



# Anterior cruciate ligament reconstruction: principles of treatment

Nikolaos K. Paschos  
Stephen M. Howell

- Anterior cruciate ligament (ACL) reconstruction is one of the most common procedures in sports medicine. Several areas of controversy exist in ACL tear management which have engaged surgeons and researchers in debates towards identifying an ideal approach for these patients.
- This instructional review discusses the principles of ACL reconstruction in an attempt to provide guidelines and initiate a critical thinking approach on the most common areas of controversy regarding ACL reconstruction.
- Using high-level evidence from the literature, as presented in randomised controlled trials, systematic reviews, and meta-analyses, operative *versus* conservative treatment, timing of surgery, and rehabilitation are discussed. Also, the advantages and disadvantages of the most common types of autografts, such as patellar tendon and hamstrings as well as allografts are presented.
- Key considerations for the anatomical, histological, biomechanical and clinical data ('IDEAL') graft positioning are reviewed.

**Keywords:** anterior cruciate ligament; ACL tear; reconstruction; timing; rehabilitation; autograft; allograft; tunnel position

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## Introduction

Anterior cruciate ligament (ACL) reconstruction is one of the most common orthopaedic techniques performed worldwide. ACL injuries occur with increasing incidence, from approximately 33 cases in 100 000 in 1994 to between 40 and 60 incidents in 100 000 in 2014. Individuals participating in organised sport activities are most affected.<sup>1-4</sup> It is estimated that approximately 200 000 ACL reconstructions are performed each year in the USA alone, a number expected to increase further as a result of increased participation in athletic activities by adolescents and young adults.<sup>1,2,5</sup>

It is of paramount importance to understand the long-term consequences that develop as a result of an ACL tear. The incidence of knee osteoarthritis (OA) increases to between approximately 15% and 20% after an ACL tear, which represents a ten-fold increase.<sup>6</sup> It is suggested that more than 50% of patients that sustain an ACL injury will develop symptomatic OA in the following 10 to 20 years.<sup>7</sup> When combined with a meniscectomy, an ACL tear can further increase the prevalence of OA.<sup>6</sup> Specifically, in a cohort study with a ten year mean follow-up, the presence of intact menisci was associated with normal radiographic findings in approximately 88% of patients *versus* only 63% when meniscectomy was performed. When compared with meniscal injury alone, the ACL tear has been shown to cause radiographic changes at a younger age than meniscal tear, which indicates its importance.<sup>8</sup>

Despite the frequency in development of OA post-ACL injury, one of the main issues is whether ACL reconstruction can minimise the risk of osteoarthritis progression. Indeed, the reported incidence of osteoarthritis post-ACL reconstruction ranges from between 39% and 47% at seven years' follow-up,<sup>9-11</sup> and appears to increase to between 74% and 80% after a period of 13 to 15 years.<sup>12,13</sup> Interestingly, of all the cases with degenerative arthritis only 40% were symptomatic.<sup>12,13</sup> Male gender, increased BMI, time from injury to reconstruction and previous meniscectomy as well as presence of cartilage degeneration in the medial compartment at surgery were all associated with the future development of radiographic knee OA.<sup>11</sup>

A correlation between osteoarthritic changes and increased knee laxity was also suggested by some studies.<sup>13</sup> Thus, the development of knee OA post-ACL tear is far more complex than initially suggested. ACL reconstruction appears to reduce the incidence of OA progression, but it does not fully restore knee function comparatively with the uninjured knee. Additional research is necessary to highlight further the initial phenomena that occur during knee injury, and to clarify whether the technique of ACL reconstruction can improve the prognosis and slow or reverse the natural history of the cartilage degeneration.

This review discusses the principles of ACL reconstruction in an attempt to provide guidelines and initiate a critical thinking approach on the most common areas of

controversy regarding ACL reconstruction. Using information collected from systematic reviews and meta-analyses, this instructional review discusses operative *versus* conservative treatment, timing of surgery and rehabilitation as well as the principles of graft selection and ideal graft positioning.

### Conservative *versus* surgical treatment

In young adults that desire to return to pre-injury activity, surgical management of an ACL tear is considered the 'gold standard' of care. The non-operative management of ACL-deficient knees has been proposed in the past as an alternative, but has been associated with poor functional outcome.<sup>14-18</sup> Specifically, non-operative treatment resulted in poor and fair functional outcome scores that prevented a return to pre-injury activities in the majority of patients, as well as an increased incidence of secondary ACL and meniscus surgery.<sup>16-20</sup> As a result, the more favourable outcome of ACL reconstruction establishes surgery as the first-line treatment for ACL-deficient knees in active patients.

