1 Ribbonlike Anatomy of the Anterior Cruciate Ligament from Its Femoral Insertion to the Midsubstance

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Contents

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1.1 Introduction

A deep understanding of the morphology of the anterior cruciate ligament (ACL) is fundamental for its anatomical reconstruction, and most surgeons would agree that anatomical ACL reconstruction is the "restoration of the ACL to its native dimensions, collagen orientation and insertion sites" [16].

From previous anatomical studies it is well known that the bony femoral ACL insertion is in the shape of a crescent, with the resident's ridge (= lateral intercondylar ridge) as its straight anterior border and the posterior articular margin of the lateral femoral condyle as its convex posterior border [3, 5, 6, 8, 9, 12, 14, 15, 17, 19, 21, 34, 37, 39, 41, 44, 50]. Most ACL fibers are aligned posterior to and directly along the lateral intercondylar ridge. The longitudinal axis is in extension to the posterior femoral cortex and creates an angle to the femoral shaft axis which varies between 0° and 70° [6, 13, 23, 39–41, 44]. The most posterior fibers of the femoral insertion are blending with the posterior cartilage of the lateral femoral condyle and with the periosteum of the posterior femoral shaft [13, 17, 23, 40, 41, 44]. The femoral insertion site area shows big variations in size. According to the literature, the area varies between 46 and 230 mm^2, the length between 12 and 20 mm, and the width between 5 and 13 mm [6, 9, 13, 17, 19, 22, 23, 27, 34, 40, 44]. Girgis et al. [17] described the midsubstance of the ACL to be broad and flat with an average width of 11.1 mm.

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Other authors reported the diameter in the range between 7 and 13 mm and the cross-sectional area to be "irregular," "oval," "corded," or "bundled" [2, 4, 6, 12, 17, 25–27, 34, 36, 49].

Recent detailed observations of the femoral insertion site were reported by Mochizuki et al. [29], Iwahashi et al. [23], and Sasaki et al. [40]. Histologically they described the ACL midsubstance fibers to form a narrow "direct" insertion posterior and along to the lateral intercondylar ridge which was continued by a fanlike "indirect" insertion towards the posterior femoral cartilage. Interestingly they found the configuration of the ACL midsubstance to be "rather flat, looking like lasagna" [28].

1.2 Material and Methods

To reconfirm the above findings and to further explore the ACL anatomy, Smigielski et al. performed this cadaveric study. They included 111 fresh frozen cadaveric knees from an international accredited tissue bank. For detailed demographic data see Table 1.1. The key point in the dissections was to very carefully remove the synovial tissue surrounding the collagen fibers of the ACL. Measurements were performed under direct visualization using calipers. In addition, 30 knees were then sent for CT and MRI scans as well as histological examination of the femoral insertion site.

1.3 Results

In all dissected knees, the intraligamentous part of the ACL from close to its femoral insertion to the midsubstance was observed to have a ribbonlike structure (Fig. 1.1a–c). The femoral bony insertion of the ribbon was in exact continuity to the posterior femoral cortex (Fig. 1.2a, b). A clear separation into bundles was not possible. The morphometric measurements of the ACL were performed with calipers. The results for the width and thickness were as follows (Fig. 1.3a–c):

Mean width 2 mm from femoral insertion, 16.0 mm (range, 12.7–18.1)

Mean thickness 2 mm from femoral insertion, 3.54 mm (range, 2–4.8)

Mean width at midsubstance of ACL, 11.4 mm (range, 9.8–13.8)

Mean thickness at midsubstance of ACL, 3.4 mm (range, 1.8–3.9)

Mean cross-sectional area 2 mm from femoral insertion (calculated), 56.6 mm^2

Mean cross-sectional area at midsubstance of ACL (calculated), 39.8 mm^2

3D CT reconstruction, MRI, and histology reconfirmed the ribbonlike structure of the ACL. The collagen fibers approached to the femoral insertion in an acute angle creating a doubled tidemark at the bone. This may be interpreted as a place within the whole attachment with either greater stress forces or microinjuries. In both interpretations that would be the place where the greatest force is applied (Fig. 1.4a, b).

1.4 Discussion

The most important finding of this cadaveric study was that the ACL formed a flat ribbonlike ligament from its femoral insertion to the midsubstance in all dissected knees.

