Med Pregl 2024; LXXVII (9-12): 291-297. Novi Sad: septembar-decembar.

THREE-DIMENSIONAL SURFACE AREA OF THE ANTERIOR CRUCIATE LIGAMENT TIBIAL INSERTION, AND ITS CORRELATION WITH THE ANATOMICAL CHARACTERISTICS OF THE PROXIMAL TIBIA

TRODIMENZIONALNA POVRŠINA PRIPOJA PREDNJEG UKRŠTENOG LIGAMENTA NA GOLENJAČI I NJEGOVA KORELACIJA SA ANATOMSKIM KARAKTERISTIKAMA PROKSIMALNE GOLENJAČE

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Original study
Originalni naučni rad
UDK 616.718.5:616.728.3]-07/-08
https://doi.org/10.2298/MPNS2412291K

Abstract

Introduction. Precise positioning of the tibial tunnel is crucial for successful anterior cruciate ligament (ACL) reconstruction. By correlating the ACL attachment area on the tibia with tibial plateau dimensions measured on two preoperative standard radiographs, it is possible to determine the optimal drilling angle preoperatively. **Material and Methods.** This study examined 32 tibial specimens with ACL attachments obtained during total knee arthroplasty. Anteroposterior and lateral preoperative radiographs were used to measure tibial plateau dimensions. A 3D scan of the ACL attachment area, performed with a Personal HAptic iNTerface Mechanism Omni device, provided two new measurements: the ACL attachment surface area (mm^2) and its projection on the tibia (mm^2). **Results**. The average anteroposterior and medial-lateral diameters of the tibial plateau were 47.81 mm and 71.94 mm, respectively. The mean ACL attachment area was 142.4 mm^2, and the average projection area was 110.2 mm^2. Multiple regression analysis demostrated statistically significant correlations between tibial plateau dimensions and the ACL attachment area. Mathematical-statistical procedures yielded formulas for predicting the attachment surface area (P = 7.585 x AP - 0.179 x ML - 207.319) and its projection (P = 3.466 x AP + 1.261 x ML - 146.218) based on measured anteroposterior and medial-lateral diameters of the tibial plateau. **Conclusion**. Standard radiographic measurements of the tibial plateau allow for accurate prediction of the ACL attachment area. Combined with drill bit diameter, these data support individualized determination of the tibial tunnel drilling angle, enhancing surgical precision in ACL reconstruction.

Key words: Anterior Cruciate Ligament Reconstruction; Tibia; Orthopedic Procedures; Radiography; Correlation of Data

Sažetak

Uvod. Iako je položaj tunela u butnoj kosti u centru pažnje, ne sme se potceniti značaj preciznog pozicioniranja tunela u golenjači. Pronalaženjem veze između površine pripoja prednje ukrštene veze (LCA) na golenjači i dijametra platoa na standardnim radiogramima, omogućava se određivanje ugla bušenja platoa koristeći samo dva preoperativno načinjena standardna radiograma. **Materijal i metode.** Istraživanje je sprovedeno je na 32 platoa golenjače sa pripojem LCA uzete tokom totalne aloartroplastike kolena kod kojih su preoperativno izmerene dimenzije platoa golenjače. Trodimenzionalno skeniranje prostorne površine pripoja LCA na platou golenjače u odnosu na ravan zglobne površine golenjače izvršeno je korišćenjem uređaja Personal HAptic iNTerface Mechanism Omni. Dobijene su vrednosti površine (mm^2) i projekcije pripoja (mm^2) LCA na golenjači. **Rezultati**. Prosečna vrednost anteroposteriornog dijametra bila je 47,81 mm a mediolateralnog 71,94 mm. Prosečna površina pripoja LCA bila je 142,4 mm^2 a prosečna projekcija pripoja 110,2 mm^2. Analiza varijanse multiple regresije pokazuje da se merenjem oba dijametra može postići statistički značajna korelacija, te su načinjene formule za izračunavanje površine i projekcije pripoja na osnovu izmerenih vrednosti anteroposteriornog i mediolateralnog dijametra platoa golenjače. Površina pripoja može se predvideti pomoću formule P = 7.585 x AP-0.179 x ML-207.319 a projekcija pripoja formulom P = 3.466 x AP + 1.261 x ML-146.218. **Zaključak**. S obzirom na visoku korelaciju, moguće je predvideti površinu pripoja LCA na golenjači merenjem samo anteroposteriornog i profilnog dijametra platoa na standardnim radiografskim snimcima. Poznavanje površine pripoja prednjeg ukrštenog ligamenta i prečnika burgije omogućava određivanje ugla bušenja tunela u golenjači.

