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Original Research Article

Graft selection in reconstruction of anterior cruciate ligament–a biomechanical study

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Abstract

The anterior cruciate ligament (ACL) lesion is one the most frequent pathologies of the knee joint, especially in the active young population. Although reconstruction of the ACL has been performed for almost 100 years, it continues to evolve, with many technical issues still under debate. These refer to reconstruction technique, but also to graft selection, that should have biomechanical properties similar to the native ligament, while allowing a secure fixation and ligamentization. Also, there is still no consensus on the ideal graft. We performed an experimental study using 8fresh cadaveric knee specimens from 4 donors. We analyzed the anatomy of ACL and performed biomechanical tests on grafts harvested (patellar tendon, hamstring, quadriceps), testing the resistance and breaking point on the commonly used grafts in our clinic. We aimed to evaluate the grafts from the point of view of mechanical properties using a tensile failure test. The main outcome measure was the maximum failure load (N). The second outcome was elongation at failure (mm). Our results showed that the hamstrings tendon had the highest elongation and load to failure rate off all the grafts tested. Results are greatly influenced by the age of donor, size of the graft, time between harvest and testing, as well as preservation technique before testing. At this moment, graft selection usually depends upon the surgeon's preference and experience, on the activity level of the patient, tissue availability, and general and local comorbidities. The resistance of the graft is only one of the components we should take into consideration when deciding which graft to use.

Keywords: Graft choice, Anterior cruciate ligament, Reconstruction, Knee

INTRODUCTION

Although many studies have been made, ACL reconstruction continues to evolve with many technical issues and of surgeon preference still under debate (Bonasia and Amendola, 2012). These refer to tunnel placement, fixation type, graft selection and, of course, single- vs double bundle technique (Prodromos et al., 2008).

As West and Harner, (2005) showed, the ideal graft for ACL reconstruction should have biomechanical and structural properties similar to those of the native ligament, also it should permit a secure fixation and a fast bone integration, all this with minimum donor site morbidity (West and Harner, 2005). Although many graft choices have shown clinical success, the ideal graft is still to be discovered (Sedeek and Chye, 2013; West and Harner, 2005).

The rupture of the ACL is one of the most common sport injuries when it comes to the injuries of the knee (Miayaska et al., 1991). The anterior cruciate ligament provides stability during joint movement, but it is relatively susceptible to injuries in comparison to other ligaments (Marieswaran et al., 2018). It functions as the main stabilizer for anterior tibial translation, with a secondary function of limiting the internal knee rotation (Odensten and Gillquist, 1985; Dienst et al., 2002).

An ACL rupture significantly reduces the knee stability, increases the risk of injury to the meniscus and early degeneration of the injured knee, mainly due to sporting activities (Arnold et al., 1979).

Among various injury modes, non-contact actions (during sports) are a major cause of ACL injury (Boden et al., 2000). The ACL is injured partially or completely during the non-contact action when the knee is flexed with the tibia rotating laterally simultaneously (Boden et al., 2000; Ferretti et al., 1992; McNair et al.,1990; Olsen et al., 2003; Olsen et al., 2004). During flexion the ACL is stretched (Levangie and Norkin, 2011) and it is 2orque during medial/lateral rotation.

Silvers and Mandelbaum classified injuries to the ligament into three types. Grade I injuries are associated with a tear of less one-third of the fibers in the ligament and presents knee laxity of less than 5mm (Marieswaran et al., 2018). The second grade includes injuries of one-third up to two-thirds of the ACL fibers, with a knee laxity of 5–10mm (Marieswaran et al., 2018). Grade III injuries issue from the tear of more than two-thirds of the fibers, associated with a knee laxity of 10–15mm (Marieswaran et al., 2018). The loss of function and tenderness can be seen in grade II and grade III injuries (Marieswaran et al., 2018). The laxity of the knee is measured as the tibial translation. The anterior drawer test and Lachman test are performed clinically to diagnose ACL failure and subsequent laxity of the knee (Silvers and Mandelbaum, 2011).

