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Review Article

# ACL Reconstruction and Biomechanics

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## ABSTRACT

The goal of ACL reconstruction is to restore the normal knee anatomy and biomechanics. However, not all ACL reconstructions protect the knee joint from developing osteoarthritis.

It's difficult to replicate both the original anatomy and original biomechanics. All knee structures interact geometrically and mechanically with each other. The overall strength behavior of the ACL is the result of the sum of the individual strength behavior of each of its fibers. And each of its fibers length changes according to the knee movement. Typically, single-bundle (SB) transtibial ACL reconstructions have been performed taking into account "isometric" criterion. In this respect, replicating the anteromedial (AM) fibers of original ACL. But it has been suggested that transtibial SB reconstructions can lead to some degree of rotational instability when the knee is close to extension.

Recently, in order to have greater rotational stabilizing different surgical options have been proposed. One of those is "anatomic" SB ACL reconstruction selecting the femoral footprint center. But "anatomic" ACL reconstructions cause greater changes in length during the range of movement of the knee than the transtibial ACL reconstructions.

Another one of them is the double bundle (DB) ACL reconstruction which involves reconstructing each of these original AM and posterolateral (PL) bundles separately. It achieves better anteroposterior and rotational knee stability "in vitro" but is more technically demanding.

Lateral extra-articular procedures in combination with ACL reconstruction has been proposed as a way of potentially improving rotational stability and clinical outcomes.

**Keywords:** ACL reconstruction, Biomechanics

## Introduction

Anterior cruciate ligament (ACL) rupture is one of the most frequent knee sport injuries. Reconstruction of the ACL may be justified because delay in surgery leads to an increasing prevalence of meniscal damage, an later cartilage damage [1]. However, not all studies have shown that ACL reconstruction protects the knee joint from developing osteoarthritis [2].

The goal of ACL reconstruction is to restore the normal knee anatomy and biomechanics. But the complexity of anatomy and biomechanics is not faithfully reproduced by ACL reconstructions. In addition, neither anatomy nor biomechanics are taken into account in the assessment of surgical outcomes.

The quality of the ACL anatomy reproduction is simply not assessed. The abilities of ACL reconstructions to restore biomechanics are assessed indirectly. Biomechanics is simplified in the anterior-posterior and rotatory stability to the knee measured by physical examinations and arthrometry. Besides this, the patients are evaluated for knee function and stability according to knee score questionnaires.

From the reconstructions point of view, during the decade of the 'nineties (twentieth century), the reference model of the ACL reconstructions were overall single-bundle (SB) "isometric" reconstructions mostly by means of transtibial single-tunnel technique [3].

Since transtibial SB reconstructions can lead to some degree of rotational instability when the knee is close to extension, in the first decade of the twenty-first century two different surgical options have been suggested: the double-bundle (DB) reconstruction [4] and the “anatomic” reconstruction (selecting the femoral footprint center) [5].

Hovewe, widely practiced surgical techniques have yet to prove their efficacy in restoring normal knee joint function and preventing long term joint degeneration. On the one hand, the reality. On the other hand, our reconstructions attempt.

## ACL Functional Anatomy

The ACL is an intracapsular but extra synovial structure. The ACL is divided into two bundles based on their insertion on the tibial footprint, namely anteromedial (AM) and posterolateral (PL) (Figure 1).

The femoral insertion footprint is approximate oval, with a largest diameter of 18 ± 2 mm and a smallest diameter of 11 ± 2 mm [6]. The surface area varies from 83 $mm^2$ to 197 $mm^2$ [7]. The lateral intercondylar ridge is particularly useful because it serves as the anterior margin of both the individual bundles and the overall ACL femoral attachment. And the subtler bifurcate ridge separates the AM and PL bundle femoral attachments. The footprint of the AM bundle is approximately 52% of the total femoral ACL insertion area whereas that of the PL bundle is approximately 48 % [8]. The tibial insertion footprint is approximate oval in anteroposterior direction largest diameter of 17 ± 3 mm and a smallest diameter of 11 ± 2 mm. The surface area varies from 114 $mm^2$ to 229 $mm^2$ [6,9]. It has been reported that the tibial insertion of the ACL is 120% of the area of the femoral insertion site [10]. The cross-sectional area at midsubstance varies between 36 and 44 $mm^2$ whereas ACL has an average length of 32 mm (22 -41) [9].

