Rev esp. cir. ortop. traumatol. 2009;**53(1)**:13-19

Revista Española de Cirugía Ortopédica y Traumatología

www.elsevier.es/rot

ORIGINAL PAPERS

Double-bundle anterior cruciate ligament reconstruction

A. Maestro[a,*], A. Álvarez[b], M. Del Valle[c], L. Rodríguez[d], A. Meana[d], P. García[d], E. Suárez[e] and C. Rodríguez[e]

[a] *FREMAP, Hospital for Occupational Accidents, Gijón, Asturias, Spain*
[b] *Center for Sports Medicine, San Sebastián, Guipúzcoa, Spain*
[c] *Department of Morphology and Cell Biology, University of Oviedo, Oviedo, Spain*
[d] *Cabueñes Hospital, Gijón, Asturias, Spain*
[e] *Polytechnic Engineering School, Gijón, Asturias, Spain*

Received August 10, 2007; accepted July 3, 2008

KEYWORDS:
Knee;
Anterior cruciate ligament;
Double bundle;
Single tunnel

Abstract
Purpose: To design a technique aimed at reducing the incidence of residual laxity in anterior cruciate ligament (ACL) surgery.
Materials and methods: An anatomic study was performed in 20 cadaver knees and in 50 human femurs and 50 human tibias. In addition, a mechanical study was made of the consequences of sectioning the bundles in the cadaver knee.
Results: The ACL presented with a tibial piriformis attachment, with an oblique greater axis and an area of 15.8?11.6mm. The femoral attachment was egg-shaped (15?8mm) with a 15-30° inclination with respect to the posterior cortex. The length of the anteromedial (AM) bundle was 34±4,5mm and of the posterolateral (PL) bundle 22±4mm. The double-bundle technique caused 32.8% more bone resection than the single tunnel technique, but resulted in 62.5% less stress on the fixation system; maximum load to failure was 785N. On being sectioned, both bundles showed, at neutral rotation and 30° flexion, identical behaviors. The greatest strains were withstood by the AM bundle when the knee was at 95° flexion and neutral rotation, and by the PL bundle when the knee was in extension and external rotation.
Conclusions: Reproducing the double-bundle morphology of the ACL is a successful method that is well-adapted to the anatomy and biomechanics of the ACL and that can be carried out through a single tibial tunnel.

*Corresponding author.
E-mail: antonio_maestro_fernandez@fremap.es (A. Maestro).

1888-4415/$ - see front matter

PALABRAS CLAVE
Rodilla;
Ligamento cruzado anterior;
Doble fascículo;
Monotúnel

Reconstrucción anatómica bifascicular del ligamento cruzado anterior

Resumen

Objetivo: diseñar una técnica que mejore las laxitudes residuales en las cirugías del ligamento cruzado anterior (LCA).

Material y método: se efectuó un estudio anatómico en 20 rodillas de cadáver y en 50 fémures y 50 tibias humanas. Además, se analizó mecánicamente el comportamiento tras la sección de los fascículos en la rodilla del cadáver.

Resultados: el LCA presentó una inserción piriforme en la tibia, con eje mayor oblicuo y un área de 15,8 ? 11,6mm. La inserción femoral fue ovoidea (15 ? 8mm) con 15-30° de inclinación respecto a la cortical posterior. La longitud del fascículo anteromedial (AM) fue de 34 ± 4,5mm y el posterolateral (PL) de 22 ± 4mm. La técnica de doble fascículo mostró un 32,8% más de resección ósea que el monotúnel, pero con un 62,5% menos exigencias para el sistema de fijación; las cargas máximas hasta la rotura fueron de 785N. La sección de los fascículos mostró, en rotación neutra y 30° de flexión, un comportamiento idéntico de ambos fascículos; con la rodilla en flexión de 95° y rotación neutra, el fascículo AM soportó mayores tensiones mientras el PL las mantuvo en extensión y en rotación externa.

Conclusiones: la reproducción de la morfología bifascicular del LCA se adapta a la biomecánica y a la anatomía del LCA, siendo posible hacerlo a través de un único orificio tibial.