Since the ACL has a deficient healing capacity (Kiapour and Murray, 2014), a rupture of the ACL requires surgery in most cases and ACL reconstruction aims to restore the knee's stability. Recent advances in understanding the biomechanical and biological properties of the intact native ACL, have led to the development of numerous surgical techniques for the reconstruction, conducive to different graft choices (Scheffler et al., 2002), still the most ideal graft tissue is the subject of ongoing debate (Freedman et al., 2003). The graft must be easily obtainable, should possibly lead to less donor site morbidities, and should allow urgent rigid fixation. All this while undergoing relatively rapid healing and replication of the mechanical properties of the native ACL, in order to restore function and permit a return to pre-injury activities (Goldblatt et al., 2005).

One of the roles of the surgeon in ACL reconstruction is to personalize the choice of graft for the needs of each patient (Fu, 2009). The surgeon should take into consideration while planning the surgery the clinical examination, isolated vs. multiligament knee instabilities, the age, the activity level, as well as the occupational and recreational activities of the (Bonasia and Amendola, 2012).

The graft options available are autograft and allograft tissue, also synthetic ligaments are available, classified as scaffolds, stents, or prostheses (West and Harner, 2005). Autograft and allograft options include the patellar, hamstring, quadriceps tendons, fascia lata, but for the allograft choice we can also consider Achilles and anterior and posterior tibialis tendons, as well as the fascia lata. Patellar tendon autografts have long been the most popular graft choice because of their strength, easy harvest, rigid fixation, bone-to-bone healing, and favorable clinical results, nevertheless their donor site morbidity has led to the search of alternative graft sources.

Both autograft and allograft have generated outstanding results and are by far the most frequently used grafts in reconstruction of the ACL. Among the advantages of autograft, we find enhanced stability associated with a lower rate of graft failure (Prodromos et al., 2007), lower rate of infection (Crawford et al., 2005), no risk of transmission of infectious disease with also no risk of immune reaction from the organism (Arnoczky et al., 1986), reduced costs (Prodromos et al., 2007), faster integration and timely return to full activities, including high contact sports (Malinin et al., 2002). The advantages of allograft tissues also include a faster immediate postoperative physical recovery, less pain, no donor-site morbidity as there is no need for graft harvest, a greater variety and availability of graft sizes and shapes (Bonasia and Amendola, 2012).

Anatomy and biomechanics of the normal ACL

The anterior cruciate ligament lies in the middle of the knee, connected to the femur somewhat posterior to the medial surface of the lateral condyle and to the tibia, at the anterior part of the intercondylar region, at the insertion of the anterior horn of the lateral meniscus, as shown in Figure 1.

It varies in length from 25 to 35mm, with a breadth of approximately 10mm and has a width of 4 to 10mm. It is more or less triangular in cross-section and it diminishes along its length from both ends up to the midsection; that is, the ACL has a higher cross-section at the osseous interfaces, being slimmer in the midsection (Marieswaran et al., 2018) – Figure 2.

The native ACL functions as the primary restraint against anterior tibia translation, and as a secondary restraint against tibial rotation on varus or valgus stress (Butler et al., 1980; Markolf et al., 1976). The literature