Supposing a 9 mm diameter circular graft, both of the ACL single bundle reconstructions (“isometric” or “anatomic”) only result in a footprint occupancy of 63.5 $mm^2$. Contrary to what it could seem, the occupancy of ACL double-bundle reconstructions is not bigger. In the same way (two circular grafts), using the most frequent grafts diameters (AM: 5 mm diameter; PL: 7 mm diameter) an ACL double-bundle reconstruction covers 58,11 $mm^2$ [11]. Regardless of the ACL reconstruction model, the surgeon is able to cover only half of the original footprint [12] (Figure 1). This means that whatever ACL reconstruction leaves the other half empty. Does it affect the behavior of reconstruction?. Moreover, commonly used ACL autograft areas do not correlate with the size of the ACL footprint or the femoral condyle [13]. These observations reaffirm the difficulty of replicating the original anatomy. In addition, the knees themselves are constitutionally different in size.

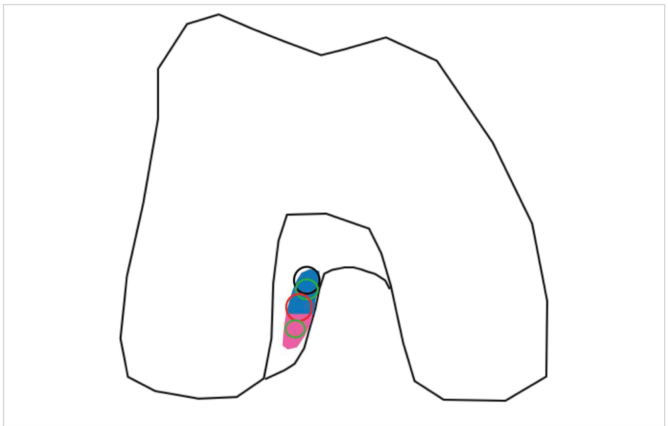

**Figure 1:** Blue area; femoral footprint anteromedial area. Pink area: femoral footprint posterolateral area. Black circle: femoral socket for “isometric” single bundle ACL reconstruction. Red circle: femoral socket for “anatomic” single bundle ACL reconstruction. Green circles: femoral sockets for double bundle ACL reconstruction.

From a biomechanical point of view, the length change patterns of ACL fibers are controlled principally by their femoral attachment sites [14]. Footprint areas are reached by fibers (understood as the straight line fiber from a point of the tibial footprint area to another one in the femoral footprint area). Each fiber works in one way only: either as AM fiber or as PL fiber. As a consequence, the overall behaviour of the ACL is the result of adding of the individual behaviour of each of its fibers.

The length changes of the ACL fiber bundles provide an important guide to their functional behavior in controlling both anterior drawer and rotational laxity. Much of that length change can cause slackening of the fiber and it indicates that contribution of that fiber is likely to be reduced or absent [14]. The surgeon must take into account that selecting footprint area determines the overall behavior of the graft. Thereby, the greater or lesser covering of a footprint area determines the greater or lesser participation of its fiber in the overall behavior of the ACL.

## ACL and Knee Biomechanics

The articular function of the knee is regulated passively by the shape of the bones and by the joined work of the capsule and ligaments. They stabilize the joint permitting its mobility and preventing it from abnormal movements. Essentially knee changes from flexion to extension. And coupled, rolling of the femorotibial joint predominating near extension and gliding mainly as the knee is flexed [15]. Besides, the ratio of gliding and rolling, differs between the medial and the lateral condyle. But all together sets the normal movement pattern. In this functional context, the main function of the ACL is to avoid the anterior displacement of the tibia with regard to the femur. Also, ACL collaborates in the rotational control along with other structures.

All knee structures interact geometrically and mechanically with each other. To explain the function of one, it is necessary to consider its interactions with the others. In this respect, it has been published that anatomic pattern between the cruciate ligaments in the knee reproduces a four-bar linkage model that can be represented by an anthropometric constant [16]. The goal of ACL reconstruction is to recover ACL involvement in this physiologically stable pattern of knee movement.

