ACL reconstruction in the professional or elite athlete: state of the art

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Received 13 June 2020
Revised 27 October 2020
Accepted 7 November 2020
Published Online First 16 February 2021

To cite: Buerba RA, Zaffagnini S, Kuroda R, *et al*. *J ISAKOS* 2021;**6**:226–236.

ABSTRACT

Anterior cruciate ligament (ACL) injuries are on the rise at all levels of sport, including elite athletics. ACL injury can have implications on the athlete's sport longevity, as well as other long-term consequences, such as the development of future knee osteoarthritis. In the elite athlete, ACL injury can also have ramifications in terms of contract/scholastic obligations, sponsorships and revenue-generating potential. Although the goal of anterior cruciate ligament reconstruction (ACLR) is to return any athlete to the same preinjury level of sport, management of ACL injuries in the elite athlete come with the additional challenge of returning him or her to an extremely high level of physical performance. Despite outcome studies after ACLR in elite athletes showing a high return-to-sport rate, these studies also show that very few athletes are able to return to sport at the same level of performance. They also show that those athletes who undergo ACLR have careers that are more short-lived in comparison to those without injury. Thus, returning an elite athlete to 'near peak' performance may not be good enough for the athletic demands of elite-level sports. A possible explanation for the variability in outcomes is the great diversity seen in the management of ACL injuries in the elite athlete in terms of rehabilitation, graft choices, portal drilling and reconstruction techniques. Recently, the advent of anatomical, individualised ACLR has shown improved results in ACLR outcomes. However, larger-scale studies with long-term follow-ups are needed to better understand the outcomes of modern ACLR techniques—particularly with the rise of quadriceps tendon as an autograft choice and the addition of lateral extra-articular tenodesis procedures. The purpose of this article was thus to provide an up-to-date state-of-the-art review in the management of ACL injuries in the elite athlete.

INTRODUCTION

Anterior cruciate ligament (ACL) injury is one of the most common sports-related injuries, and its incidence is increasing at all levels of competition. In a 12-year period in the USA alone, rates of anterior cruciate ligament reconstruction (ACLR) increased significantly from 10.36 to 18.06 and from 22.58 to 25.42 per 100 000 person-years for women and men, respectively.[1] These patterns of increased injury rates have also been observed in elite athletes. Over a 14-year period, 157 ACL injuries were identified in European professional soccer players with a 6% average increase in the ACL injury rate per year.[2] In the National Football League (NFL), there were 219 ACL injuries in just a 3-year period, also with an increased injury rate per year.[3] In collegiate athletics, an analysis of 16 years of injury data from 15 sports from the National Collegiate Athletic Association (NCAA) demonstrated a 1.3% average annual increase in the rates of ACL injuries.[4] In this study, American football had the highest number of reported ACL injuries (53% of all recorded ACL injuries). Women's gymnastics and Spring American football, however, had the highest injury rates out of all sports—both with an injury rate of 0.33 per 1000 athlete exposures (A-Es).[4] Three of the four sports with the highest ACL injury rates were women's sports: gymnastics, soccer and basketball (with 0.33, 0.28 and 0.23 injury rates per 1000 A-Es, respectively).[4]

ACL injuries in the elite athlete tend to occur more frequently during competition rather than during practice. In European professional soccer, the match ACL injury rate was noted to be 20-fold higher than the practice injury rate (0.340 vs 0.017 per 1000 hours).[2] In a 10-year period, the NFL saw more than twice as many ACL tears during games compared with practice (142 vs 67, respectively).[5] In a 5-year period, the ACL game injury rate in NCAA American Football was 8.06 per 10 000 A-Es vs a practice injury rate of 0.8 per 10 000 A-Es.[6]

Although the goal of any ACLR is to return the athlete to his or her preinjury level of performance, management of ACL injuries in the elite athlete come with additional challenges for the team physician. Some of these include managing patient confidentiality with the coaches, athletic organisations and the media—particularly when the ACL injury can have implications regarding contract/scholastic obligations, sponsorships and revenue-generating-potential.[7] Another challenge is managing expectations on return to sport (RTS) at the elite level. In order to win competitions, elite athletes are expected to perform at the highest levels. Consequently, returning an elite athlete to 'near peak' performance may not be good enough for the athletic demands of elite-level sports.[7]

Given the increased ACL injury rates in elite athletes and confidentiality and conflict-of-interest challenges associated with the management of ACL injuries, there is interest in ACL injury prevention strategies and in obtaining excellent outcomes after ACLR in the elite athlete. There have thus been several studies that have evaluated ACL injuries in elite athletes.