While conservative treatment of ACL-deficient knees fell out of favour in the last ten to 15 years due to poor outcomes,<sup>14-20</sup> a recent randomised controlled trial (RCT) suggested that some patients with certain characteristics can be effectively managed non-operatively.<sup>21,22</sup> It was suggested that a structured rehabilitation programme with optional ACL reconstruction at a later stage, if needed, could result in similar outcomes to early ACL reconstruction.<sup>21</sup> This study was criticised because of problematic design and data interpretation.<sup>23</sup> Specifically, 23 of 59 patients (39% in the optional surgery group) underwent ACL reconstruction.<sup>21</sup> Furthermore, an increased percentage of patients suffered from instability and meniscal complaints (32% and 22% *versus* 3% and 2% for optional and early ACL reconstruction groups, respectively).<sup>21</sup> Previous reports showed a higher risk of symptomatic instability and late meniscus tear with conservative management.<sup>15,17</sup> Therefore, the morbidity and associated risk of late knee injuries appears to significantly exceed any potential benefits of a conservative approach, especially in young active patients who wish to return to pre-injury activity levels.

The frequency of subsequent meniscal and chondral injuries in ACL-deficient patients is higher in skeletally immature patients. An association between medial meniscal tears and time to ACL reconstruction was identified early in skeletally immature patients, suggesting that a delay in treatment may be aetiologically responsible for these meniscal injuries.<sup>24</sup> Similar studies not only confirmed the above link but also identified an increased incidence of chondral injuries in association with medial meniscal tears.<sup>25,26</sup> In prospectively-collected MRI data, it

was suggested that approximately 20% of skeletally immature ACL-deficient patients would sustain a new meniscal injury within the next four years.<sup>27</sup> As a consequence, the decision of whether to operate or not on an ACL injury in children should take into consideration the high risk of ensuing knee injuries and their associated long-term consequences.

### Principles of ACL reconstruction

In ACL reconstruction technique, there are several debates that have engaged orthopaedic surgeons and researchers. Specifically, the timing of repair and rehabilitation and the type of graft used are areas of contention.<sup>28</sup> Also, allograft *versus* autograft has also been a topic of controversy. Regarding the intervention type, the description of the double-bundle technique created expectations for a more anatomical technique, but there is dispute regarding the validity of this claim.<sup>29</sup>

#### *Timing of repair and rehabilitation*

Three main factors should be considered and balanced for the timing of ACL reconstruction. The increased incidence of meniscus and chondral injuries following delayed ACL reconstruction, the risk of arthrofibrosis associated with early ACL reconstruction, and the associated loss of muscle strength due to inactivity when surgery is delayed.

The number of patients that will sustain a meniscus tear in a previously intact meniscus at the time of ACL tear ranges from between 10% and 50%.<sup>30-32</sup> In a retrospective analysis of 205 patients, the mean time from the initial injury to meniscus tear was between 11 and 32 months for those with an injury to one or both menisci respectively.<sup>33</sup> For chondral lesions, as discussed above, the risk of cartilage degeneration following an ACL tear increases significantly, with most reports suggesting that 20% of chondral lesions occur at the time of the ACL injury, and another 20 to 30% developing later due to ACL deficiency.<sup>31,34</sup>

Arthrofibrosis - joint stiffness that prevents restoration of full range of motion (particularly the loss of the 5° to full extension) - has been associated with early ACL reconstruction. In a large retrospective analysis, 52% of patients who were operated on within the first week following their injury developed a loss of 5° extension while only 17% of patients operated on from day eight to day 21 developed arthrofibrosis. None of the patients treated after week three had loss of extension.<sup>35</sup> A post-operative rehabilitation programme introducing full passive extension, early motion and immediate weight-bearing was associated with a lower rate of joint stiffness in ACL reconstructed knees.<sup>35,36</sup> Interestingly, loss of extension was also seen in ACL reconstructions performed after six months following the initial injury.<sup>37</sup> Arthrofibrosis was also described in approximately 8% of children and

adolescents post-ACL reconstruction.<sup>38</sup> Some studies reported an extremely low incidence of arthrofibrosis when rehabilitation is used, and questioned its existence as a clinical entity.<sup>35,39,40</sup> Orthopaedic surgeons should be aware of the possibility of arthrofibrosis, avoid reconstruction within the first weeks of injury and introduce an appropriately-designed rehabilitation protocol.