Introduction

Greater knowledge of anatomical and biomechanical characteristics of the anterior cruciate ligament (ACL) helps to improve surgical techniques, and to prevent and rehabilitate knee joint lesions.

The ACL is a three-dimensional structure of dense connective tissue that joins the tibia and the femur. In the tibia its insertion is on the pre-spinous area of the tibial plateau, and from there it runs up, back and outwards, inserting on the posterior half of the intercondylar notch of the femur condyles[1]. The ACL is one of the structures that suffers most damage during sports activities[2] and given its lack of spontaneous repair capacity, once there is joint instability, it requires repair surgery to restore damaged knee stability and kinematics, and prevent degenerative changes and damage to the menisci[3]; although there is no proof that reconstruction eliminates all risk[4,5].

If lack of stability on rotation persists after ACL reconstruction, it is our opinion that surgery restoring double-bundle anatomy may prevent joint instability. In this study we describe the types of fibers that compose the ACL and its insertions; furthermore we analyze the contribution of each one of its bundles to joint stability, so as to design a double-bundle technique that will preserve the two original ligament bundles.

Materials and methods

Knee joints of 18 fresh cadavers were studied (36 knees), corresponding to adult males of 35 to 75 (mean, 66) years of age with a height of 162 to 173 (mean, 167) cm, to examine the structure and type of fibers, as also the insertions, length and diameter of the ACL.

After removing the synovial membrane by microdissection with a surgical microscope (Zeiss®) the in situ ligament was studied, then the 2 bundles were extracted, detached proximally and distally, their length and their diameter measured with a digital caliper (Vernier®). To measure and determine the location of the insertion areas, 50 femurs and tibias from previously classified cadavers were used.

The biomechanical study was based on an engineering mathematical analysis and a biomechanical cadaver analysis.

A theoretical mathematical analysis was carried out to determine the volume of the cylinder formed by the bone tunnel and the contact area of the ligament or area of the cylinder. A double tunnel in the femur means that the bone volume to mechanize is equal to the addition of the volume of the bundles within the tunnel, which will be determined by the thickness of each independent hamstring ligament repair, since the size of the tunnel is directly proportional to the thickness of each of the bundles, to obtain a complete fill.

On the medial facet of the external femur condyle there is a cylinder with a bone volume to be mechanized which is equal to the volume of the ligament repair within the bone according to the formula: $v=\pi r^2 h$, in which r is radius, h length of the portion of the ligament within the bone, and which in the case of a double tunnel would be the addition of: $v=\pi r_1^2 h+\pi r_2^2 h$.

Furthermore, the bone contact area is equal to the contact area of each bundle within the bone, which in this case, as there is transfixing femoral fixation, will be 360° of the tunnel and will be calculated by the formula v=2 π r h, also r is the radius and h the length of the part of the ligament within the bone, which in the double tunnel is the addition of $v=2 \pi r_1 h+2 \pi r_2 h$.

If a parallel double tunnel (such as we suggest), or a double oblique tunnel, or a diverging one (such as is used by double bundle techniques in the therapeutic armamentarium) are used it is possible to study how the forces are decomposed. Applying a mathematical study it is seen that the traction of both bundles, whether they are divergent or parallel, decompose their forces in three directions with relation to the axis of application of said forces, and according to angle α or the angle of bundle attack. These three directions are known as: force F_t or transverse traction or grazing force of the bundle at the entrance to the bone tunnel, force F or pure traction force or force of the ligament on the bone in the tunnel, and F_1 force, which is the force of the bundle or neo-ligament on the fixations in the same direction as the bundle and the tunnel axis.

Ligament laxity was assessed and, using a type KT-1000 (Medmetric®) arthrometer, the involvement of the ACL and each of the bundles on anteroposterior and rotation stability in the cadaver was determined, as also the application of the necessary anterior force on the tibial plateau to obtain the so-called "maximum manual measurement". We determined laxity in 20 knees with intact ACLs, at 30° and 95° flexion in neutral rotation of the leg and in external rotation of 30° . Subsequently, in 8 cadaver joints, we excised the anteromedial bundle (AMB), and in another 8 the posterolateral bundle (PLB), and in 4, both bundles (AMB and PLB); and assessed the effect of each of these changes on the same degrees of rotation and flexion as those studied with the intact ACL.