Reviews and state-of-the-art or current concept articles

A recent systematic review of the literature after ACLR in elite athletes demonstrated that 83% returned to a similar level of sport and that 5.2% sustained a subsequent graft rupture.[8] Other studies, however, have shown that elite athletes after ACLR have decreased performance and less playing time.[2 9–11] In a 15-year prospective study of European soccer players, only 65% still played at the top level 3 years after ACL rupture.[2] Another study of professional soccer players showed that although the return-to-play (RTP) rate was high after ACLR (93.2%), the athletes exhibited poorer statistical performance, including fewer starts per season and fewer goals/90 min at three seasons post-ACLR.[9] In the US Major League Soccer (MLS), players who undergo ACLR are not used in regular/postseason games as frequently and have shorter careers than their age-matched controls. Similar trends are seen in the National Hockey League (NHL) despite ACL injuries being less common (incidence of 0.42/1000 player game hours).[11] NHL players who had ACLR had significant decreases in goals and points per game/season despite not showing differences in number of games and seasons played compared with matched controls.[11] In the NFL, only 61% of defensive players who underwent ACLR successfully returned to play at least half a season.[10] They also tended to retire sooner and to have fewer starts and a decreased number of solo tackles.[10]

The type of sport played may also affect outcomes after ACLR. A retrospective cohort study of 344 professional athletes from the NFL, NHL, National Basketball Association (NBA), and Major League Baseball demonstrated that NFL athletes had the worst outcomes after ACLR compared with the other sports.[12] They had sustained decreases in performance and earliest retirements.[12] NHL athletes, on the other hand, fared the best. They had the highest rates of RTP, longest postoperative career lengths and no significant changes in performance.[12] A possible explanation for these differences in outcomes likely has to do with the unique physical demands that each sport requires.[12]

Besides inherent differences in athletic demands by sport, an additional explanation for differences in outcomes after ACLR could be that there is significant variability in ACLR technique, graft choice and postoperative protocols in elite athletes. For example, there appears to be regional differences regarding graft choice for ACLR in elite soccer players. Hamstring (HS) autografts are used more often in Sweden than in Europe (67% vs 34%, $p<0.05$), with no apparent differences in time to return to play after ACLR.[13] In the USA, 68% of MLS physicians prefer bone–patellar tendon–bone (BPTB) autograft for ACLR in elite soccer players.[14] This is in line with other sports in the USA as BPTB autograft is the preferred graft of choice for NHL,[15] US Olympic/World Cup Ski/Snowboard,[15] NFL[16 17] and NCAA American Football athletes.[16–18] Despite the popularity of BPTB autograft use in elite athletes in the USA, it should be noted that this is not the most popular graft choice in the world among a diverse patient population. On an international survey on ACLR reconstruction practices of 261 surgeons from 57 countries, HS autograft was the most popular graft choice (63%), followed by BPTB (26%) and then allograft (11%).[19] More specifically, HS were the preferred graft choice for the majority of European surgeons and surgeons from other countries (72% and 66%, respectively), whereas it was the preferred graft choice for only 42% of North American surgeons.[19]

Besides graft choice, there is also significant variability in the tunnel drilling preferences of physicians performing ACLR in elite athletes—despite several studies demonstrating that transtibial drilling frequently fails to place the femoral tunnel within the native ACL footprint[20 21] and that non-anatomical tunnel placement results in inferior restoration of joint kinematics compared with anatomical ACLR achieved by independent, transportal drilling.[22] A study evaluating ACLR practice patterns in elite athletes in the USA showed that 44.7% of surgeons drilled the femoral tunnel through a transtibial portal, 36.2% through an anteromedial (AM) portal and 12.8% by a two-incision technique.[15] In the MLS, surgeons were split regarding femoral tunnel drilling (50% transtibial, 46% accessory medial).[14] Interestingly, on an international survey performed in 2011, 68% of surgeons performed AM portal drilling over the traditional transtibial portal (31%).[19]

To further confound the pooled outcomes after ACLR in elite athletes, techniques have evolved over time and differ by sport. For example, a study evaluated the evolving treatment patterns of NCAA Division I American Football players over a 10-year period and showed that the preference for BPTB reconstruction for primary ACLR increased from 67% in 2008 to 83% in 2016 ($p<0.0001$) among orthopaedic team physicians.[18] Most recently, quadriceps tendon (QT) autograft is being increasingly used as an autograft option[23 24] in all kinds of athletes, including elite athletes. Unfortunately, the cited studies do not report on outcomes after ACLR with QT autograft in elite athletes.