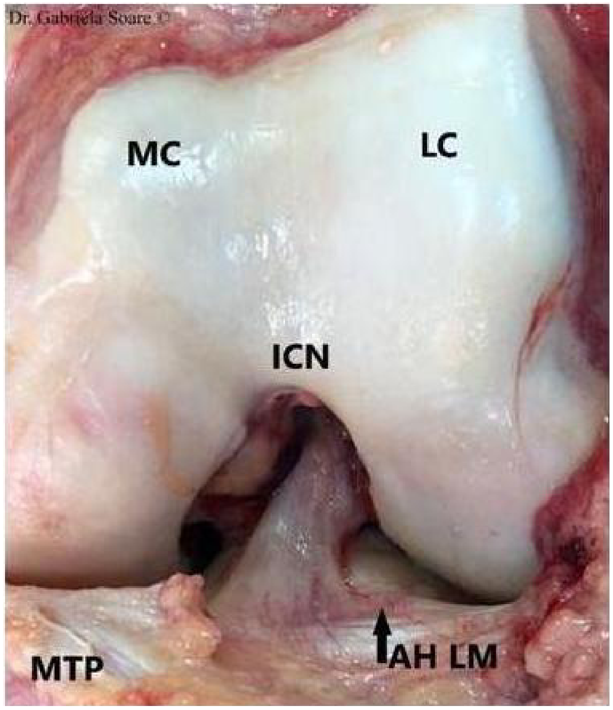

Figure 1. The ACL is connected to the femur slightly posterior to the medial surface of the lateral condyle (LC) and to the tibia towards the medial tibial plateau (MTP) next to the insertion of the anterior horn of the lateral meniscus (AH LM), at the anterior of the intercondylar notch (ICN)

Figure 2. Insertion sites of ACL on lateral femoral condyle and tibial plateau

shows that the native ACL has an average cross-sectional area of 44mm^2, an ultimate tensile load of up to 2,160 N, a rigidity of 242 N/mm, and a strain rate of 20% before failure (Noyes et al., 1984; Woo et al., 1991). Intact ACL forces range from 100 N in passive knee extension to about 400 N in walking and up to 1,700 N for cutting and acceleration-deceleration (Markholf et al., 1996; Butler et al., 1985). Only in unusual load patterns the native ACL exceeds its failure capacity (West and Harner, 2005).

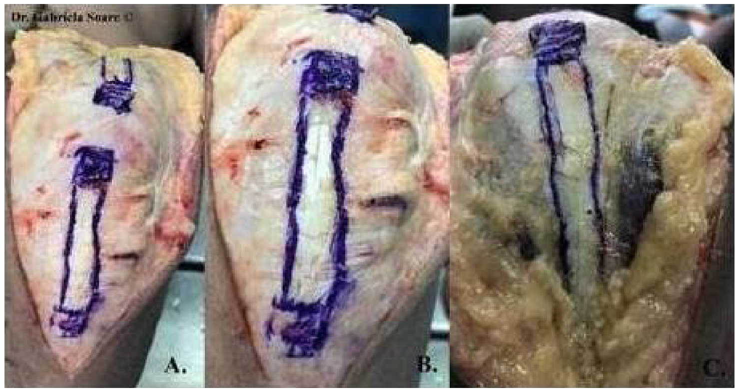

Figure 3. A. midline incision; B. BTB graft marked for harvest; C. quadriceps marked for harvest

The Biology of Healing

The incorporation of all ACL grafts into the host knee follows a sequential process (Falconiero et al., 1998; Beynnon and Johnson, 1996; Rodeo et al., 1993; Lephart et al., 1993). The first incorporation phase consists of an inflammatory response which degenerates the graft. Behind the cell death of the donor fibroblasts, the remaining tissue is used as a scaffold for host cell migration and matrix development. In the second phase a period of revascularization takes place in which the host fibroblasts migrate into the graft tissue (West and Harner, 2005). This phase starts within 20 days from the graft insertion and usually takes 3 to 6 months (Falconiero et al., 1998). Material properties of the graft change as the revascularization process occurs, also known as "ligamentization". During graft maturation, graft strength decreases to as low as 11% of that of normal ACL strength and the stiffness decreases to as low as 13% (Beynnon and Johnson, 1996). The final stage is graft healing, which transforms the collagen structure into a highly organized pattern, during which its mechanical properties improve, but it never reaches the rigidity and strength of the graft at the time of implantation (Beynnon and Johnson, 1996).

After transplantation, the healing of the graft attachment is responsible for most graft strength. From a biologic point of view, patellar tendon grafts as well as quadriceps tendon with bone plug have the advantage of healing bone-to-bone, as compared with soft-tissue grafts, that is a stronger and faster healing similar to that of a fracture. With bone-to-bone healing, the graft can be healed and integrated in 6 weeks (West and Harner, 2005), while soft-tissue grafts normally take 8 to 12 weeks to incorporate into the host bone (Rodeo et al., 1993).

Both autografts and allografts undergo a similar process, but even so, allografts have a slower rate of biological inclusion (West and Harner, 2005), the healing time could take 6-9 months (Fu, 2009).