In the human knee it can be stated that there is no fixed axis of flexion. For a long time, the mechanical model of the “instantaneous center of rotation” based on the Reuleaux method was taken as valid [17,18]. In that model, and with the knee extended, the axis of rotation is in its most proximal (higher) position. Conversely, and as the flexion advances, the axis of rotation occupies a more distal and posterior position. The estimated distance between the axis with the knee in extension and the axis with the knee in flexion is in average 11 mm [19] (Figure 2).

The ACL (or any fiber) lacks sense without tension. Essentially, it works in distraction (when a force tries to separate its ends). The fibers of the ACL reach the femoral footprint, not on the same axis of rotation. In reality, they attach to the bone at a certain distance from that axis of rotation (Figure 3). ACL stabilizing function (or any fiber) changes according to the distance existing between its femoral insertion and the axis of rotation.

If the movement of the knee separates the insertion point in the femur with regard to the axis of rotation, the fiber is tightened. By contrast, the movement of the knee moves the insertion closer to the axis, the fiber is slackened [20] (Figure 3). The overall strength behavior of the ACL is the result of the sum of the individual strength behavior of each of its fibers. And each of its fibers changes its strength according to its distance to the axis of rotation. Consequently, the mechanical behaviour of the ACL depends on the quantity of fibers that are tightened at each moment. Faults placing the grafts can lead to an asymmetric distribution of the fibers function (Figure 4).

## ACL Intra-articular Single Bundle Reconstructions

Generally, in any ACL surgery reconstruction, a bone tunnel must be performed in each knee bone. Thus, a single bundle ACL graft reaches the femur tunnel from the tunnel tibia (ACL single bundle reconstruction). In this sense, for the biomechanical behaviour of graft, the important issue is where the tunnels are located. More than how they were performed.

There may be a different controversy as to whether the selected location of the tunnel can be achieved by drilling a transtibial tunnel. Recently, surgeons may use two anteromedial portals: a high portal providing visualization and a second more medial portal just above the meniscus for instrumentation. The use of different devices (such as flexible drilling systems) may also improve safe tunnel positions.

The length change patterns of the fibers of the ACL are controlled

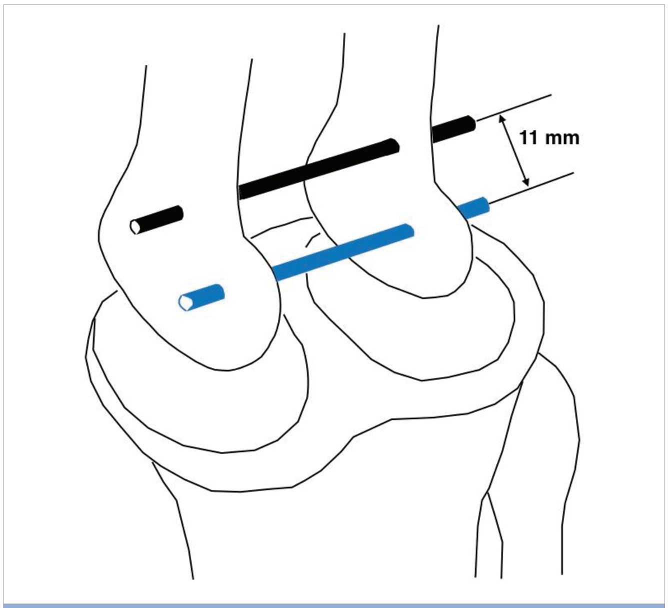


**Figure 2:** Position of axes of rotation (sagittal plane). Axis for extension (shown in black) is placed more proximally. Axis for extension (shown in blue) is placed more distally. The average distance between both is 11 mm.