Aside from evolving graft preferences, there is also great variability regarding return-to-play criteria and bracing after ACLR in elite athletes. In the NHL and MLS, 81.8% of surgeons recommended RTS only after an athlete has passed a series of RTS tests (eg, single-leg hop).[15] For MLS athletes, this is usually around the mark of 6–8 months.[14] In the NFL and NCAA, RTS most commonly occurs at least 6 months postoperatively, with some surgeons requiring a normal examination and normal RTS testing.[16] Interestingly, the percentage of NCAA American Football physicians who allowed RTS within 6 months or less after ACLR was significantly higher than that of NFL surgeons ($p<0.05$).[17] There are also differing opinions regarding postoperative bracing among surgeons of professional athletes. In Erickson *et al*'s[15] study, 70.2% of surgeons did not recommend bracing during play on RTS. In NFL and NCAA American football, most surgeons do not recommend a brace on RTS in running backs.[16] Interestingly however, prophylactic knee bracing was used at a significantly higher rate by NCAA teams versus NFL teams (89% vs 28%, respectively; $p<0.05$).[17] In the MLS, 68% of surgeons did not recommend functional bracing; however, surgeons who routinely used functional bracing after ACLR tended to use HS autografts ($p<0.05$).[14]

CURRENT STATE OF THE ART

Prevention

Prevention of ACL injury in elite athletes is a worthy endeavour, given the implications of ACL tear in this group of athletes in terms of the athletes' longevity, scholarships, contracts and revenue-generating-potential. Meta-analyses have shown that preventive training programmes that focus on biomechanics, proprioception and sport-specific training can significantly reduce the per-season risk of ACL injury.[25 26] Particularly in soccer, the FIFA 11+ injury prevention programme has been shown to decrease the rate of ACL injury in collegiate soccer players.[27 28] The FIFA 11+ is an on-the-field dynamic warm-up programme of 15–20 min used before training and games.[27 28] In a prospective, randomised control trial involving 61 collegiate soccer players, there was a 4.25-fold reduction in the likelihood of incurring ACL injury ($p<0.05$) in the FIFA 11+ intervention group. Aside from training programmes, prophylactic bracing has been proposed as a means for ACL injury reduction given that the ligament experiences lower peak strain in a functional brace.[29] In American Football, a randomised trial of 21 570 A-Es showed that prophylactic brace use resulted in a significant reduction in overall knee injuries; however, it could not be determined whether the brace was effective in preventing ACL injuries given the small number of this type of injury in the study.[30] Despite some weak evidence that prophylactic bracing may play a role in ACL injury prevention, controversy remains regarding whether prophylactic knee bracing should be recommended for ACL injury prevention.[31]

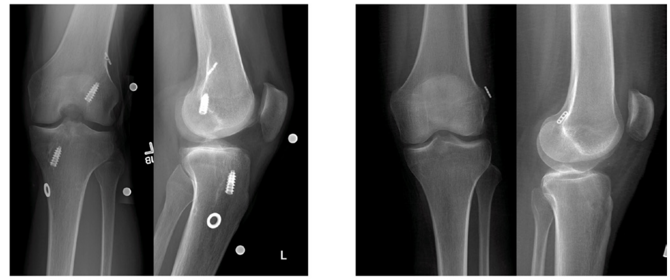
Timing of surgery

The optimal timing of ACLR is an important clinical decision that can affect outcomes. The decision as to when to undergo ACLR may include multiple factors such as the preoperative status of the knee, scholastic obligations, timing during the season, as well as mental preparedness.[32] Although there is some evidence supporting no differences in subjective or objective measures regarding the timing of ACL surgery,[33] late surgery (>5 months) has been associated with worsening of concomitant soft-tissue knee injuries and with the development of new soft-tissue injuries in the knee.[34] Commonly, late-onset soft-tissue injuries preferentially involve the medial compartment of the knee and tend to affect the medial meniscus and medial tibiofemoral cartilage.[34]

Regarding when to operate, there is evidence supporting both acute/early (<48 hours–8 days) and delayed ACLR (>3–10 weeks). Some studies on ACLR outcomes are proponents of delayed reconstruction as there is an increased risk for arthrofibrosis when surgery is performed <3 weeks after injury.[35 36] However, it is believed that the arthrofibrosis develops in these cases likely due to the knee not being ready for surgery rather than the actual timing of surgery itself.[37] It has been shown that outcomes are improved once objective criteria have been met, such as reduced swelling, oedema, hyperthermia and a full range of motion.[37] Preoperative strength can also influence outcomes after ACLR, and thus it is recommended that athletes undergo ACLR once the involved quadriceps muscle strength is at least 80% of the uninjured leg.[38]