Ključne reči: rekonstrukcija prednjeg ukrštenog ligamenta; golenjača; ortopedske procedure; radiografija; korelacija

Introduction

The anterior cruciate ligament (ACL) plays a crucial role in preventing anterior displacement of the tibia relative to the femur and maintaining normal knee kinematics [1]. ACL injuries most commonly occur during sports activities [2]. The increasing number of ACL reconstructions each year has height-

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Abbreviations

ACL – anterior cruciate ligament
CGAL – The Computational Geometry Algorithms Library
AP – anteroposterior
ML – mediolateral
BMI – body mass index
MRI – Magnetic Resonance Imaging
P – tibial insertion area

ened interest among orthopedic surgeons in optimizing surgical techniques and achieving superior outcomes in restoring anterior knee stability [3].

The primary objective of ACL reconstruction is to restore knee stability throughout the full range of motion [4]. Over the past two decades, advancements in our understanding of the ACL anatomy and function have led to a shift from the traditional isometric tunnel placement to anatomical reconstruction. Improper tunnel positioning remains the most frequently cited cause of ACL reconstruction failure. While femoral tunnel placement has received significant attention, precise tibial tunnel positioning is equally critical [5, 6]. Understanding the geometric characteristics of the ACL insertion site, including cross-sectional and three-dimensional surface area, is essential for determining the ligament mechanical properties and optimizing reconstruction outcomes [7]. Since grafts only partially cover the anatomical footprint, identifying the most functional position within the tibial attachment is necessary. Recent studies have emphasized the role of tibial tunnel positioning in ensuring translational control and rotational stability following ACL reconstruction [8–11].

In approximately 78% of cases, the ACL tibial insertion is elliptical, while in 22% it is triangular [12, 13]. However, in ACL reconstruction, the tibial graft

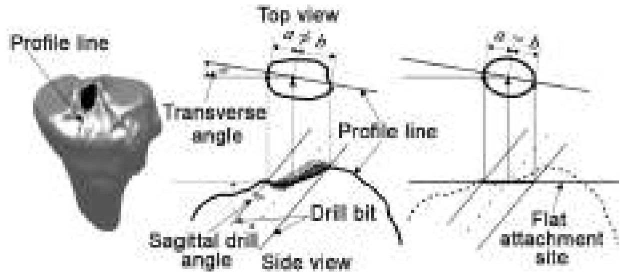


Figure 1. Tibial tunnel drilling; actual shape of the tunnel opening on the plateau created by the drill (center) and the elliptical opening on the plateau (right) if the ACL tibial attachment is assumed to be flat. (Adapted from: Milojević et al. [15]. Analysis of the tibial tunnel aperture area in ACL reconstruction. Med Pregl. 2016)

insertion site is often approximated as a circle or ellipse, which does not fully capture the graft's actual positioning. The size and location of the elliptical area of the tibial tunnel **(Figure 1)** are influenced by drill diameter and sagittal and transverse angles (the angle at which the tunnel intersects the tibial plateau) [14]. The tunnel opening on the tibia is analyzed as an ellipse formed by the intersection between the tibial articular surface and the tibial tunnel. However, since the tunnel opening on the tibia is not a perfect ellipse, patient-specific characteristics must be considered during reconstruction **(Figure 2).** Although the insertion surface is irregular, it is often approximated as an ellipse for simplicity. By establishing the relationship between the three-dimensional ACL tibial insertion area and the tibial plateau dimensions on standard radiographs, we propose a method for determining the optimal tibial drilling angle using only two standard preoperative radiographs.