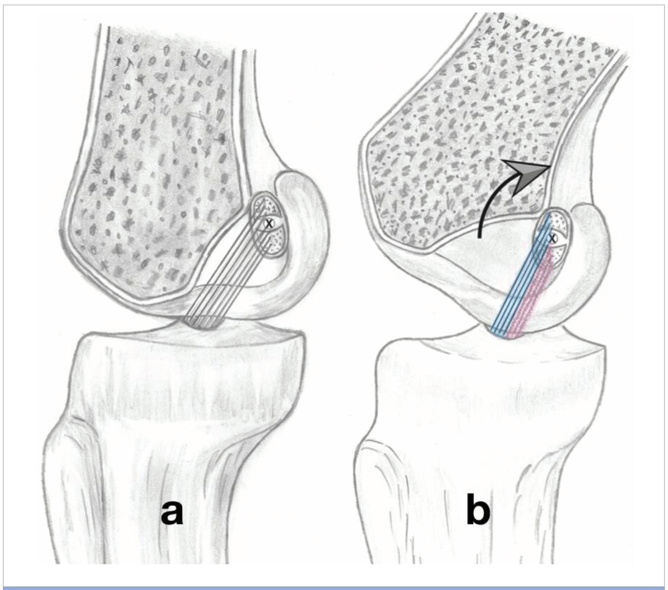


**Figure 3:** Knee in extension: all fibers are tighten (blue area). (b) knee flexion: some of these fibers slack (pink area). X: axis of rotation.

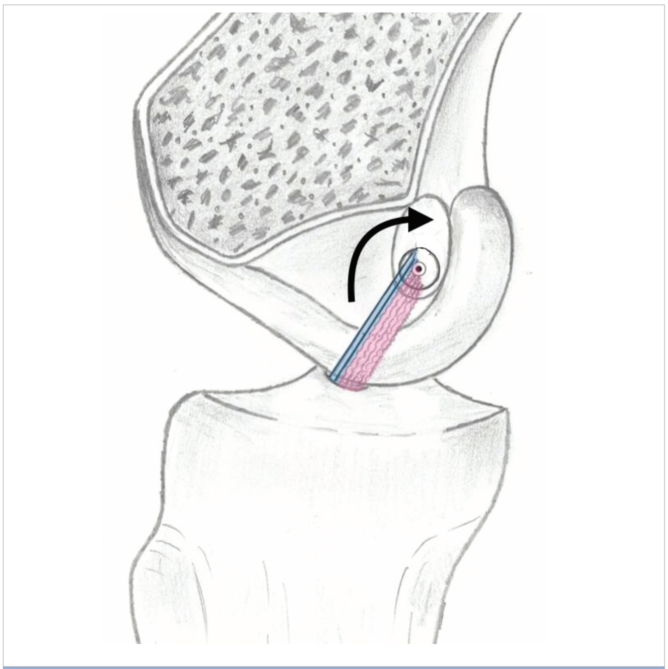

**Figure 4:** If the tunnel is performed in a more distal position, higher proportion of fibers slack (pink area). It causes unbalanced ACL stabilizing function.

principally by their femoral attachment footprints. From a single bundle reconstruction point of view, patterns of tightening or slackening behavior have been measured in order to define the area with the least deviation from zero-length change, or "isometry" [20,21]. Isometry protects graft against excessive elongation. Ligaments work within a small range of tensile elongation and typically rupture at 20% strain [22].

Isometry has not been possible to obtain in either in vivo or in vitro observations [23]. But in order to avoid nonphysiological strain patterns of a ligament graft throughout the functional range, which also avoids graft failure and any limitation in knee motion, isometric ACL reconstructions have been emphasized for successful reconstruction. Thus, conventional single-bundle ACL reconstruction, with the femoral attachment relatively high in the intercondylar notch, usually replicates only the AM bundle [24] with only 2–3 mm length changes [25].

In an experimental study where different points were compared and proposed as "isometrics" by published literature. The most isometric region was the most proximal area of the femoral insertion footprint [21].

This suggests that from the point of view of the isometry, the center of the footprint is not the best option. Points in the center of the footprint in this study show a slackening during flexion [21]. In addition, "anatomic" ACL reconstructions, cause greater changes in length during the range of movement of the knee than the transtibial reconstructions [26]. Also, "anatomic" ACL reconstructions have greater anteroposterior instability with the knee flexed. "Anatomic" technique leaves the AM region of the footprint relatively uncovered. Perhaps, this lesser presence of fibers with AM behavior, may be related with the larger number of revisions noticed in anatomic ACL reconstructions [27,28]. In ACL reconstructions, femoral tunnel drilling can be completed through a number of different techniques. Drilling techniques can be categorized mainly as either transtibial or independent tunnel drilling. Any of them or their modifications, should allow us to access the best point to perform the femoral tunnel.

