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Stereophotogrammetric surface anatomy of the anterior cruciate ligament's tibial footprint: Precise osseous structure and distances to arthroscopically-relevant landmarks

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ABSTRACT

Background: While femoral tunnel malposition is widely recognized as the main technical error of failed anterior cruciate ligament (ACL) surgery, tibial tunnel malposition is likely underrecognized and underappreciated.
Purpose: To describe more precisely the qualitative and quantitative anatomy of the ACL's tibial attachment in vitro using widely available technology for stereophotogrammetric surface reconstruction, and to test its applicability in vivo.
Methods: Stereophotogrammetric surface reconstruction was obtained from fourteen proximal tibias of cadaver donors. Measurements of areas and distances from the center of the ACL footprint and the footprint of the obtained bundles to selected arthroscopically-relevant anatomic landmarks were carried out using a three-dimensional design software program, and means and 95% confidence intervals were calculated for these measurements. Reference landmarks were tested in three-dimensional models obtained with arthroscopic videos.
Main findings: The osseous footprint of the ACL was described in detail, including its precise elevated limits, size, and shape, with its elevation pattern described as a quarter-turn-staircase-like ridge. Its internal indentations were related to inter-spaces identified as bundle divisions. Distances from the footprint center to arthroscopically relevant landmarks were obtained and compared to its internal structure, yielding a useful X-like landmark pointing to the most accurate placeholder for the ACL footprint's "anatomic" center. Certain structures and reference landmarks described were readily recognized in three-dimensional models from arthroscopic videos.
Conclusions: Stereophotogrammetric surface reconstruction is an accessible technique for the investigation of anatomic structures in vitro, offering a detailed three-dimensional depiction of the ACL's osseous footprint.

Abbreviations: AIA, anterior intercondylar area; AIAR, anterior intercondylar area's ridge; ACIK, anterocentral intercondylar knob (*ACL tubercle*); ACL, anterior cruciate ligament; ACL AM, anterior cruciate ligament, anteromedial bundle; ACL-AML, anterior cruciate ligament, lateral part of the AM bundle; ACL-AMM, anterior cruciate ligament, medial part of the AM bundle; ACL PL, anterior cruciate ligament, posterolateral bundle; AFIR, anterior frontal intercondylar ridge; AIS, anterior intercondylar staircase; AISX, anterior intercondylar staircase X-point; AL, anterolateral; ALF, anterolateral fossa; ALIR, anterolateral intercondylar ridge; AM, anteromedial; AMF, anteromedial fovea; AMIR, anteromedial intercondylar ridge; ARMM, anterior root of the medial meniscus; ARLM, anterior root of the lateral meniscus; LT, lateral tubercle; MT, medial tubercle; P, Parsons' knob/tubercle; PA, posterior arch; PCL, posterior cruciate ligament; PL, posterolateral; PM, posteromedial; POE, post-eminence; PRE, pre-eminence; PRLM, posterior root of the lateral meniscus; PRMM, posterior root of the medial meniscus.

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1. Introduction

The most popular surgical techniques available today for reconstructing a torn anterior cruciate ligament (ACL) involve replacing it with a graft. It is critical, therefore, to know the exact position, area, and shape of its footprint, as well as its relationship with neighboring structures.

There are no general standard guidelines and fewer reports on the bony landmarks for anatomic placement of the tibial tunnel, which have been disparately described in recent studies. It is suspected, therefore, that tibial tunnel malposition is likely underrecognized and underappreciated as a cause of failed ACL reconstruction surgery.

The ACL has long been described as a group of fascicles that change in tension and length through the range of motion [1,2], with the simplest division proposed as an anteromedial (AM) part that tightens with knee flexion, and a posterolateral (PL) part that tightens with knee extension [3–6].

Norwood & Cross [7] divided the ACL into three functional bundles, a division supported by later studies [8–10]. The function and footprint of the three bundles have since been further investigated mainly by Japanese researchers [11–14], who have applied it to surgical repair [12,15–18], and their findings have been supported in many mammal species [19–21]. Support for a three-bundle reconstruction is also given for more “anatomic” and functional ACL restoration [12,13,22].

The aim of this work is to describe with detail the qualitative and quantitative anatomy of the ACL's attachment to the proximal tibia, with reference to pertinent surgically identifiable osseous landmarks.

It was hypothesized that widely available technological means for stereophotogrammetric surface reconstruction is capable of offering highly detailed three-dimensional (3D) models. These models should allow for a precise and consistent depiction of the ACL attachment in relation to known (and potentially yet unknown) anatomic landmarks, to help guide future surgical repair and reconstruction protocols.

2. Material and methods

2.1. Specimen collection and preparation

Fourteen adult formaldehyde-preserved tibial plateaux were donated and used in this study under a protocol approved by the research ethics committee of our hospital. Exclusion criteria included previous knee surgery (one patient, arthroscopic debridement in osteoarthritis), and lack of integrity of ligamentous or meniscal structures, verified during dissection. There were five males (three paired, two non-paired) and three females (paired), and the mean age of the cadaveric specimens was 49 years (range, 16 to 76 years). Specimens were graded according to the Outerbridge classification [23], with two specimens (paired) showing grade II, and two specimens (paired) showing grade IV.

A fixed temperature solid-point burner was used to delineate soft tissue insertions. The ACL was reflected to reveal the native insertion of the anterior root of the lateral meniscus (ARLM), and its attachment to the posterior aspect of the ACL was cut, being then marked and detached before ACL preparation.

The ACL was marked and detached, with, dissection of individual bundles documented qualitatively and drawn schematically but not marked, to avoid damaging the topographic relief of the ACL footprint.

As a potential division of fiber bundles, fat-filled proximal inter-spaces were identified and documented during dissection. Detachment began at the anteroposterior inter-space, and was then completed by separating the stump through the identified mediolateral inter-space. Blunt division of the ACL stumps could not be carried out to their tibial origin, and the blade had to be used in all cases to finish dissection to bone.

Remaining soft tissues were stripped off specimens using a scalpel, periosteal elevator, and rongeur, and then placed for 24 h in a container filled with enzymatic liquid detergent (Instrunet 4EZ + T®, Inibsa, Lliçà de Vall, Spain).

2.2. Digital processing and 3D surface

Pyrography marks of soft tissue insertions were retouched with a marker pen. A high-resolution digital camera (EOS 6D, Canon Inc., Ōta, Tokyo, Japan) was used to take photographs of specimens placed over a sanding sponge, in 11.25-degree intervals at five constant heights, plus 16 photographs above the specimen, obtaining a total of 176 photographs per specimen.

Images were processed with a photogrammetry software program (Autodesk Memento Beta version 1.13, Autodesk Inc., San Rafael, California, U.S.) to create 3D models, which were then scaled using the known measure of the sanding sponge (see Video 1). Models were then processed in 3D point cloud and mesh processing software application (CloudCompare, version 2.6.1 64 bit, GNU GPL software), and contour plots were built and exported.

2.2.1. Scan system validation

To compare real measures with those of the 3D models, a 3D design software program (Geomagic Studio 2014 64 bit, 3D Systems, Rock Hill, South Carolina, U.S.) was used to measure mediolateral (ML) width and anteroposterior (AP) depth, and to select the maximum height at the medial tubercle's (MT) apex, and the same measurements were taken with a digital caliper over the actual specimens. A Pearson product–moment correlation was run between them and the difference obtained was