Pre-operative rehabilitation programmes are also important to retain muscle strength while waiting for reconstruction. A pre-operative quadriceps strength deficit of 20% was found to be among the most important predictors of poor clinical outcome, associated with an approximately 15% decrease at two years post-operatively, when a deficit was present.<sup>41</sup> Furthermore, quadriceps with strength lower than 85% compared with the contralateral side was associated with a lower score in hop tests and a lower, but not statistically significant, International Knee Documentation Committee (IKDC) functional score.<sup>42</sup> Indeed, a rehabilitation exercise programme of five weeks' duration in patients with ACL injury was shown to significantly improve their knee functional outcome.<sup>43</sup>

Interestingly, the timing of ACL reconstruction and autograft choice can also influence rehabilitation strategy. Early ACL reconstruction has been linked with delay in quadriceps recovery. Specifically, 80% of patients treated with delayed ACL reconstruction (mean 40 days) reached a 65% quadriceps strength at two months *versus* 53% of patients treated with early ACL reconstruction (mean 11 days), respectively.<sup>44</sup> By six months, 73% of patients that had delayed ACL reconstruction (mean time from injury of 40 days) exhibited 80% muscle strength *versus* only 47% in those reconstructed early.<sup>44</sup> Muscle weakness can also result from autograft harvesting for ACL reconstruction. A trend towards extensor and flexor muscle strength deficit was shown in ACL reconstructions when bone-patella-tendon-bone (BPTB) and hamstring (HST) autograft was used, respectively.<sup>45</sup> Therefore, carefully designed rehabilitation applied both pre- and post-operatively aiming to preserve quadriceps strength and retain knee range of motion appears to be a strategically important step towards a successful outcome post-ACL reconstruction.<sup>46</sup>

### Type of graft

The two most commonly-used autografts for ACL reconstruction are the patellar tendon (PT) (also known as a BPTB graft) and the hamstring tendon (HT). The general notion, as indicated by most RCTs and meta-analyses, is that both grafts exhibit excellent results with no differences between them regarding functional outcome and activity level.<sup>47</sup> Strong advocators for each graft type exist, and certain advantages and disadvantages have been suggested in the literature for each graft.

**Table 1. Advantages and disadvantages of most commonly used autografts**

	Patellar tendon	Hamstrings
Advantages	<ul style="list-style-type: none"> <li>• Higher strength</li> <li>• Lower re-tear rate</li> <li>• Earlier graft remodeling and healing</li> <li>• Better knee stability</li> </ul>	<ul style="list-style-type: none"> <li>• Smaller incision/better cosmesis</li> <li>• Minor functional impairment from graft harvesting</li> <li>• Earlier regeneration of hamstrings</li> </ul>
Disadvantages	<ul style="list-style-type: none"> <li>• Higher incidence of anterior knee pain and kneeling pain</li> <li>• Increased incidence of OA post-ACL reconstruction</li> <li>• Higher rate knee extension deficit due to adhesions</li> </ul>	<ul style="list-style-type: none"> <li>• Higher incidence of tunnel widening</li> <li>• Electromechanical delay in knee flexors/weakness</li> </ul>

OA, osteoarthritis; ACL, anterior cruciate ligament

### Advantages of the patellar tendon graft

Biomechanical data comparing PT graft and HT with native ACL found that PT graft had a maximum load of 2730 N or 2900 N (depending on whether the central or middle portion of BPTB was tested), and a stiffness of approximately 57 MPa that is translated as being between approximately 160 to 170% stronger and 150% stiffer than native ACL.<sup>48</sup> In contrast, HT components - semiten-dinosus and gracilis tendons - were found to have 1220 N and 840 N maximum load as well as 89 MPa and 112 MPa stiffness, corresponding to 70% and 49% of native ACL for load as well as 234% and 295% of native ACL for stiffness.<sup>48</sup> Notably, the use of multiple stands resulted in doubling of maximum load and stiffness for both semiten-dinosus and gracilis tendons, and therefore the exact technique needs to be considered and related to the expected outcome.<sup>49</sup> In summary, both grafts used in ACL reconstruction exceed the biomechanical strength and stiffness of native ACL and this has been proven to be a safe approach in an attempt to eliminate the risk of graft tear.<sup>28</sup>

One of the main advantages of the PT graft is the lower re-tear rate reported in comparison with hamstring graft. PT graft is believed to be associated with lower failure rate, with a meta-analysis showing an incidence of 1.9% graft failure *versus* 4.9% for HT graft.<sup>50</sup> This was also confirmed in a meta-analysis of only level-I studies that showed a 7.2% and 15.8% failure rate for PT and HT, respectively. Another meta-analysis reported a lower rate, but it failed to show significance (2.5% vs 3.3%, RR 0.78, 95% CI 0.41 to 1.50) for PT and HT, respectively,<sup>28</sup> while other analyses demonstrated no significance between the groups regarding failure rate.<sup>28,51,52</sup>