Results

The ACL has its insertion on the pre-spinous area of the tibial plateau, and runs up, back and outwards, to insert on the posterior half of the intercondylar notch of the external femur condyle (fig. 1), with two clearly identifiable bundles: the anteromedial and the posterolateral.

The osteoligament junction at the femur insertion is on the posterior part of the medial facet (intercondylar) of the external femur condyle. Our results show that the ACL insertion on the femur has a semicircular shape in 58% of cases and an oval shape in the rest (62%), although individual variations are important. The greater diameter was found to be almost vertical. The measurements of the ACL insertion on the 50 femurs studied had a diameter greater than 15±2.6 mm in length and 8±2.9 mm in width.

Both ACL ligament bundles widened at the femur insertion. The major axis of the insertion area was not found –in any of the cases studied– to be parallel to the longitudinal axis of the posterior cortical plane of the femur, on the contrary it had a variable 15° to 30° angle gradient (fig. 2) and the insertion area was at a minimum distance from the cartilage (3±0.9 mm).

From its femur insertion, the ACL goes forward, towards medial and distal, takes on a fan shaped distribution, and increases its diameter when it reaches the tibial insertion area (fig. 3) the tibial insertion area is in a fossa on the anterolateral part of the spine with relation to the anterior horn of the lateral meniscus to which it sends some expansion fibers.

We measured the shape of the ACL insertion on 50 tibias and determined that it is pear-shaped, oval and semi-triangular, with the widest part facing forward, with a greater oblique axis from anterior to posterior and from lateral to medial, measuring 15.8±1.9 mm, and a lesser axis measuring 11.6±2.2 mm The anterior part of the tibial insertion was found to be 2.5±0.5 mm behind the anterior insertion of the lateral meniscus.

The measurements of the length of the ACL, once it is detached from its bony insertions, showed different values for the AMB and the PLB, with mean values of 34±4.5 mm and 22±4 mm, respectively. The AMB originates in the most anterior and proximal part of the femur and has its insertion on the anterior part of the tibial spine. And the PLB

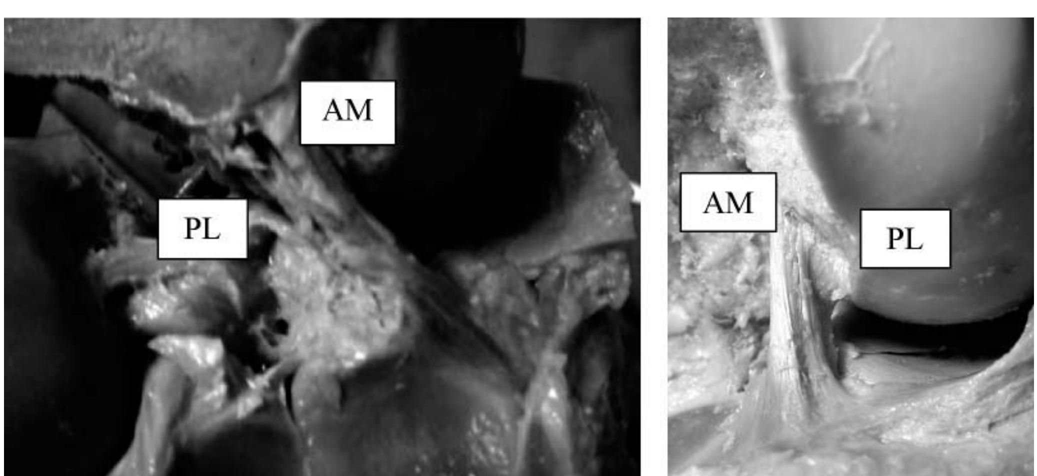

Figure 1 Medial view of the ACL after excising the medial femoral condyle in which both bundles can be clearly seen: anteromedial (AM) and posterolateral (PL).