Tibial tunnel placement has been reported to be less sensitive with respect to knee isometric behavior [26]. However, in order to avoid anterior o lateral graft impingement, the tibial tunnel should be placed within the posterior half of the native ACL footprint [29].

## ACL Intra-articular Double Bundle Reconstructions

From another biomechanical point of view, from tibial bone (from one single tunnel o two different tunnels), two independent bundles can reach two different femoral tunnels. In this case, a double bundle ACL reconstruction has been performed. Once again, biomechanically the relative positions of the tunnels on the wall of the femoral condyle are more important than how they've been performed. It is assumed that the knee movement provides each of them, at different angles, the best torque. As a consequence, each bundle has a different role in control for both anterior tibial translation and rotational instability.

SB ACL reconstruction has been the most widespread technique giving good clinical results that are acceptable in most cases. However, there is an appreciable failure rate that may necessitate revision surgery and in some cases that are partially successful, including a group of patients who have a residual 'pivot-glide' (14–30% of cases) [30,31]. However, it is currently unknown whether ACL reconstructions actually decrease the rate of degenerative joint disease [32].

The goal of ACL reconstruction is to restore the physiologic flexion-extension and roll-glide mechanism of the femorotibial joint and to avoid pathologic patterns of knee motion. The traditional "isometric" SB ACL reconstruction technique with a high anteromedial (AM) femoral tunnel and posterolateral (PL) tibial tunnel does not restore native ACL function [33]. Several factors (tunnel placement, graft selection, graft fixation...) have been explored as important to achieve successful ACL reconstructions. But recent publications have focused on the role of double-bundle reconstruction [34].

Anatomically, the native ACL consists of two different AM and PL bundles, which respectively account for translational and rotational stability. Functionally, the ACL does not function as a simple tube of fibers with a constant tension, In other words, it consists of a group of fibers that are subjected to episodes of lengthening and slackening throughout the range of motion. As stated above, the length change patterns in this case of the bundles of the ACL, are also controlled principally by their femoral attachment sites. The PL bundle is taut in full knee extension, slackened by 5–6 mm in mid-flexion, then re-tightened somewhat beyond 90 degrees of knee flexion. Contrastingly, the AM bundle is taut across the range of flexion-extension, tending to be tighter in the flexed knee, with only 2–3 mm length changes [8,27].

DB ACL reconstruction involves reconstructing each of these bundles separately [11]. It consists of aggregating to "isometric" SB ACL reconstruction (AM) an assistant to stabilize the knee in extension (PL). The more oblique orientation in the coronal plane allows PL bundle to have the greater ability to resist tibial rotation (better than the more vertical AM fiber bundle). The PL bundle shows a greater tension towards extension, particularly when resisting either anterior drawer or internal rotation torque and its contribution reduces rapidly with knee flexion through 30 degrees [14,35].

Two tunnels are performed in biomechanically different subareas of the femoral footprint. Biomechanically speaking point of view, two stabilizers are placed instead of only one. It can be argued that DB ACL reconstruction achieves better anteroposterior and rotational knee stability according to the KT-1000 Arthrometer and the pivot shift test. But it is similar to SB techniques for functional outcomes (Lysholm, Tegner, IKDC) [36]. But in exchange, it is more technically demanding than conventional single-bundle technique.

Under a technical point of view, DB ACL reconstruction can be challenging for the surgeon. Conventionally, 4-tunnel techniques have been described and that includes two tibial tunnels [11]. This has potential drawbacks such as the graft impingement against the posterior cruciate ligament or femoral notch, predisposing to early failure. As a result, DB ACL reconstruction variations using 3 tunnels have been developed yielding good outcomes [37,38]. They produce smaller tibial insertion sites without compromising the advantages of a double-bundle procedure. This could be because the axis of rotation moves. And this may be in part due to torque mechanism. As stated above, the axis of rotation moves. And with the knee in full extension, the axis of rotation is in the highest position. The PL bundle femoral attachment fibers in this moment are far away from high axis of rotation and as a consequence are taut in extension. This is the relative contribution of PL bundle. That is why when PL bundles (performing DB ACL reconstructions) are too deep, cause a residual pivot shift phenomenon [39].