Some recent studies using modern ACLR techniques and rehabilitation protocols have shown excellent outcomes after acute/early ACLR. In a prospective cohort study of 160 high-level athletes, Herbst *et al*[39] demonstrated that acute ACLR (<48 hours) had favourable outcomes compared with delayed (during the inflammation-free interval) reconstruction. In this study, there were no differences in outcomes after *isolated* ACLR; however, for combined ACLR and meniscus repairs, the acute group had significantly fewer patients with an extension deficit at 12 months postsurgery compared with the delayed group (3.7% vs 22.2%, respectively; $p<0.05$).[39] In another prospective randomised study, Eriksson *et al*[40] compared ACLR outcomes within 8 days of injury (early) vs ACLR within 6–10 weeks postinjury (delayed). At 6 months of follow-up, the early ACLR group not only did have significantly less muscle atrophy but also did have a higher proportion of patients who passed or nearly passed the one-legged hop test compared with the delayed group (47% vs 21%, respectively, $p=0.009$).[40]

Although there is evidence supporting both acute and delayed ACLRs, operative timing should be individualised to each athlete's unique situation (ie, type of sport, extent of injury, preoperative status of the knee, scholastic and professional obligations, timing during the season and mental preparedness)[32] If the patient is somehow unable to undergo acute ACLR, it is thus imperative that the patient meets objective criteria such as reduced swelling, oedema, hyperthermia, full range of motion and improved quadriceps strength prior to ACLR.[37 38]



A B

Figure 1 (A) AP and lateral X-rays of a two-times failed non-anatomical ACLR via a transtibial technique. Note how the femoral tunnel is anterior and vertical. (B) AP and lateral X-rays of an anatomical, soft-tissue quadriceps tendon autograft ACLR with an independent transportal drilling technique. Note how the femoral tunnel is more posterior and oblique. ACLR, anterior cruciate ligament reconstruction; AP, anteroposterior.

Individualised, anatomical ACLR

One of the most recent advances in ACLR, particularly in elite athletes, has been the concept of anatomical, individualised ACLR.[41 42] In addition to having different athletic needs based on their particular sport, athletes also have different anatomical variations. Therefore, a one-size-fits-all approach or a non-anatomical approach to ACLR could explain some of the variability seen in outcomes after ACLR.[43] Traditional transtibial ACLR techniques have been shown to place the graft outside of the native ACL femoral footprint.[20 21] Also, most non-anatomical tunnel placement techniques have been demonstrated to result in inferior joint kinematic restoration compared with anatomical ACLR achieved by independent, transportal drilling.[22] More recently, a systematic review with a minimum 10-year follow-up demonstrated that anatomical ACLR reduces the risk of post-traumatic osteoarthritis compared with non-anatomical techniques.[44] An example of a two-times failed non-anatomical ACLR with a transtibial technique is shown in figure 1A. An example of an anatomical, soft-tissue QT autograft ACLR with an independent, transportal drilling technique is shown in figure 1B.

A key component to performing anatomical, individualised ACLR in the elite athlete is an understanding of the variation that exists among individuals regarding the size and shape of the native ACL and its femoral and tibial insertion sites.[45 46] Therefore, anatomical, individualised ACLR aims to restore the function of the native ACL by customising ACLR to best match the patient's native ACL insertion, knee bony anatomy and particular athletic needs.[45 46] Using this concept, the treating surgeon should thus choose the particular graft and reconstruction method (single vs double bundle) that will provide the best results based on the individual athlete's anatomy and sport.

The basis of anatomical individualised ACLR begins with meticulous preoperative planning. Given the anatomical variations,[45 46] preoperative MRI measurements need to be performed in order to determine the best reconstruction method for each patient (figure 2). Based on MRI measurements, the surgeon can determine preoperatively the cross-sectional area of the available grafts so that the chosen graft for ACLR can restore 50%–80% of the native ACL's tibial insertion site.[47] For example, when a patient has a large tibial insertion area as shown in figure 2A,B, full-thickness QT autograft would restore a larger percentage of the patient's native ACL tibial insertion site than a BPTB autograft, since it is nearly double in size (figure 2D). A double-bundle reconstruction could also achieve a larger reconstruction than a single-bundle reconstruction, pending on graft sizes.