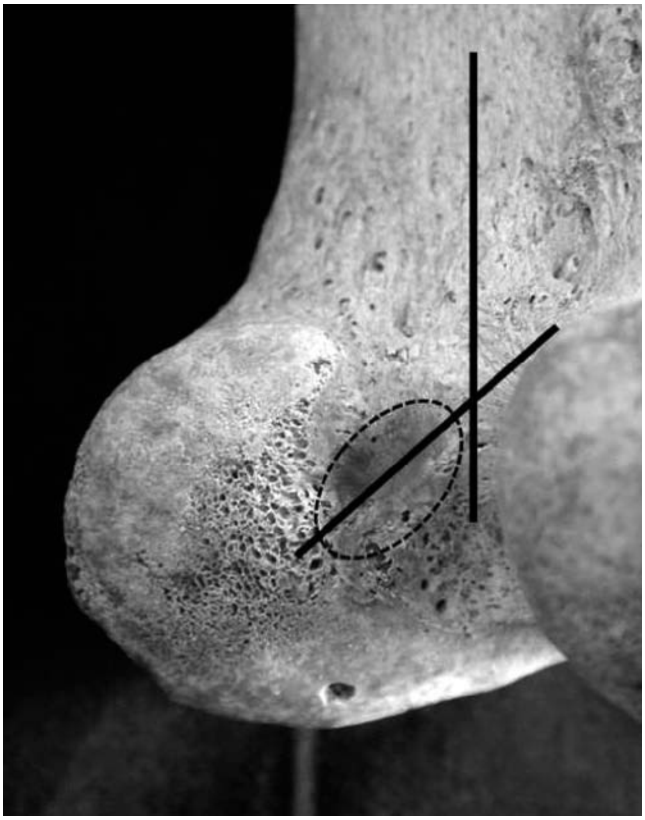

Figure 2 ACL attachment area on the femur and angle with respect to the posterior cortical plane; its oval or semicircular shape can be seen.

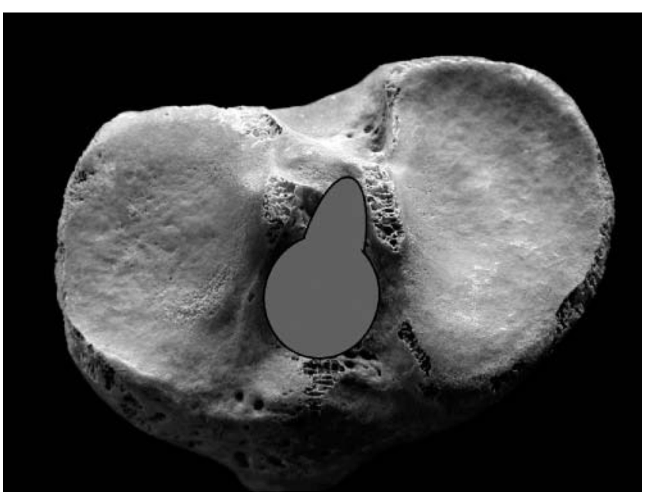

Figure 3 Attachment area of the ACL on the joint surface of the tibia and its relation to the A-P axis and the piriformis area.

originates more distally and slightly posteriorly on the femur and ends on the tibia, posterior to the insertion of the AMB.

On a sagittal view, with the knee in extension, the ACL bundles are parallel; during flexion there is a slight rotation of the ligament on its longitudinal axis, with the AMB covering the rest of the ligament (fig. 4). In all the cadavers we saw that, with the knee in extension, the fibers of the two bundles of the ACL were parallel and the PLB was under greater tension than the AMB.

Moving the knee from flexion to extension, the tension of the PLB remains high, up to approximately 45° of flexion, whereas when the knee is placed at 90° of flexion, the posterior fibers relax and the AMB achieves its maximum tension. The anatomical movements carried out after dissection show that lengthening and tension of the AMB are accompanied synchronically, harmonically and constantly by PLB relaxation.

With reference to ACL participation in rotation movements, when the knee was close to 30° flexion, we assessed tensions after section of the bundles (table 1), and we saw that internal rotation of the leg increased ACL tension more than external rotation.