## ACL Extra-articular Reconstructions

In its origin, lateral extra-articular reconstruction procedure was devise to address the ACL failure (as an isolated procedure), in the management of tibial hyper-rotation associated to anterior cruciate ligament insufficiency. Although it became popular, in the late 1980s several studies suggested that intra-articular ACL isolated reconstructions would be sufficient in the treatment of knee instability after isolated ACL tear [40]. Then, they were largely abandoned due the superior results of intra-articular ACL reconstruction techniques. As the incidence of ACL reconstruction has increased significantly over the past 2 decades, so have the revision rates for this procedure. Revision rates after undergoing ACL reconstruction now represents a significant surgical burden. That's why today, a way of measuring quality of any ACL reconstruction technique is to quantify its re-rupture rate.

The current concept of combining a lateral extra-articular procedure with an intra-articular reconstruction for the treatment of ACL injury has emerged due to a group of patients for whom rotational instability remains an issue. One the one hand, this biomechanical default is related with the failure rate of intra-articular ACL isolated reconstructions. In this respect, SB ACL reconstructions have significantly more graft failures than the DB reconstructions [31]. As a consequence, lateral extra-articular procedure in combination with ACL reconstruction in the primary setting has been proposed as a way of potentially improving rotational stability and clinical outcomes compared with isolated ACL reconstructions [41]. On the other hand, currently have been recognized patients with high risk of either primary ACL injury or re-injury after ACL reconstruction [42].

In the context of ACL injury generally produces both translational and rotational abnormalities. But until recently, the mean goal ACL reconstruction attempted to address only anterior tibial translation. Anterolateral rotatory instability is a combined anterior translational and internal rotational movement of the tibia that occurs after injury to the ACL and the anterolateral structures of the knee.

Recently, authors have reported the anatomic and functional characteristics of the anterolateral ligament (ALL), describing a structure that originates near the lateral epicondyle on the femur and inserts on the lateral meniscus and broadly in a fanlike attachment on the tibia between the Gerdy tubercle and the fibular head [43,44]. The ALL works in synergy with the ACL and its injury seems to be correlated with the pivot-shift phenomenon [45].

Under biomechanical point of view, the ALL is not the only one structure controlling providing anterolateral rotatory stability. Also, the ACL PL bundle function is to provide anterolateral rotatory stability [31]. Both structures are tight in knee extension [46]. Based on biomechanical reports, the ALL description has led to the development of anterolateral ligament reconstructions. Then, several techniques have been described and have provided promising preliminary clinical results [47]. A combined DB ACL reconstruction and anterolateral ligament reconstruction has also been published [48].

For other authors, iilio-tibial band and its attachment to the distal femur via Kaplan's fibers provide the most important restraint to internal rotation [49]. In this sense, the modified Lemaire tenodesis could restore native knee laxity regardless of the angle of knee flexion for graft tensioning and fixation. A modified Lemaire type procedure combined with intra-articular ACL reconstruction has been developed.

It is therefore important to understand that the goals of a combined ACL and ALL reconstruction are to reduce the ACL graft re-rupture rate, and improve control of the rotational stability of the knee. Specific factors or populations have a greater risk of persistent pivot shift and/or subsequent ipsilateral ACL tears. Improving the control of the rotational stability is mandatory for these patients [50]. Females, paediatric patients, active patients who want to return to their preinjury level of activity, delayed ACL reconstruction, and meniscal deficiency show a high rate of re-rupture and contralateral tears [41,50,51].

## Conclusion

Patients are different in age, size gender, specific sport activities expectations etc. From a surgical point of view, it seems that surgeons have many surgical techniques with different biomechanical characteristics. Also, some of them are more technically demanding than others. Perhaps, in the near future in order to customize, ACL reconstruction model will be chosen according to differences among patients.

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