MATERIALS AND METHOD

We performed an experimental study using 8 cadaveric knees from 4 donors. The study was performed with the help and collaboration of the National Institute for Forensic Medicine. The donors had a mean age at death of 51,5 years, ranging between 38 and 63. Cadavers were stored at 4^{o} C. At study the knees had no macroscopic signs of injury, with full range of motion measured with a goniometer.

Graft harvesting and preparation

The surgical techniques were reproduced exactly. We harvested the most used graft types in our clinic – bone patellar tendon bone (BTB), hamstrings (semitendinous and gracillis) and quadriceps tendon. We used a midline skin incision for visualization of the knee and graft harvest. We used the incision to visualize the anatomy of the native ACL (Figure 1 and 2) Semitendinosus and gracillis tendons were identified at their insertion site in the distal end of the incision and were detached from the muscle body using a tendon stripper and then cut from their tibial insertion in line with the periosteum.

The patellar and quadriceps tendons were harvested using a standard technique through the midline incision (figure 3). 10 mm wide grafts were harvested for both patellar and quadriceps tendon, with bone plugs.

The various grafts were harvested and prepared under the same conditions used during surgery in terms of graft size, configuration and suture placement (figure 4). AVicryl® 2 suture was used.

After graft harvest, we used the incision to visualize the joint and assess the anatomy of the normal ACL.

The grafts were kept for 48 hours before testing in saline solution at 2^{o} C. Each graft was attached to the testing system to apply tensile loads.

For tensile testing we used a Housfield H10KT static stress equipment with the following specifications: force

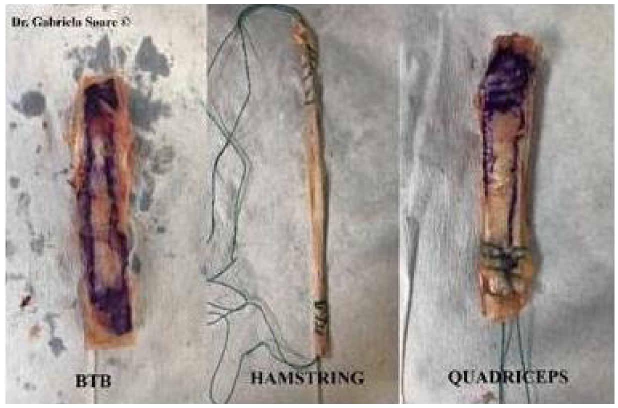

Figure 4. Types of graft used in the study

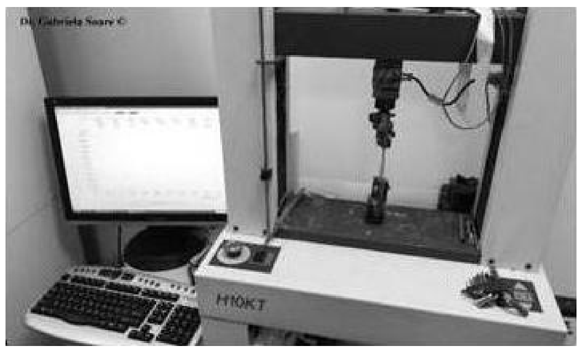

Figure 5. Materials testing system, software and test configuration used in study.