The ACL fibers were in exact continuity with the posterior femoral cortex and inserted from and posterior to the lateral intercondylar ridge. A clear separation into bundles was not possible. Anatomical observations were based on dissections of 111 cadaveric knees and were reconfirmed on CT, MRI, and histology.

Table 1.1 Detailed demographic data of the study subjects

Sex	Side	Age	Height	BMI	Weight	Races
66 female 45 male	49 right 62 left	Mean 67 years (32–74 years)	Mean 1.70 m (1.50–1.96 m)	Mean 22.6 (12.1–34.7)	Mean 64.3 kg (36–116 kg)	104 Caucasians 6 African Americans 1 Indian American

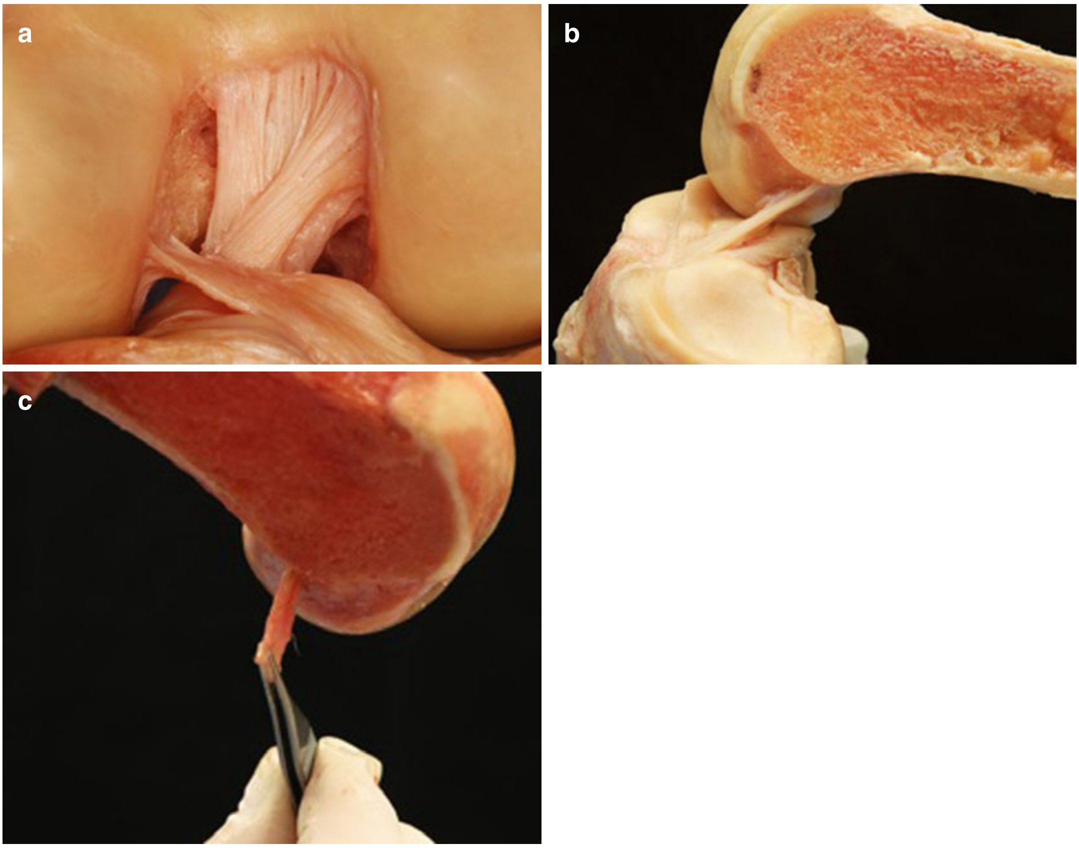

Fig. 1.1 (**a–c**) The ribbon shape of the ACL after careful removal of the synovial tissue: the ACL fibers form a flat ribbon 2 mm from its femoral attachment to the midsubstance