Using a 7 mm single femur tunnel technique, or a 6 mm double femur tunnel technique, both with a depth of 30 mm; from a mathematical point of view and after applying the formula detailed above, we found that the tunnel bone volume that had to be regenerated, or equally the volume of bone to be excised, in the single tunnel was 1,507.2 μl and in the double tunnel was 2,001.7 μl (1,153.9 μl and 847.8 μl in each tunnel). Furthermore, the bony contact area or the area of contact between the ligament repair and the bone was, with a single bundle, 753.6 mm^2 and with a double bundle 1,224.6 mm^2 (659.4 mm^2 and 565.2 mm^2 in each tunnel).

Clinically these findings translate into the need for 2 independent tunnels of 7 and 6 mm, instead of a single 8 mm tunnel, excision of 32.8% more bone than with the single tunnel technique, and an increase of contact area of 64.5%with this ligament repair.

We analyzed the forces of the ligament repair with two parallel tunnels (fig. 5), the angle of attack of the PLB was 135°, so on force decomposition (as was explained above) there was a transverse force of traction or F_t tending to graze and possible enlarging the greater opening that with a divergent bundle (fig. 6) so that in said F_t it will be 0, since the force is always applied in the direction of the bundle and the tunnel. Therefore, with our technique there will be a greater index of friction or grazing according to said angle.

Assessment of traction forces by means of fixation means that apply a traction force to the bundle at an · angle of 135° (PLB) with the technique of the double parallel bundle ($F_1<F$), in comparison with the divergent technique where these forces are equal ($F=F_1$): Therefore at an α angle of 135° the tensions supported by the double parallel bundle are 30%less than with the divergent double technique, with the same bundle traction. So that said fixations have a lower cyclic or repetitive traction load.

Discussion

The ACL is formed by two bundles[6-9], the AMB, which originates near the joint cartilage and ends in the pre-spinous area of the tibia, and the PLB, which originates

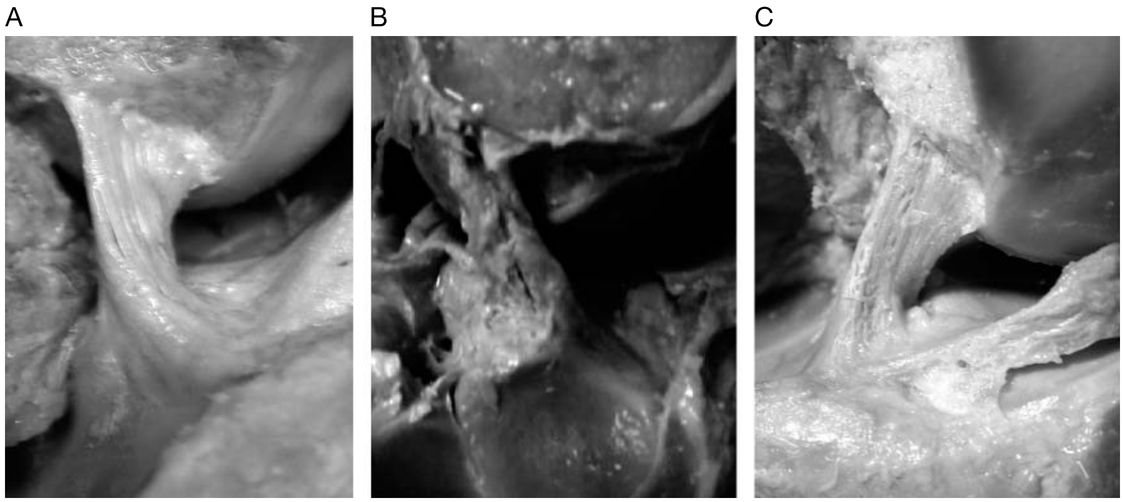

Figure 4 Anterior (A) and lateral (B) views, of the ACL with the knee in extension where it is possible to see the greater tension of the PLB and the large anterior insertion area (in relation to the anterior horn of the lateral meniscus) of the fibers of the AMB.

Table 1 Anteroposterior laxity of the knees after bundle section

	30° flexion	95° flexion
Neutral Rotation		
ACL	3.8±1.2	3.1±1.5
PLB	4.2±1.8	4.6±1.5
AMB	3.9±1.2	3.3±2
External Rotation 30°		
ACL	3.4±1.4	3.9±1.2
PLB	4.6±2.1	4.8±1.9
AMB	4.4±1.2	3.4±2

AMB: Anteromedial bundle; ACL: anterior cruciate ligament; PLB: posterolateral bundle.