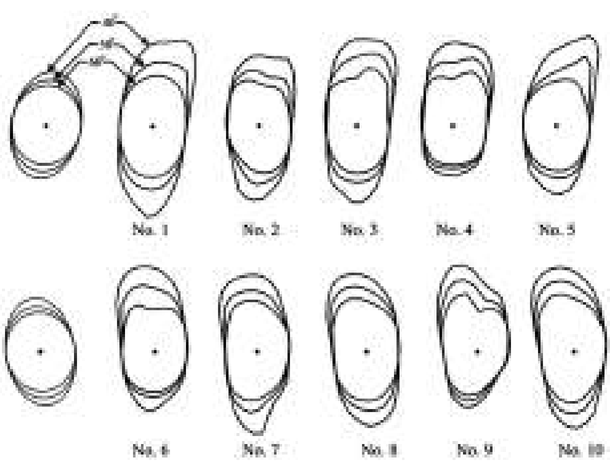
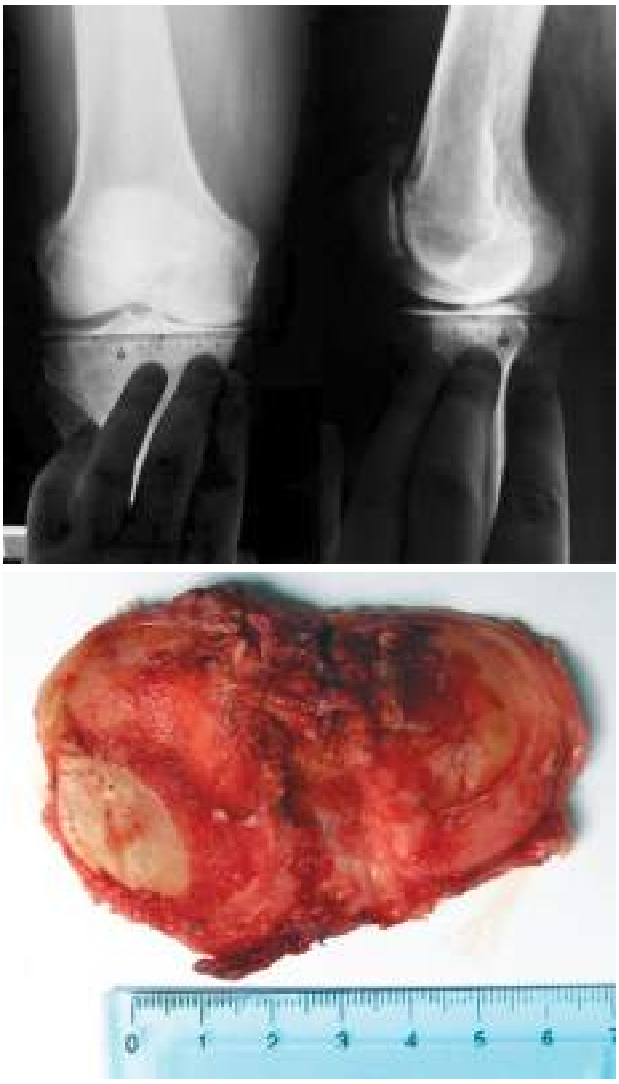


Figure 2. Different shapes and sizes of the tibial plateau aperture depending on the drilling angle: sagittal (40°, 50°, and 60°), transverse (10°), and a drill bit diameter of 10 mm. The correlation with the elliptical shape is also shown. (Adapted from: Milojević et al. [15])

Material and Methods

Following approval from the Ethics Committee of the University Clinical Center of Vojvodina, a prospective study was conducted at the Clinic for Orthopedic Surgery and Traumatology in collaboration with the Faculty of Technical Sciences, University of Novi Sad. The study analyzed 32 tibial plateau specimens with intact ACL tibial attachments obtained during total knee arthroplasty. Standard AP and lateral radiographs with standard magnification were obtained preoperatively to measure tibial plateau dimensions **(Figure 3a).** Two numerical parameters were recorded: the anteroposterior (AP, in millimeters) and medial-lateral (ML, in millimeters) diameters.