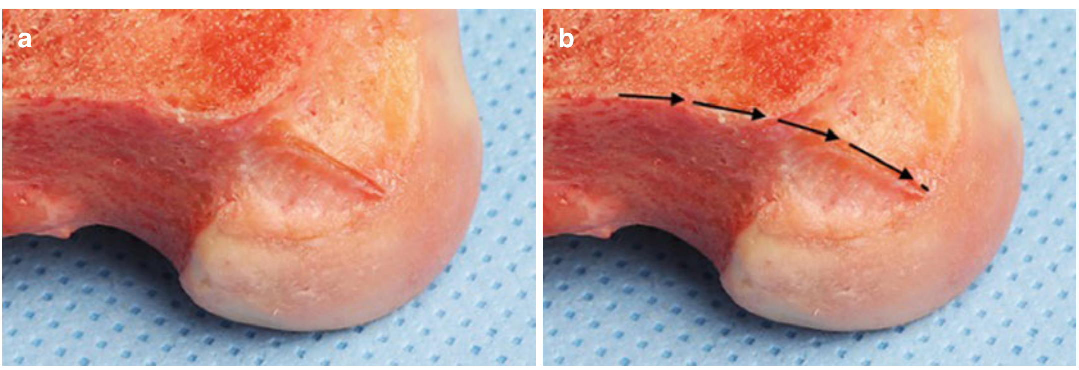

Fig. 1.2 (**a**, **b**) The direct insertion of the ribbonlike ACL fibers is in continuity of the posterior femoral cortex

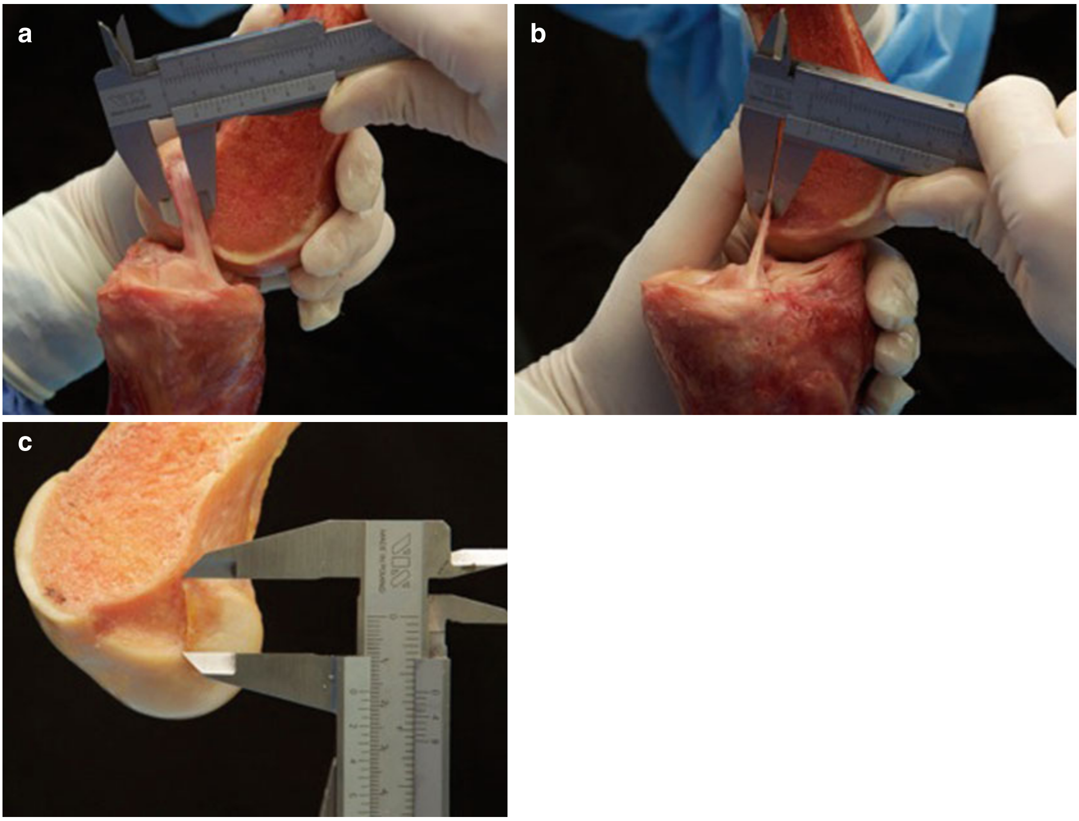

Fig. 1.3 (**a–c**) Measurement of the midsubstance width, thickness, and long axis of the ACL using a caliper