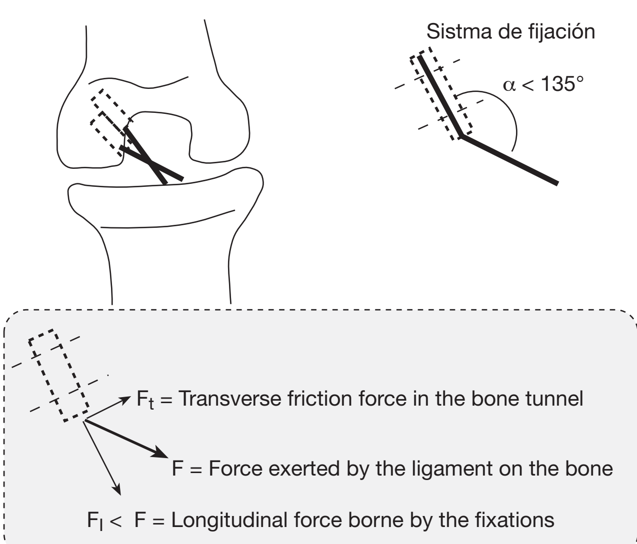

Figure 5 Double parallel bundle forces decomposition.

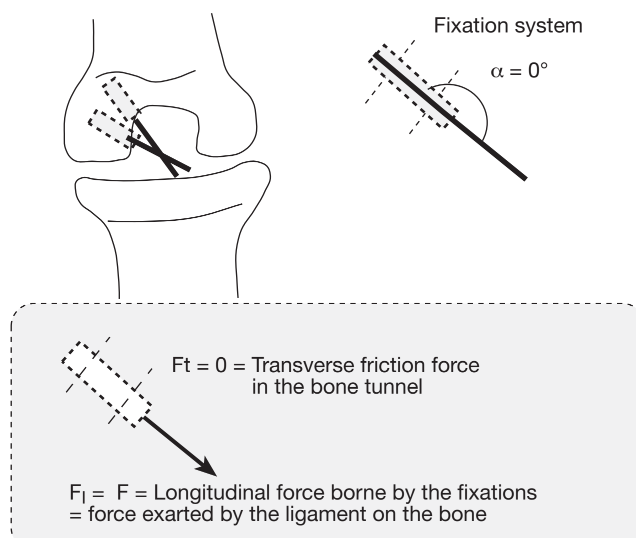

Figure 6 Double oblique bundle forces decomposition.

beneath and behind the AMB and ends on the tibia behind the AMB. Other authors define the ACL as formed by 3 bundles (AMB, intermediate bundle, and PLB)[10–13]. We have not been able to establish this anatomical difference. As far as its insertion areas, we agree with what is held by many publications in that the ACL widens into a sort of funnel[6,7,14,15] that has a width 3 to 3.5 times the thickness of the mid-section of the ligament[16].

According to some authors, the femur insertion is semicircular, for others it is oval[1,17]; in our study it was semicircular in 58% of cases, with values for the greater diameter of 15±2.6 mm and for the lesser diameter of 8±2.9 mm, these numbers are slightly inferior to published data, but we consider this may be related to anthropometric characteristics of the population. We agree with most authors in that the greater axis is not parallel to the longitudinal axis of the femur, and although variable, its inclination is of 15° to 30°[18].

Tibial insertion is in a small fossa[18] slightly behind the insertion of the anterior horn of the lateral meniscus, it is pear-shaped with the widest part to the front and oval, with the major axis from anterior to posterior and from medial to lateral measuring 15.8±1.9 mm, and with a lesser axis of 11.6±2.2 mm. These values are slightly inferior to those found by other authors, due, possibly to the characteristics of our population. The location of the pre-spinous insertion area means that the anterior fibers of the AMB are more anterior and this affects their horizontal position.

The ACL, according to the literature[6,10,12], has a length of 22 to 41 mm and a width of 7 to 12 mm. The values we found are similar to those specified above[18]. We assessed the length of both bundles, and found anterior fibers of 37±4 mm that decrease posteriorly in such a way that the posterior fibers measure 24±4 mm.