Microdissection techniques were used to clearly define the ACL tibial attachment site **(Figure 3b).** A three-dimensional scan of the attachment area on the tibial plateau was then performed using the PHANToM



Figures 3a and b. a. Preoperative knee radiographs in two projections – AP (left) and lateral (right) – showing the AP (in mm) and ML (in mm) diameters of the proximal tibia. **b.** Tibial plateau with the ACL attachment.

Omni device **(Figure 4),** which allows precise determination of object position (three degrees of freedom along x, y, and z axes) and orientation (three rotational

Figure 4. PHANToM Omni haptic device

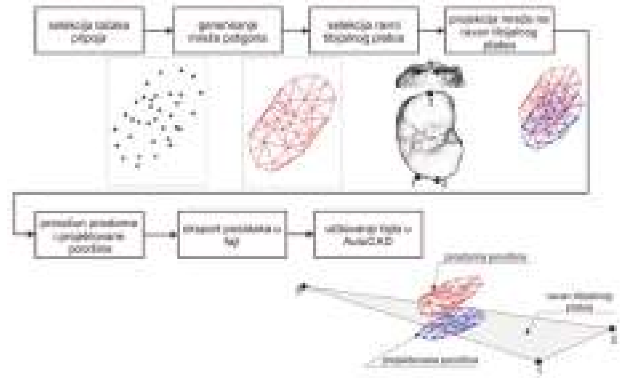


Figure 5. Model of the developed software solution

degrees of freedom). The device also provides force feedback in the x, y, and z directions, enabling the user to "feel" contact with virtual objects. This method yielded two additional numerical parameters: the three-dimensional surface area of the attachment (mm²), and its projected area (mm²) onto the tibial plateau plane.

A specialized software solution, developed in the C++, was used to generate the tibial insertion area, store collected data, and facilitate further analysis. The model of the developed software solution is shown in **Figure 5.**

The first step involves selecting the attachment points. Using the haptic device, the user selects reference points on the tibial surface, pressing a button to record each point's coordinates. The attachment area is computed using a mesh of triangular polygons, generated with the Delaunay_triangulation_2 class from the Computational Geometry Algorithms Library (CGAL).

To determine both the spatial area of the insertion and its projection onto the tibial plateau plane, three points defining the tibial plateau plane are selected using the same method. A second triangular mesh is then created as a projection onto this plane (the blue surface in **Figure 5**). The total spatial and projected areas of the ACL insertion are calculated as the sum of the individual triangular areas in each mesh.

The final step in the software solution is data storage. The calculated areas, along with the coordinates of the triangles and plateau plane points, are saved in a file for further analysis. The data can be imported into AutoCAD if needed.

Results

The mean AP diameter was 47.81 mm, and the mean ML diameter was 71.94 mm. The mean ACL tibial insertion area was 142.4 mm², while the mean projected area was 110.2 mm². Three-dimensional scanning identified three distinct shapes of the ACL tibial insertion: triangular, oval, and irregular. Strong correlation was observed between the following parameter pairs: AP and

Table 1. Age, nutritional parameters, attachment dimensions, and statistical results in patients whose tibial plateau surfaces were analyzed

		SD	SE	min	max	CV	Confidence interval		Skewness	Kurtosis	p
Age	68.59	8.63	1.52	45.0	81.0	12.58	65.48	71.71	-0.58	-0.06	0.952
Height	167.1	8.73	1.54	152.0	189.0	5.22	163.9	170.24	0.68	0.40	0.572
Weight	84.22	12.19	2.16	60.0	110.0	14.48	79.82	88.62	0.26	-0.64	0.371
BMI	30.15	4.76	0.84	23.4	41.6	15.80	28.43	31.87	1.41	1.33	0.024
AP	47.81	3.77	0.67	43.0	57.0	7.89	46.45	49.17	1.00	0.03	0.188
ML	71.94	5.15	0.91	65.0	85.0	7.16	70.08	73.79	0.93	0.61	0.341
Footprint area	142.4	38.95	6.89	62.2	238.9	27.35	128.4	156.46	0.32	-0.16	0.086
Footprint projection	110.2	32.44	5.74	46.6	202.4	29.44	98.52	121.92	0.60	0.67	0.531