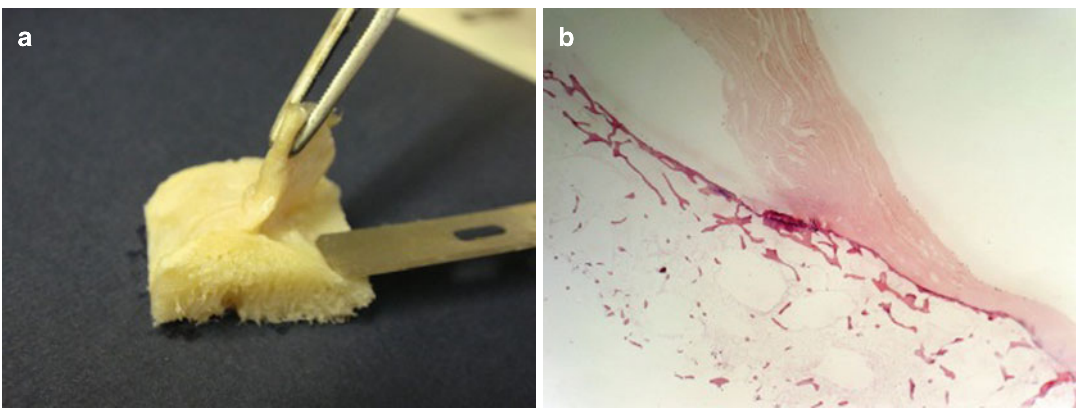

Fig. 1.4 (**a**, **b**) Histology of the direct femoral insertion of the ACL: macroscopic view (**a**) and microscopic view (**b**) (light microscopy, H&E stain, original magnification ×4). 6b: Note the sharp angle at which the fibers attach to the bone

1.5 Direct and Indirect ACL Femoral Insertion

These findings reconfirm earlier anatomical and histological studies. In 2006 Mochizuki et al. [28] emphasized "that – after removal of the surface membrane – the configuration of the intraligamentous part of the ACL was not oval" "but rather flat, looking like 'lasagna,'" 15.1 mm wide and 4.7 mm thick. Mochizuki et al. [28] also described the femoral insertion of the ACL to be very similar to the midsubstance configuration after the ligament surface membrane was removed from the attachment site. In 2010 Iwahashi et al. [23] reported on the "direct" femoral ACL insertion in which dense collagen fibers were connected to the bone by a fibrocartilaginous layer. This "direct" insertion was located in the depression between the lateral intercondylar ridge and 7–10 mm anterior to the articular cartilage margin. It measured 17.9 mm in length and 8.0 mm in width and covered an area of 128.3 mm^2. These findings were reconfirmed by Sasaki et al. [40] who observed a narrow "direct" ACL insertion area posterior and along the lateral intercondylar ridge and a "lateral intercondylar posterior ridge." The lengths of the long and short axes of the insertion were 17.7 and 5.3 mm, respectively. Another "indirect" ACL insertion was located just posterior to the direct insertion. The ACL from type I collagen blended into the posterior cartilage on immunohistological observations [40].

In a second report Mochizuki et al. [29] just recently differentiated between the main attachment of the midsubstance ACL fibers and the attachment of the thin fibrous tissue. Later extended from the midsubstance fibers and broadly spread out like a fan on the posterior condyle. The authors termed these fibers "fanlike extension fibers" and described that these two different structures formed a fold at the border between the midsubstance fibers and the fanlike extension fibers in knee flexion.

1.6 MRI Findings

Our MRI measurements as well as MRI reports from the literature also reconfirm the flat ribbonlike midsubstance of the ACL. Staeubli et al. [45] measured the midsubstance in 53 knees using a 0.23 T MRI and found a width of 6.1 mm in men and 5.2 mm in women; Muneta et al. [31] reported 5.5 and 5.1 mm, respectively, and Pujol et al. [38] 6.1 mm. Cohen et al. [8] scanned the knees of 50 patients using a 1.5 T MRI and measured the dimensions of the AM and PL bundles in the sagittal and coronal plane to be 5.1 mm by 4.2 mm and 4.4 mm by 3.7 mm, respectively.