Each bundle has an established function in knee stability[6,19,20]. When the knee is in extension, the fibers of both ACL bundles are parallel and under tension; however, the PLB is under greater tension than the AMB; this tension remains high in the PLB up to 45° of flexion. When the knee was placed in flexion at 90°, the posterior fibers were more relaxed and the AMB was under greater tension. In general, the AMB bundle is under greater tension during flexion and the PLB is relaxed, while in extension the contrary is true.

The data we have obtained show the importance of an intact ACL to control anteroposterior laxity of the knee joint and, indirectly, its stabilizing action during joint rotation. It has been proven that during neutral rotation, with the knee at 30° flexion, the stability of cadaver knees depends on both bundles, mainly the AMB, and with the knee in 95° flexion, the AMB bundle is more important. This proves that, with the knee in 30° flexion or more, the laxity generated is almost identical for both bundles, which shows the importance of synchrony of both bundles to maintain joint stability.

Keeping in mind the limitations of this study, since it is an *in vitro* analysis of cadavers, the assessments of laxity we have carried out also support the idea that both bundles (AMB and PLB) behave differently. Section of the AMB causes a positive anterior drawer test and a negative Lachmann test, whereas PLB section has the contrary effect. This data has been proven clinically[24] when performing isolated reconstruction of the AMB, in which anteroposterior laxity is reduced in 50–60%with the knee in 30° flexion. This goes against the rationale of current surgical techniques for ACL reconstruction which are based on single bundle reconstruction, which functionally restore the AMB, and this can never duplicate total ligament function[25,26].

It is true, however, that double bundle reconstruction requires comprehensive and correct knowledge of the location of ACL insertions, since the technique requires duplication of these insertions. The wide tibial insertion leads us to think of the location of the tunnel which is maybe not as posterior as usual, and it is necessary to try and locate it pre-spinously so as to place the AMB "horizontally and not vertically" so that it remains in posterior. In the same way, the impossibility of restoring normal kinematic movement of the knee, especially on the rotation plane, after a single bundle technique, in which in spite of surgical techniques carried out by expert surgeons, it is seen that control of rotation is impossible[28,29]. For this reason, nowadays, double bundle ACL reconstruction must be considered.

In conclusion, the ACL is made up of 2 anatomically and functionally well differentiated bundles, perfectly duplicable, that travel through a single tibial bone tunnel, with a fixation system resistance behavior similar to that of the single bundle technique, and furthermore, with sufficient resistance to make it possible to carry out accelerated physiotherapy.

Conflict of interests

The authors have declared that they have no conflict of interests.

References

1. Odensten M, Gillquist J. Functional anatomy of the anterior cruciate ligament and a rationale for reconstruction. J Bone Joint Surg Am. 1985;67:257-62.
2. Ryder SH, Jhonson RJ, Beynnon BD, Ettiger CF. Prevention of ACL injuries. J Sports Rehabil. 1997;6:80-96.
3. Irvine GB, Glasgow MM. The natural history of the meniscus in anterior cruciate insufficiency. Arthroscopic analysis. J Bone Joint Surg Br. 1992;74:403-5.
4. Bach BR, Levy ME, Bojchuk J, Tradonsky S, Bush-Joseph CA, Khan NH. Single-incision endoscopic anterior cruciate ligament reconstruction using patellar tendon autograft: minimum two-year follow-up evaluation. Am J Sports Med. 1998;26:30-40.
5. Jacobson K. Osteoarthritis following insufficiency of the cruciate ligament in man: a clinical study. Acta Orthop Scand. 1977;48:520-6.
6. Girgis FG, Marshall JL, Monajem A. The cruciate ligaments of the knee joint: anatomical, functional and experimental analysis. Clin Orthop. 1975;:216-31.
7. Girgis FG, Marshall JL, Monajem A. Reiman PR, Jackson DW. Anatomy of the anterior cruciate ligament. En: Jackson DW, Drez D, editores. The anterior cruciate deficient knee. St Louis: Mosby; 1987. p. 17–26.
8. Girgis FG, Marshall JL, Monajem A. Arnoczky SP, Warren RF. Anatomy of the cruciate ligaments. En: Feagin JA, editor. The Crucial Ligaments. New York: Churchill Livingstone; 1988. p. 179–95.
9. Franceschi JP, Sbihi A, Champsaur P. Arthroscopic reconstruction of the anterior cruciate ligament using double anteromedial and posterolateral bundles. Rev Chir Orthop. 2002;88:691-7.
10. Amis AA, Dawkins GP. Functional anatomy of the anterior cruciate ligament: fibre bundle actions related to ligament replacements and injuries. J Bone Joint Surg Br. 1991;73:260-7.
11. Amis AA, Scammell BE. Biomechanics of intra-articular and extra-articular reconstruction of the anterior cruciate ligament. J Bone Joint Surg Br. 1993;75:812-7.
12. Norwood LA, Cross MJ. Anterior cruciate ligament: functional anatomy of its bundles in rotatory instabilities. Am J Sports Med. 1979;7:23-6.