This led to the suggestion that graft fixation is also an important aspect of surgical failure. It is suggested that, depending on the graft used, the type of fixation should be adjusted accordingly.<sup>53-57</sup> Specifically, it was found that interference screws offer the maximum load and stiffness properties for PT grafts, resembling those of native ACL.<sup>56</sup>

This is extremely important since PT graft is suggested to promote graft remodeling and healing due to the presence of the bone plug. In an animal study, maximum failure load was higher in PT grafts at three weeks in comparison with flexor tendon grafts, suggesting that PT graft may undergo earlier ligamentisation and revascularisation and that this may allow earlier return to activity.<sup>58-60</sup> Biological strategies that may enhance graft healing are becoming popular; however additional research is needed before making any definite conclusions about their effectiveness.<sup>61-63</sup>

Finally, in some reports, PT graft was shown to be able to restore knee stability more closely. Indeed, in a meta-analysis the percentage of patients that exhibited a KT-1000 arthrometer side-to-side difference of < 3 mm was 73.8% versus 79% for hamstring patients ( $p < 0.05$ ).<sup>50</sup> Another meta-analysis of 22 studies with approximately 2000 patients showed a lower risk of positive pivot shift (RR = 0.7, 95% CI, 0.53 to 0.93;  $p = 0.01$ ).<sup>52</sup> Analysing eight studies with 550 patients, it was shown that PT was associated with a higher chance to return to pre-injury level of activity (OR = 1.48, 95% CI, 1.03 to 2.12;  $p = 0.03$ ).<sup>52</sup> The same trend was shown in a recent long-term RCT with follow-up at 15 years, suggesting that a higher percentage of patients reconstructed with PT grafts participated in sports-related activities ( $p = 0.05$ ). This finding was in accordance with similar reports favouring the patellar graft for Lachman and pivot shift tests.<sup>28,51</sup>

#### *Disadvantages of patellar tendon graft*

Patellar tendon is associated with a higher percentage of anterior knee pain and kneeling pain. A recent meta-analysis of 12 studies, with data from approximately 850 patients, showed a significantly higher incidence of anterior knee pain in PT grafts (RR = 1.71, 95% CI, 1.35 to 2.16;  $p < 0.01$ ).<sup>52</sup> Kneeling pain was also worse in PT patients (RR = 2.05, 95% CI, 1.51 to 2.77;  $p < 0.01$ ).<sup>52</sup> In another meta-analysis, the patellar tendon group suffered from anterior knee pain in 17.4% versus 11.5% in the hamstrings group.<sup>50</sup> The increased incidence of anterior knee pain and kneeling pain, as part of PT graft harvest morbidity is a consistent finding from multiple reports.<sup>51</sup>

Apart from pain during kneeling, another concern with PT grafts was the increased incidence of OA reported with PT compared with hamstring grafts (45% versus 14% of patients, respectively ( $p = 0.002$ )).<sup>10</sup> This was confirmed in a meta-analysis of studies with > five-year follow-up, where patellar graft was associated with higher incidence of radiographic osteoarthritis.<sup>64</sup> Specifically, in four studies that included 290 patients, patellar tendon graft had a higher incidence of degenerative arthritis. (RR = 1.61, 95% CI, 1.08 to 2.4;  $p = 0.02$ ).<sup>64</sup> However, a higher incidence of meniscus surgery was present in the patellar tendon group, and not all studies were randomised.<sup>64</sup> This finding has not

been confirmed from other long-term reports,<sup>28,65,67</sup> and it may be associated with the increased laxity found in the PT group at seven years versus two-year follow-up.<sup>10</sup> However, further research with long-term follow-up studies is necessary in order to clarify whether this association exists.

Finally, patellar grafts were found to be associated with a higher rate of adhesions that would lead to manipulation under anaesthesia.<sup>50</sup> This complication is probably related to the significant percentage of extension deficits found in patellar tendon graft patients. Specifically, in a meta-analysis sub-group of more than 1000 patients the risk of patellar tendon patients having an extension deficit > 3° was higher (1.71, 95% CI 1.25 to 2.33;  $p < 0.01$ ). All of the above disadvantages are associated with a high degree of morbidity, also associated with PT graft reconstruction that could potentially lead to a lower performance and level of activity in PT graft-treated, high-performance athletes.<sup>49</sup> As a consequence, it is suggested that the lower re-tear rate may be a result of lower participation in sports post-operatively.