1.7 Cross-Sectional Area of ACL

The calculated cross-sectional area of the midsubstance ACL among our specimen was 52 and 55 mm^2 for women and men, 2 mm close to its femoral insertion site and 33 and 38 mm^2 at midsubstance, respectively. This is in agreement with several previous reports. Mochizuki et al. [28] approximated 65 mm^2 as the femoral attachment area, Harner et al. [19] calculated approximately 40 mm^2 at midsubstance, Hashemi et al. 46.8 mm^2 [20], and Iriuchishima et al. 46.9 mm^2 [22]. Differentiating between gender Anderson et al. [4] calculated a cross-sectional area of 44 mm^2 for men and 36.1 mm^2 for women, Dienst et al. [11] of 56.8 mm^2 for men and 40–50 % less for women on MRI, and Pujol et al. [38] of 29.2 mm^2 (range 20.0–38.9 mm^2).

1.8 Double-Bundle Structure?

From our dissections the intraligamentous collagen fibers of the ACL could not clearly be separated into bundles. This is in agreement with Welsh [47] and Arnoczky [5] and others reporting that the intraligamentous part of the ACL is a collection of individual fascicles that fan out over a broad flattened area with no histological evidence for two separate bundles [5, 10, 12, 24, 34, 47]. However, the recent approach to the ACL is to differentiate between anteromedial and posterolateral bundle [1, 6, 7, 13, 16–19, 27, 32, 44, 48]. Some authors even described three separate ACL bundles [2, 33, 35]. The separation of the ACL into an AM and PL bundle was reconfirmed by Ferretti et al. [15] which found a fine synovial septum in dissected ACLs of fetus.

In any case, the macroscopic anatomical separation of the ACL into two or three bundles remains very difficult and is controversial. According to Arnoczky et al. [5], the bundle anatomy oversimplifies somewhat as the ACL is actually a continuum of fascicles. In 1991 Amis and Dawkins [2] described that it was “sometimes difficult to separate the ACL into three discrete bundles. In these cases the anterior aspect of the ACL was folded itself in flexion suggesting an arrangement of bundles. It was still possible to develop a three-bundle structure corresponding to the folding, but it felt, that the teasing apart was artefactual.” In older specimens, however, the separate bundles were often obvious. Amis and Dawkins [2] concluded, “that the ACL wrinkles into the appearance of three bundles as the knee flexes. These bundles are often demonstrably separate structures, twisted together during flexion, but the use of the dissector to separate the fibre bundles can cross the threshold between demonstration of bundles and their creation.” From our observation the “double-bundle effect” was created by the twisted flat ribbonlike structure of the ACL from femoral to tibial, which leads to the impression of two or three separate bundles when the knee was flexed. This would reconfirm reports of Amis and Dawkins [2] who made similar observations.

1.9 Consequences for ACL Reconstruction

The ribbonlike shape of the ACL and the flat but long femoral “direct” insertion site would support a rather flat anatomical footprint and midsubstance reconstruction. A double-bundle ACL reconstruction using two 5–6 mm hamstring grafts (see Chap. 29) [23, 28, 30, 40, 42, 43], a flat 5–6 mm patella tendon graft [41], or a flat 5–6 mm quadriceps tendon graft may be a better anatomical option than a large (and too wide)-diameter graft for a single-bundle ACL reconstruction. Sasaki et al. [40] concluded that whereas the indirect insertion plays a role as a dynamic anchorage of soft tissue to bone allowing certain shear movements, the strength of anchoring is weaker than the direct insertion [46]. Therefore, it would be ideal to make the femoral tunnel on the direct insertion in the native ACL [40]. Mochizuki et al. [29] found that it is very difficult to reconstruct the fanlike indirect extension fibers by a bone tunnel; however, the midsubstance fibers of the ACL can be reconstructed. Of course the most efficient anatomical and biomechanical ACL reconstruction has still to be proven in prospectively designed clinical long-term studies.

Memory

This is a detailed anatomical study describing the ribbonlike structure of the ACL from its femoral insertion to the midsubstance. A key point was to carefully remove the surface fibrous membrane of the ACL. Two millimeter from its bony direct femoral insertion, the ACL formed a flat ribbonlike ligament without a clear separation between AM and PL bundles. The ribbon was in exact continuity of the posterior femoral cortex. The findings of a flat ligament may change the approach to femoral ACL footprint and midsubstance ACL reconstruction and to graft selection.

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