ML diameters (0.941), insertion area and its projection (0.915), insertion area and AP diameter (0.712), and insertion area and ML diameter (0.667). Moderate correlations were found between the projection and AP diameter (0.591), and the projection and ML diameter (0.579). Additionally, correlations were noted between tibial plateau dimensions and anthropometric characteristics: AP diameter and patient height (0.585), AP diameter and patient weight (0.418), ML diameter and patient height (0.619), ML diameter and patient weight (0.435), ACL insertion area and patient height (0.447), ACL insertion area and patient weight (0.466), and ACL insertion area and BMI (0.118) **(Table 1).**

Multiple regression analysis demonstrated that measuring both AP and ML diameters enables a statistically significant prediction of the ACL insertion area and its projection. The following mathematical models were derived:

ACL insertion area (mm^2): **P = 7.585 x AP - 0.179 x ML - 207.319**

Projected insertion area (mm^2): **P = 3.466 x AP + 1.261 x ML - 146.218**

When applying these formulas, differences between the measured and calculated insertion areas ranged from 2.478 to 54.933 mm^2, while for projections, they ranged from 0.636 to 57.953 mm^2. Regarding deviations between the computed and the measured insertion area, 26 patients (81.3%) had values within one standard deviation of the mean, while 6 patients (18.7%) were beyond this range. For the projected insertion area, 25 patients (78.2%) fell within one standard deviation of the mean, while 7 patients (21.8%) were outside this range. These findings suggest that the derived formulas allow for highly accurate predictions of the ACL insertion area and its projection.

Discussion

One of the primary causes of early recurrent instability following ACL reconstruction is improper graft placement, particularly non-anatomical tunnel positioning [16]. While femoral tunnel malpositioning is more frequently implicated [17], poor tibial tunnel placement can also lead to recurrent instability. An anteriorly placed tibial tunnel can lead to graft impingement, graft failure, or reduced flexion, whereas a posteriorly placed tunnel may result in excessive laxity in flexion [18, 19]. Additionally, factors such as inadequate graft tension, insufficient graft size, and improper graft fixation can contribute to failure [20].

Since final graft positioning is determined by both femoral and tibial tunnel placement, there is a growing consensus that tunnels should be drilled within the native anatomical footprints rather than using conventional, non-anatomical techniques. This anatomical approach aims to restore stability and normal knee kinematics [21]. Conventional tunnel drilling methods typically reconstruct only about 57% of the native ACL tibial footprint [22], which, despite short-term postoperative success, does not fully restore knee biomechanics and may lead to degenerative changes over time. Anatomical ACL reconstruction, tailored to individual patient anatomy, seeks to address this limitation. Sadoghi et al. [23] reported that anatomical ACL reconstruction produces knee kinematics similar to those of an uninjured knee. Similarly, Bedi et al. [24] found that ACL fiber bundles contribute to distinct knee functions, and optimal graft placement is essential for stability and minimizing impingement. Their biomechanical study emphasized that the tibial tunnel should be centered within the native ACL tibial footprint, which is not merely the geometric center of the tibial plateau aperture but rather a patient-specific three-dimensional structure.

Arthroscopic identification of ACL footprints can be challenging. Siebold [25] proposed the use of an “insertion site table”, which involves preoperatively measuring the anteroposterior diameter of the tibial plateau with a ruler. Rabuck et al. [26] suggested preoperative measurement of the sagittal MR images of the patellar tendon, ACL length, and tibial attachment. Quiles et al. [27] introduced a technique involving labeling and stereophotogrammetry that provides a detailed three-dimensional representation of the ACL insertion in vitro, including its raised borders, internal quarter-turn step-like structure, and indentations corresponding to intervals between fiber bundles. Wang and Lee's histological study showed that the ACL tibial insertion exhibits a medially eccentric staining pattern in the cartilage attachment area.

Standard AP and lateral radiographs are commonly used to assess graft positioning, but their accuracy is limited due to patient-specific bone morphology and limb position [28]. Computed tomography (CT), particularly with 3D or multiplanar reconstructions, offers the most precise assessment of graft placement but is constrained by high radiation exposure and cost. MRI can be an alternative, although artifacts from metal interference screws may obscure details. Additionally, specialized computer software can analyze tibial graft positioning using standard radiographs [29].