#### *Advantages of hamstring tendon*

The main advantage of the hamstring tendon graft is the lower donor site morbidity associated with its harvesting. Indeed, hamstring harvesting may be a technically challenging technique, but it causes a smaller incision which results in better cosmetic appearance of the wound, an outcome that may be important in young female patients. Also, it causes significantly less anterior knee pain and less incidence of kneeling pain, as described above.<sup>28,50,52</sup> Complications associated with hamstring graft are rather minor (for example, electromechanical delay in knee flexors and weakness) and are not proven to cause a functional impairment.<sup>68,69</sup> Interestingly, most reports suggest a regeneration of hamstrings within two years from surgery, while patellar tendon reconstitution may be a more prolonged process.<sup>68,70-72</sup>

#### *Disadvantages of hamstring tendon*

Tunnel widening is reported more frequently with hamstring grafts. This was against the initial belief that, since hamstring graft fills the drilled tunnels completely, it would be associated with less tunnel widening. Specifically, it was found that tunnel increase was approximately double compared with patellar tendon graft (~20% versus ~10% and 25% versus 15% increase in tibial tunnel increase for anteroposterior and lateral views,  $p = 0.003$  and  $p = 0.01$ , respectively). An animal study highlighted the importance of graft stiffness and graft hypertrophy due to remodeling for the development of tunnel widening.<sup>73</sup> Three randomised controlled studies showed a higher percentage of femoral tunnel widening in patients treated with hamstring graft,<sup>14,47,74</sup> however, only one of them reported significantly higher knee laxity in the



**Table 2.** Advantages and disadvantages of allografts

Allografts	
Advantages	<ul style="list-style-type: none"> <li>• No donor site morbidity</li> <li>• Shorter surgical time</li> <li>• Ensure adequate graft length and diameter</li> </ul>
Disadvantages	<ul style="list-style-type: none"> <li>• Higher failure rate</li> <li>• Higher cost</li> <li>• Worse knee stability measured in some studies</li> <li>• Potential disease transmission and higher infection rate</li> </ul>

hamstring group.<sup>47</sup> Compaction of an autologous bone dowel into the tibial tunnel was shown to reduce the cross-sectional area of the tibial tunnel and prevent tunnel expansion in approximately 90% of patients after one to two years post-operatively.<sup>75</sup>

### Allograft versus autograft

Allograft choices for ACL reconstruction are the patellar, Achilles, and tibialis tendon. The main advantages of allografts are the lack of donor site morbidity, shorter surgical time and the guarantee of adequate graft tissue. In contrast, allografts are associated with risk of disease transmission, potential delayed incorporation and immune response, while increased cost may be also a concern.

#### Advantages of allografts

Allografts have no associated donor site morbidity, which may be an important limitation for autografts, as seen in the percentage of anterior knee pain that affects up to 40% of patients.<sup>47,76</sup> Furthermore, the operative time when allograft was used was significantly shorter compared with autograft, as shown in a meta-analysis comparing hamstring allograft and soft-tissue allograft (59 mins vs 77 mins,  $p = 0.008$  respectively). Finally, in certain cases, the length and diameter of tissue used as an autograft can be variable and inadequate for the intended reconstruction.<sup>77</sup> These issues are addressed with the use of an allograft. The importance of these factors can be underestimated in clinical assessment analysis, but all need to be considered; donor morbidity can adversely affect patient subjective outcome and the patient–physician relationship, while shorter surgical time is typically translated into the ability for the surgeon to perform an additional ACL reconstruction per day.

#### Disadvantages of allografts

Higher failure rate remains the main concern for allografts. In a prospective cohort design, ACL reconstructions using an allograft were demonstrated to have up to a four times higher failure rate when compared to those using an autograft.<sup>78</sup> In a meta-analysis that included more than 5000 patients with patellar tendon allograft/autograft, it was also shown that allograft resulted in a

three-fold increase in the re-rupture rate. In a meta-analysis including more than 500 patients, PT allografts were shown to have a higher risk of re-rupture compared with PT autografts (OR = 5.03,  $p = 0.01$ ). Recently, a meta-analysis of nine RCTs and ten systematic reviews reported lower clinical failure for autograft (RR, 0.47;  $p = 0.0007$ ).<sup>79</sup> Two other meta-analyses failed to show a difference in clinical failure and re-operation rate between allografts and autografts.<sup>80,81</sup> Interestingly, this difference was abolished when grafts processed with irradiation or chemicals were excluded,<sup>82</sup> suggesting that graft irradiation and chemical processing is a critical factor for graft failure. Indeed, when analysed separately, BPTB non-irradiated allograft had a similar graft failure rate to autograft (8.8% and 6.1%, respectively).<sup>83</sup> Despite the trend indicating a better performance for autograft, additional randomised controlled studies are important to resolve the existing controversies between allografts and autografts.