Figure 6. Mid-substance fail

Table 1. Summary of load to failure (N) for all graft types

	Min.	Max.	Mean
BTB	208	504	320.3
Hamstrings	158.7	595	390.96
QT	149	491	312.93

Table 2. Summary of elongation at failure (mm) for all graft types

	Min.	Max.	Mean
BTB	0.38	26.32	8.38
Hamstrings	0.24	41.2	15.5
QT	0.32	31.7	9.38

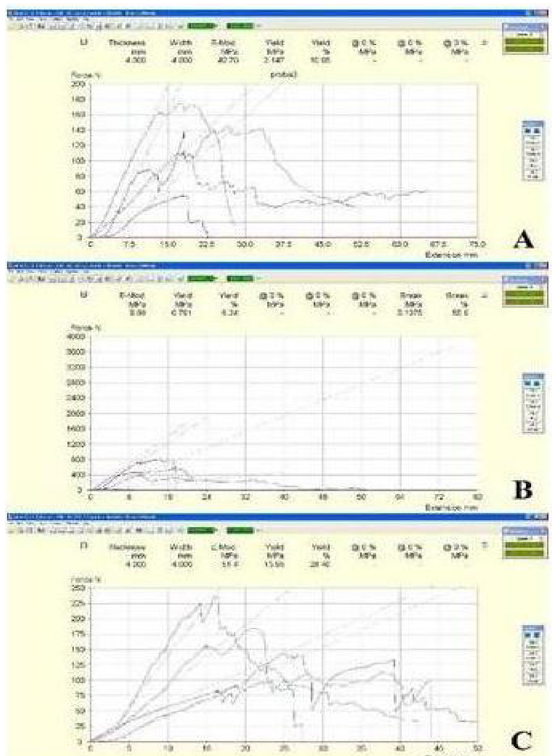

Figure 7. A. overlay of multiple BTB testing; B. overlay of multiple hamstring testing; C. overlay of multiple QT testing

cells up to 10.000 N, force measuring accuracy of 0,5% of the force applied, force reading rate of 200 times/sec, accuracy of vertical movement 0,0001 mm, accuracy of travel speed of 0,005%.

Each graft was attached to the testing system and tensile loads were applied until failure. The maximum load of failure and elongation at failure were automatically measured by the system's software (figure 5).

RESULTS

As difficulties during testing that we encountered was the clamp design as we had one graft slippage during testing. Also, the clamp can crush the graft, resulting in premature failure and lower strength values.

Most grafts failed mid-substance (figure 6), also inter and intra fiber failure was noted on all grafts tested.

Maximum load at failure

Data is provided in table 1. The hamstrings graft had the highest mean load to failure of all grafts tested (figure 7), followed by the BTB and quadriceps tendon. Despite these results, we must bear in mind that the integration of bone to bone occurs at a higher rate than the ligamentous incorporation into the bone.

Elongation at failure

Table 2 and, in part, figure 7 provide data. The hamstrings structure had the greatest elongation at failure, followed by the quadriceps. The patellar tendon graft had the lowest mean elongation at failure of all tendons tested.

DISCUSSION

The aim of this study was to test the biomechanical properties of commonly used grafts in reconstruction of the anterior cruciate ligament. The hamstrings graft had a significant higher maximum load at failure associated with a larger elongation at failure compared to other tendons.

But the results are susceptible to alterations due to the study's limitations. Tensile testing was performed with tissues that had been kept in saline solution for 48 hours which could affect their mechanical properties. The fixation method on the testing machine is another important issue as it can affect the tensile strength. Also, the age of donor is a possible problem, as it is higher that the age of patients normally undergoing surgical reconstruction of ACL.

Apart from the tensile strength we should take into consideration the in vivo capacity of graft integration, the methods of fixation and their limitations. From a functional point of view a graft that integrates at a more rapid rate and associated with fewer comorbidities leads to a faster recovery and a better long-term outcome.

Results are greatly influenced by the age of donor, size of the graft, time between harvest and testing, as well as preservation technique before testing.

Patellar tendon

The patellar tendon autograft requires both a tibial tubercle and a patellar bone plug to be harvested. The main risks are both intra-operative and post-operative patellar fractures, tibial stress fractures, articular cartilage damage to the patella and tendon ruptures. In terms of minimizing the risks for cartilage damage, it has been suggested that trapezoidal bone cuts rather than triangular ones are useful (West and Harner, 2005). The BTB autograft is also associated with an increased risk of anterior knee pain, mainly during kneeling, and many studies have shown that using a hamstring autograft reduces this risk (Freedman et al., 2003).

Other complications described include patellar tendonitis and anterolateral knee numbness due to the damage to the infrapatellar branch of the saphenous nerve during harvest. The use of the central third of the patellar tendon does not reduce the extensor strength nor its functional potential in highly active patients undergoing intensive rehabilitation (Lephart et al., 1993).

