraoperative measured mean area of the tibial insertion site was 123.8 ± 21.5 mm^2. Figure 4 demonstrates the distribution of tibial insertion site area based on the intraoperative measurements. The size of the area was approximately normally distributed.

The mean area of the tibial insertion site was 132.8 ± 15.7 mm^2 when determined by rater 1 and 136.7 ± 15.4 mm^2 when determined by rater 2 using MRI. Table 2 shows the detailed MRI measurements and intraoperative measurements of the lengths and the widths of the tibial insertion site as well as the calculated areas.

Inter-rater (0.89; 95 % CI 0.84, 0.92; $p < 0.05$) and intrarater reliability (rater 1: 0.97; 95 % CI 0.95, 0.98; $p < 0.05$; rater 2: 0.95; 95 % CI 0.92, 0.96; $p < 0.05$) demonstrated excellent test–retest reliability. There was also good agreement between the MRI and intraoperative measurement of tibial insertion site area (ICCs rater 1: 0.80; 95 % CI 0.71, 0.87; $p < 0.05$; rater 2: 0.87; 95 % CI 0.81, 0.91; $p < 0.05$).

The area of the tibial insertion site did not correlate with weight, BMI or age of the patients. Weak correlations existed between tibial insertion site area and patient height (0.24, $p < 0.05$) as well as sex (0.25, $p < 0.05$; coded "female = 1", "male = 2").

In an attempt to predict intraoperative tibial insertion site area by preoperative MRI, the linear regression analysis was highly significant ($\beta = 0.76$; R2-change 0.58; $p < 0.05$). On the contrary, multivariate linear regression analysis showed no significant differences when adding the demographic information (R2-change 0.02; n.s.).

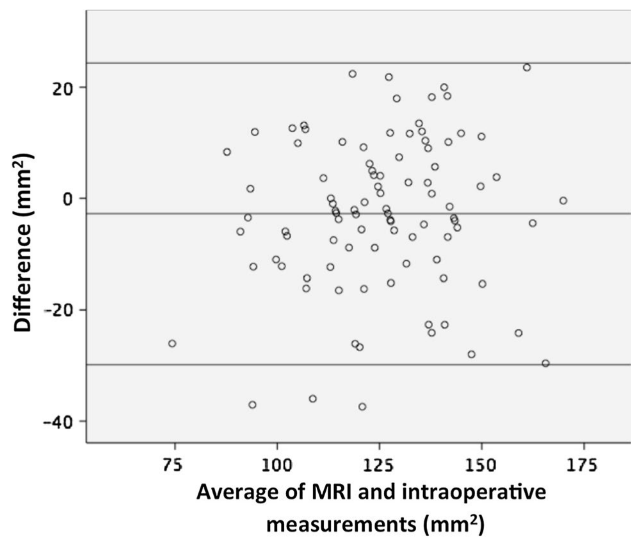


Fig. 5 Bland–Altman plot: agreement between MRI and intraoperative measurements. Three of 94 patients (3.2 %) are outside the limits of agreement

Regarding the agreement between MRI and intraoperative measurements, Bland–Altman plots showed an agreement inside the limits in 91 patients (3 %) (Fig. 5).

Discussion

The most important finding of the present study was that the area of the tibial insertion site varies and is approximately normally distributed. Furthermore, preoperative determination of the area using MRI is repeatable and enables planning of graft choice and size to optimally cover the tibial insertion site. In the past, ACL reconstructions were performed on a one-size-fits-all base. Over time, more individualized approaches have been developed. Double-bundle procedure [4], anatomical tunnel positioning [1] or augmentation surgeries [20] have proven to increase patient outcomes significantly, if chosen in the correct setting. Furthermore, different kinds of grafts have been utilized to adapt reconstruction techniques on patient' individual anatomy, lifestyle habits and rupture pattern. Different autografts such as quadriceps tendon and patella tendon, each with or without bone plug, or hamstring tendon all have their strength and weaknesses. In some cases, when the autograft is small in diameter, adding an allograft can help to improve coverage of the tibial insertion site. However, in such cases, a longer graft healing time has to be considered and later return to high function should be conducted [26]. All these approaches have the aim to optimize restoration of the native ACL and its tibial insertion site.