In terms of knee stability, the literature is extremely controversial. Allografts were shown to be associated with a higher percentage of unstable knee measurements compared with autografts (14% vs 5.3%) respectively.<sup>84</sup> A meta-analysis of 38 studies that included data for more than 2500 patients showed that the percentage of patients with a side-to-side difference < 3 mm was 75.3% and 60.2% for autograft and allograft, respectively.<sup>85</sup> Interestingly, functional outcomes were also in favour of autograft with better Lachman test (RR, 1.18;  $p = 0.03$ ), and Tegner score (WMD, 0.36;  $p = 0.004$ ).<sup>79</sup> However, other reports found no difference; a meta-analysis of hamstring autograft *versus* soft-tissue allograft favoured slightly allograft for KT arthrometer laxity < 3 mm, (RR = 1.1, 95% CI 0.89 to 1.39), and Lachman negative (RR = 1.37, 95% CI 0.88 to 2.14) (81). A meta-analysis of six studies analysing approximately 650 patients also found no difference (RR = 1.19, CI 95% 0.63 to 2.24;  $p = 0.59$ , favouring allograft).<sup>80</sup>

ACL allograft has also been associated with higher costs and a higher infection rate. A statistically higher cost was reported for PT allograft with a total mean cost per case being US\$4147 *versus* US\$3154 for the PT autograft ( $p < 0.001$ ).<sup>86</sup> Another report that compared hamstring autograft and tibialis anterior allograft also showed a higher cost of approximately US\$1000 for allograft (US\$5195 vs US\$4072,  $p < 0.001$ ).<sup>87</sup> However, some reports suggest that the cost of hospital stay may increase as a result of the higher possibility of overnight hospitalisation due to autograft donor site morbidity and increased surgical time.<sup>87</sup> In a cost-effectiveness analysis, allografts were found to be the less cost-effective option.<sup>88</sup> When evaluating cost, one should consider the risk of infection which is reported as higher in allografts.<sup>89</sup> However, this finding was not confirmed in similar reports, showing no increased risk of infection with allograft tissue.<sup>88,90</sup>

## IDEAL position characteristics

Proper positioning of the ACL graft has been proven to be of paramount importance for graft longevity. Malposition of the ACL graft, for example in anterior placement of the tibial tunnel, was associated with roof impingement.<sup>91</sup> Roof impingement of the reconstructed ACL graft was recognised early as a significant factor that leads to graft failure.<sup>91-94</sup> Furthermore, the degree of impingement was associated with an increased risk of ACL graft failure at two year-follow-up (100% in severe impingement vs 29% in moderate impingement).<sup>91</sup> Therefore, it is reasonable to suggest that every attempt should be made to avoid malposition of the ACL graft.

The identification of the importance of proper placement of the ACL graft led to extensive study of the anatomical characteristics of the native ACL over the last decades, in an attempt to imitate these anatomical features during ACL reconstruction. The tibial and femoral osseous attachments of the ACL have been widely studied, and despite traditionally having an oval and crescent-like shape respectively, potential variations in their shape have been suggested.<sup>95,96</sup> The anatomical characteristics of the attachments, in conjunction with the tendency to avoid impingement, led to interesting operative concepts, such as the meticulous placement of the ACL graft within the tibial and femoral footprints, i.e. complete footprint restoration.<sup>97</sup>

Following the same concept of anatomical ACL reconstruction based on the osseous attachments, the use of a double-bundle graft was proposed to replicate anteromedial and posterolateral bundles, as described in the native ACL.<sup>98,99</sup> However, this technique did not clinically confirm the biomechanical findings, which suggested better rotational knee stability would result.<sup>100</sup> Furthermore, the tension at the PL bundle in knee extension could be so high that could cause early graft rupture or attenuation.<sup>101</sup> Currently, double-bundle reconstruction is rarely performed.<sup>5,102-104</sup>

Apart from the study of the attachments an increasing interest has developed with regard to the anatomical characteristics and shape of the ACL mid-substance. Specifically, it was recognised that the ACL has a smaller cross-sectional area at its mid-substance in comparison to that of its attachments.<sup>105</sup> Furthermore, it was described that the ACL has a band-like shape along its length, and close to its tibial attachment it fans out like a trumpet to attach to the tibia.<sup>106</sup> It is important to recognise the surgical implications rising from these observations, especially when realising that the posterior cruciate ligament occupies most of the area of the notch, leaving only a 5 mm slot for the ACL graft.<sup>106</sup> Therefore, a more complex process is essential for ACL graft positioning in an attempt to incorporate the above anatomical, histological, isometric,

and biomechanical features when making the decisions during ACL reconstruction.