Despite the three-dimensional nature of ACL tibial insertion, it is often assessed using two-dimensional techniques. In surgical practice, the tibial tunnel aperture is typically represented as an ellipse, formed by the intersection of the tibial plateau and the tibial tunnel [30, 31]. However, this schematic simplification does for fully account for the actual bone geometry, resulting in a two-dimensional projection that underestimates the true three-dimensional attachment area. The intraoperatively created tibial tunnel aperture varies individually, and significantly differs from a perfect ellipse despite the common schematic representation.

The elliptical aperture area can be adjusted by modifying drill diameter and drilling angles to better approximate the true anatomical shape of the ACL tibial attachment [30]. A smaller sagittal drilling angle increases the attachment area, making it closer to the anatomical shape. Similarly, reducing the transverse angle produces an insertion area more representative of anatomical morphology. Therefore, preoperatively selecting the appropriate drill diameter and drilling angles could enhance ACL reconstruction outcomes. Since the ACL tibial insertion is three-dimensional, further improvement in reconstruction quality can be achieved through three-dimensional investigative methods [32].

By utilizing three-dimensional scanning with the PHANToM Omni device, we identified three distinct insertion shapes: triangular, oval, and irregular. While the triangular shape was most common, oval insertion areas were also observed [12]. The drill diameter and sagittal and transverse drilling angles influence the tibial tunnel aperture area during ACL reconstruction. Previous studies, such as Siebold et al. [33] described the ACL tibial insertion as "C"-shaped. However, this configuration was not observed in our sample, likely due to degenerative changes in our older patient population.

Regarding the ACL tibial attachment size, studies suggest that this area constitutes approximately 6% of the tibial plateau surface [33]. Our study aimed to predict the insertion area based on preoperative tibial plateau dimensions. We found that the mean ACL tibial insertion area in our sample was 142.4 ± 38.95 mm^2 (ranging from 62.2 to 238.9), while the mean projected area was 110.2 ± 32.44 mm^2 (ranging 46.6 to 202.4). A notable heterogeneity of the sample was observed, with large variations in insertion area, consistent with findings by other authors [34–36]. Siebold et al. [37] found that the ACL tibial insertion is the widest part of the ligament, measuring on average 114 ± 36 mm^2, while other authors reported average areas of 133.8 ± 31.3 mm^2 and 151.53 ± 28.95 mm^2. Kopf et al. [38] noted substantial variations in the ACL tibial insertion area and a significant but weak correlation between insertion size and BMI.

Our findings also indicate correlation between AP and ML diameters of the tibial plateau and patient height and weight, as well as correlation between the ACL tibial insertion area and patient height, weight, and BMI. Murawski et al. [30] demonstrated that ML diameter of the distal femur (bicondylar diameter) can predict the ACL femoral and tibial insertion size when MRI is unavailable. Our results also suggest correlations between the ML diameter of the tibial plateau and ACL insertion area, although not statistically significant, with a more significant correlation between AP diameter and insertion area.

Even with a perfectly centered tibial tunnel, there remains risk of impingement within the intercondylar notch. This risk depends on several factors, including ACL tibial insertion size, tibial tunnel diameter, and drilling angles. Studies indicate that when using a 10 mm graft with a drilling angle of 45° or less, 45% of knees are at risk of impingement, with 20% experiencing certain impingement. Therefore, when performing single-bundle anatomical tibial tunnel during ACL reconstruction, careful consideration of tunnel size and drilling angles is crucial to minimize the risk of intercondylar notch impingement [39].

Conclusion

Based on the observed correlations, we developed a mathematical-statistical formula that can accurately predict the anterior cruciate ligament tibial insertion area in a high percentage of cases using only two preoperative radiographic parameters – the anteroposterior and mediolateral diameters of the tibial plateau on anteroposterior and mediolateral views. By determining the anterior cruciate ligament insertion area and selecting the drill bit diameter, surgeons can optimize the drilling angle for the tibial tunnel.

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Rad je primljen 10. II 2025.
Recenziran 17. III 2025.
Prihvaćen za štampu 17. III 2025.
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