13. Hollis JM, Takai S, Adams DJ, Horibe S, Woo SL. The effects of knee motion and external loading on the length of the anterior cruciate ligament (ACL): a kinematic study. J Biomech Eng. 1991;113:208-14.
14. Arnoczky SP. Anatomy of the anterior cruciate ligament. Clin Orthop. 1983;:19-25.
15. Dienst M, Burks RT, Greis PE. Anatomy and biomechanics of the anterior cruciate ligament. Orthop Clin North Am. 2002;33:605-20.
16. Harner CD, Baeck GH, Vogrin TM, Carlin GJ, Kashiwaguchi, Woo SL. Quantitative analysis of human cruciate ligament insertions. Arthroscopy. 1999;15:741-9.
17. Smith BA, Livesay GA, Woo SL-Y. Biology and biomechanics of the anterior cruciate ligament. Clin Sports Med. 1993;12:637-670.
18. Christel P. Ligament croisé anterieur et stabilité rotatoire. Rev Chir Orthop. 2005;91:18-22.
19. Sakane M, Fox RJ, Woo SL-Y, Livesay GA, LI G, Fu FH. In situ forces in the anterior cruciate ligament and its bundles in response to anterior tibial loads. J Orthop Res. 1997;15:285-93.
20. Bach JM, Hull ML, Patterson HA. Direct measurement of strain in the posterolateral bundle of the anterior cruciate ligament. J Biomech. 1997;30:281-3.
21. Kurosawa H, Yamakoshi K, Yasuda K, Sasaki T. Simultaneous measurement of changes in length of the cruciate ligaments during knee motion. Clin Orthop. 1991;265:233-40.
22. Zaffagnini S, Martelli S, Acquaroli F. Computer investigation of ACL orienttion during passive range of motion. Comput Biol Med. 2004;34:153-63.
23. Kurz MJ, Stergiou N, Buzzi UH, Georgoulis AD. The effect of anterior cruciate ligament reconstruction on lower extremity relative phase dynamics during walking and running. Knee Surg Sports Traumatol Arthrosc. 2005;3:107-15.
24. Woo SL, Kanamori A, Zeminski J, Yagi M, Papageorgiou C, Fu FH. The effectiveness of reconstruction of the anterior cruciate ligament with hamstrings and patellar tendon: a cadaveric study comparing anterior tibial and rotational loads. J Bone Joint Surg Am. 2002;84:907-14.
25. Frank CB, Jackson DW. The science of reconstruction of the anterior cruciate ligament. J Bone Joint Surg Am. 1997;79:1556-76.
26. Radford WJ, Amis AA. Biomechanics of a double prosthetic ligament in the anterior cruciate deficient knee. J Bone Joint Surg Br. 1990;72:1038-43.
27. Palmer I. On the injuries to the ligaments of the knee joint; clinical study. Acta Chir Scand. 1938;Suppl:53.
28. Petersen W, Zantop T. Anatomy of the anterior cruciate ligament with regard to its two bundles. Clin Orthop. 2006; 454:35-47.
29. Ristanis S, Stergiou N, Patras K, Vasiliadis HS, Giakas G, Georgoulis AD. Excessive tibial rotation during high-demand activities is not restored by anterior cruciate ligament reconstruction. Arthroscopy. 2005;21:1323-9.