Recently, useful guidance-instructions were described using the acronym IDEAL to summarise the important features of the ACL femoral tunnel position: I- *isometric*, D – *direct*, E- *eccentric*, A- *anatomical*, and L- *low tension/flexion* pattern which occurs in a full cycle of knee motion.

During knee flexion and extension, not all fibres of the ACL are under tension throughout a full cycle of flexion/extension.<sup>107,108</sup> This is due to the changes in length observed during flexion, which results in the AM bundle being relaxed (elongated) and PL bundle being tight (shortened) at knee flexion.<sup>108,109</sup> The AM bundle is considered the centre of rotation of the ACL, which suggests a more isometric behaviour of this bundle.<sup>109</sup> Isometric studies suggested that the position at the femoral footprint that could potentially ensure isometry is located *eccentrically*, at the most anterior and superior (proximal) portion of the footprint, at the junction of the anteromedial and intermediate bundles (Fig. 1).<sup>108,110,111</sup> This position was demonstrated that could ensure reproduction of the normal tension-flexion behaviour of the native ACL.<sup>5</sup>

The collagen fibres at the femoral attachment belong to two distinct categories: the *direct* fibres, which are directly attached at the anterior portion of the osseous ACL insertion along the lateral intercondylar ridge, as well as the *indirect* fibres, that are less dense, lack the traditional four-layered structure of the ligamentous-bone attachment, and are located at the posterior portion of the ACL footprint.<sup>96</sup> Due to their histological characteristics, indirect fibres are considered a weaker mechanical link than the direct ones, and, therefore, it is suggested that the femoral tunnel should be placed at the area of the *direct* fibre insertion (Fig. 1).<sup>5,96</sup> Therefore, an area that 1) fulfills the above criteria of isometry, 2) is located within the footprint to avoid impingement, 3) restores the low flexion extension ACL pattern and 4) is located at the region of direct fibre insertion should be targeted for femoral tunnel position (Fig. 2).

As discussed above, avoiding impingement is critical for graft survival. A graft that is positioning outside the *anatomical* margins of the footprints has a greater risk of impingement and, therefore, will eventually fail. Two different types of impingement exist: roof impingement and posterior cruciate ligament (PCL) impingement that occur differently and should be treated differently. For roof impingement, it is critical to make sure that the tibial tunnel entrance is just posterior to the intercondylar roof with the knee at maximum passive hyperextension position. Roof impingement is a clinical problem presenting in extension with two consequences, ie a loss of extension and/or increased laxity. PCL impingement occurs in knee flexion where the ACL graft lies on top of the PCL graft. In order to address this problem, the surgeon should ensure