Previous studies reported pre- and intraoperative measurements of the length of the tibial insertion site [14, 28]. However, considering that the shape of the tibial insertion site varies, the area of the tibial insertion site is required to ensure proper planning of graft size. Optimized coverage of the tibial insertion site can be achieved by either adapting the size of the graft, adding an allograft [15], or changing between a single-bundle procedure [22] and double-bundle procedure [4]. Based on the results of this study, patients' demographics such as weight and height are non-reliable predictors of the tibial insertion site size. Our study provides a method to determine the required graft size based on the area of the tibial insertion site. This can be done either based on the intraoperative measurements or based on the preoperative measurements on MRI.

The tibial tunnel aperture area can be calculated using a previously described formula accounting for tibial tunnel drill angle (α) and instrument diameter (d): $A_{\text{ellipse}} = \pi\ (d^2/(4 \times \sin\alpha))$ [13].

The percentage of reconstructed area (PRA) can be calculated by dividing the tunnel aperture area by the native insertion site area: PRA = tunnel aperture area/native insertion site area [18].

Based on this, a formula to determine the required graft size can be created:

Single-bundle reconstruction: (tunnel aperture area) = (aimed percentage of reconstructed area) × (native tibial insertion site area).

Double-bundle reconstruction: (tunnel aperture area of antero-medial bundle) + (tunnel aperture area of postero-lateral bundle) = (aimed percentage of reconstructed area) × (native tibial insertion site area).

In this way, the surgeon knows exactly the required size of the graft and can adapt his technique on individuals' tibial insertion site. Table 3 shows an example of how to match graft size and tibial insertion site size for single- and double-bundle reconstructions.

Furthermore, various groups have worked on preoperative determination of graft size using MRI [5, 29]. It was shown that the diameter of a hamstring graft can be properly determined by MRI [29]. Considering this and the methodology presented in our study, preoperative planning of the reconstructed area of the tibial insertion site of the ACL is easy to perform.

However, to date it remains unclear what percentage of the native tibial insertion site should be reconstructed to achieve an optimized outcome and low failure rates. Currently, it is known that a small graft size is a predictor of poorer Knee Injury and Osteoarthritis Outcome Score (KOOS) sport/recreation function 2 years after primary ACL reconstruction [17]. Furthermore, it was shown that small grafts lead to increased failure rate [3, 5, 16]. Other studies reported impingement of the graft in situations where the diameter was chosen too big, especially if a small notch is present [27]. It was reported that the mid-substance of the ACL is approximately 50 % of the diameter of the tibial insertion site [7]. Based on these findings, we propose that a reconstruction of 50–80 % of the native insertion site is desirable to reproduce the native size of the ACL mid-substance cross-sectional area [12]. However, future clinical studies are needed to confirm this number.

Table 3 Match of graft size and tibial insertion site size for single- and double-bundle ACL reconstructions

Tibial insertion site area 141 mm^2			
Single bundle		Double bundle	
Graft diameter (mm)	Percentage (%)	Graft diameter (mm)	Percentage (%)
6	24	6, 7	58
7	33	7, 7	66
8	43	7, 8	77
9	55		

This study does have limitations. For calculation of the area, a formula based on the area of an ellipse was utilized. Some tibial insertion sites are elliptical, some triangular, and some c-shaped. This was classified in the literature as type I, type II and type III, respectively. Based on the current literature, the predominant shape is elliptical [8]. Different shapes may require different types of reconstruction to ensure proper footprint restoration. A type I "elliptical" tibial insertion site may be sufficiently restored by a single-bundle technique, while a type III "C-shaped" tibial insertion site may be better restored using a double-bundle technique. However, different shapes result in different diameters, especially in the boundary areas of the tibial insertion site. Taking only one measurement in one plane does not reflect the area of the tibial insertion site sufficiently. By taking multiple measurements in each plane, we minimized the influence of different shapes. Second, graft choice should not be based on the size or shape of the tibial insertion site alone. Size and shape of the femoral insertion site [10] and notch size [25] should be considered as well. Our clinical experience is that the size of the tibial insertion site is a good predictor; however, there might be cases where an intraoperative adaption is necessary.

The approach to calculate the tibial insertion site's area can be used right away in clinical practice, since it is a repeatable and easy planning tool, which enables the surgeon to optimize graft choice and graft placement.

Conclusion

The area of the tibial insertion site varies and is approximately normally distributed. Preoperative determination of the area using MRI is repeatable and enables planning of graft choice and size to optimally cover the tibial insertion site. Utilization of the findings of this study is recommended to achieve more individualized ACL reconstruction surgery.

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