Among the advantages of a patellar tendon graft we find rapid integration of the bone blocks within the bone tunnels; direct rigid fixation of the bone blocks and good conservation of rigidity and load to failure (West and Harner, 2005; Fu, 2009; Bartlett et al., 2001). As said earlier, the disadvantages are mainly related to the donor site and include anterior knee pain; patellar tendonitis; patellar tendon rupture; fracture ofthe patella or tibial tubercle; increased stiffness of the joint; late chondromalacia; and injury to the saphenous nerve's infrapatellar branch (Prodromos et al., 2008; West and Harner, 2005; Fu, 2009; Bartlett et al., 2001).

Hamstring

Four-strand hamstring grafts consisting of either doubled semitendinosus/gracillis or quadrupled semitendinosus tendons have become commonly used.

During hamstring harvesting, care must be taken to remove the entire tendons, without prematurely curtailing them (Bonasia and Amendola, 2012).

Saphenous nerve and vein injury, femoral arterial and vein injury, sciatic nerve harm, and residual muscle weakness and discomfort (Prodromos et al., 2008) are complications associated with this procedure. Also, mild knee flexion weakness and mild internal rotation weakness ACL reconstruction with hamstring autograft has been described, but both are only seen at fairly high knee flexion angles and do not cause deficits of the overall clinical performance (Fu, 2009).

Among the advantages of hamstring grafts are higher load to failure and rigidity; a higher cross-sectional area of the tendon; straightforward passage of the graft; smaller incision as compared to harvest of BTB or quadriceps tendon and less morbidity on the donor site (Bartlett et al., 2001). The disadvantages are slower tendon-to-bone integration into the tunnel; the possibility of injury to the saphenous nerve; weakness of the hamstring muscles after operation and widening of the tunnel (Bartlett et al., 2001).

Quadriceps tendon

There are a few elements that make the quadriceps tendon more difficult to harvest as compared to the patellar tendon: it has a condensed cortical bone, it has a curved proximal surface, and a close adhesion to the suprapatellar pouch (West and Harner, 2005).

Among the advantages of this graft we find that it is a thick tendon with good biomechanical properties, and its harvest leads to reduced anterior knee pain as compared to BTB (Bartlett et al., 2001). The disadvantages include weakness of the extensor mechanism after operation, a disagreeable scar and a more difficult graft harvest, from the technical point of view (Bartlett et al., 2001).

Allografts

Have obvious advantages such as the lack of morbidity at the donor site and the small incisions required for implantation. This led to the use of allografts in the reconstruction of the anterior cruciate ligament (Bartlett et al., 2001).

CONCLUSIONS

We have to note that during this test we did not perform a comparison with the strength of native ACL, which could change the ranking.

The ideal graft should be able to reproduce both the histological and biomechanical properties of the native anterior cruciate, so that it allows a fast biologic integration.

The obvious advantage of allografts and synthetic grafts is that harvesting is not required during surgery and that no donor-site morbidity will occur. Nevertheless, a potential problem with allografts is the infectious disease transmission, although greatly diminished.

The incidence of anterior knee pain is present with both BTB and hamstring graft, at 17.4 % in patellar tendon autograft and 11.5 % with hamstring autograft (Freedman et al., 2003). Some authors suggested that anterior knee pain is caused mainly by penurious rehabilitation methodologies and loss of knee motion, rather than that of graft choice.

The ideal graft for ACL reconstruction should have biomechanical properties similar to those of the native ACL, should allow stable initial fixation and rapid biologic incorporation, and should offer a low rate of morbidity at the donor site. It is important to understand the technical challenges and potential hazards associated with each graft. The morbidity of the harvest depends on the surgeon and technique. Graft selection depends on many factors, including the philosophy and experience of the surgeon, tissue availability, level of patient activity, comorbidities, prior surgery and patient preference.

In reconstruction of the anterior cruciate ligament, both autografts and allografts are excellent alternative options. The choice of graft should be personalized according to the patient (age, gender, level of activity, concurrence, occupational and recreational activities) and the physical examination of the patient with possible multi-ligament injuries.

Conflict of Interest

No conflict of interests is present.

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