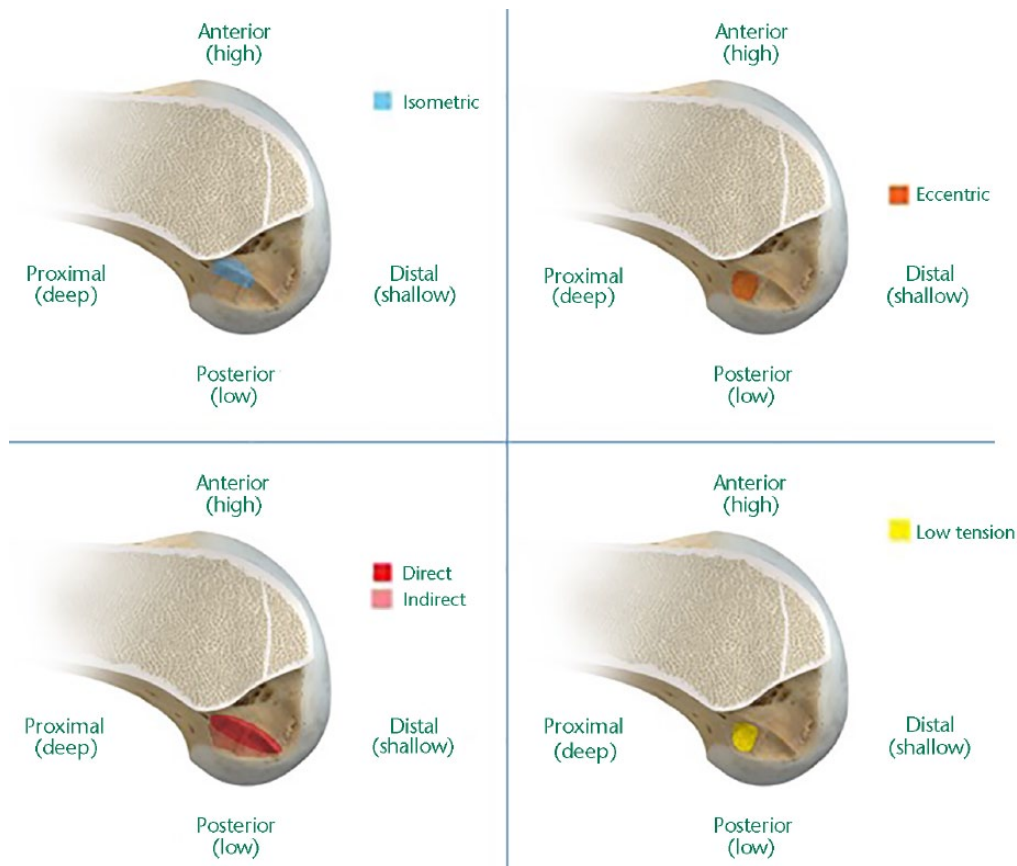


Fig. 1 Topographies at the femoral footprint that ensure isometric, eccentric, direct placement of the graft at a low-tension location.<sup>5</sup>

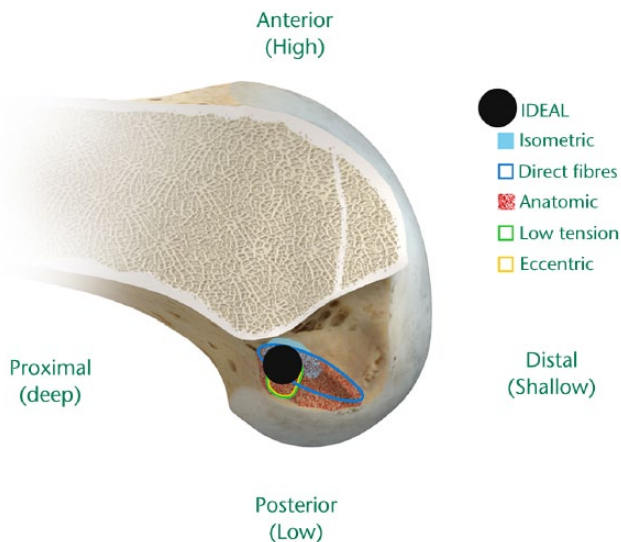


Fig. 2 The correct or IDEAL location for the femoral tunnel (see black circle) is shown superimposed on the topographic outline of the five characteristics that should be fulfilled when judging where to position the femoral tunnel.

that there is adequate triangular space between the lateral edge of the graft and the medial border of the PCL.

If adequate space exists, then the PCL impingement phenomenon cannot take place post-110° in knee flexion. Placing the graft within the native ACL footprints is suggested in order to ensure correct positioning of the graft with minimal risk of both roof and PCL impingement. It was shown that positioning the femoral tunnel at 60° in the coronal plane could lower graft tension by minimising the risk of the ACL graft impinging on the PCL during terminal flexion.<sup>112</sup> As a result, the graft should be *equidistant* between the edge of the PCL and the lower edge of the femoral condyle notch to allow for this condition to exist (Fig. 1).

Finally, an important characteristic that is associated with high survival of the ACL graft is the avoidance of high loading experienced from the graft through the flexion–extension motion of the knee. It has been shown that a graft placed posteriorly experiences high loading forces in extension.<sup>101</sup> In addition, positioning the graft low in the femoral condyle edge can cause high tension in extension. This explains the higher revision rate that has been shown in registry data with the AM portal technique, in comparison to the transtibial technique.<sup>113</sup> In contrast, positioning of the graft anteriorly resulted in force patterns resembling those of the native ACL in both anterior translation and

internal torque application.<sup>101</sup> Therefore, low tension positioning means that the graft should be placed in an area of low tension, so that the graft will not be exposed to forces that can exceed its strength and cause it to fail (Fig. 1).

## Summary

Anterior cruciate ligament tear is a detrimental event for every patient, and appropriate management is important in order to ensure return to pre-injury activity but also to prevent long-term complications due to the knee injury. Despite the presence of several controversies in ACL reconstruction, systematic research was able to provide answers to important questions. Surgical management of ACL tear appears to be the answer in patients who wish to restore their pre-injury activity level. Timing of reconstruction and rehabilitation are extremely important for a successful outcome. Each type of graft has specific advantages and disadvantages; therefore, careful selection of the graft for each patient is important. Finally, the surgical technique should follow the basic principles of ACL biomechanics and anatomy, ensuring ideal graft positioning and a successful clinical outcome.

### AUTHOR INFORMATION

University of California, Davis, USA

Correspondence should be sent to: Nikolaos K. Paschos, Department of Biomedical Engineering, University of California, Davis, CA 95616, USA. Email: paschos.nikolaos@gmail.com

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