Although the goal is to restore 50%–80% of the native ACL footprint, care should also be taken to avoid postoperative notch impingement with a large or non-anatomically placed graft. This can be prevented by preoperatively measuring the intercondylar notch width (figure 2C) and choosing the right size graft, appropriate reconstruction method and anatomical placement. A decision-making flowchart[48] and checklist[42] for anatomical, individualised ACLR have been previously described in detail, but in general, a single-bundle reconstruction with a large graft or a double-bundle reconstruction can be performed when a patient has a large tibial insertion site size (anteroposterior (AP) length > 14 mm) and a large intercondylar notch (width > 14 mm). A single-bundle technique with a smaller graft is recommended for small tibial insertion sites (< 14 mm in length) and narrow notches (< 12 mm in width).[46 48] It is also recommended that

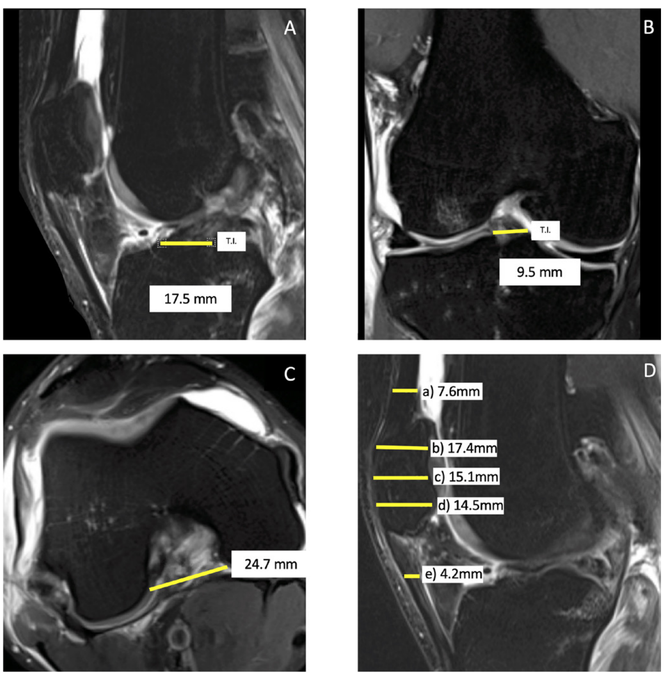


Figure 2 Preoperative planning measurements for anatomical, individualised ACLR after an ACL tear of an elite soccer player. (A) Sagittal MRI measuring the AP length of the TI of the native ACL at its mid-substance. (B) Coronal MRI measuring the medial–lateral length of the TI of the native ACL at its mid-substance. (C) Axial MRI measuring the intercondylar notch width. (D) Sagittal MRI showing the AP thickness of the (a) QT, the (b) superior, (c) middle and (d) inferior patellar bones, and (e) the patellar tendon. Based on the method described by study by Guenther *et al*,[47] the TI area was calculated to be 130.6 mm^2. Given the large AP TI site (>14 mm), the large intercondylar notch (>14 mm) and large TI area, the patient was a candidate for either a single-bundle ACLR with a graft of large diameter or a double-bundle ACLR.[48] Based on Guenther *et al*.'s study,[47] it was calculated that a 10 mm QT autograft would restore 73% of the native TI site (goal 50%–80%). The patient thus underwent a single-bundle anatomical ACLR with a QT autograft with patellar bone block. Bone–patellar tendon–bone was not chosen as the patellar tendon graft was nearly half the size of the QT graft (4.2 mm vs 7.6 mm), and it would not restore the patient's native TI site anatomy. A double-bundle or single-bundle HS ACLR was not chosen, given the increased failure rates of HS ACLR[53 54] and given that soccer players heavily rely on their HSs for their sport and that HS ACLR can lead to residual knee flexion weakness.[49 50 53] ACL, anterior cruciate ligament; ACLR, anterior cruciate ligament reconstruction; AP, anteroposterior; HS, hamstring; QT, quadriceps tendon; TI, tibial insertion.

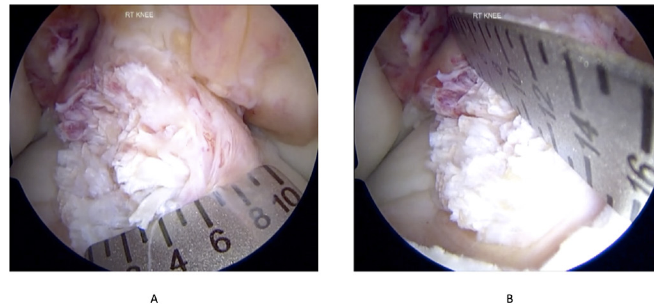


Figure 3 Intraoperative measurements of the anterior cruciate ligament tibial insertion mid-substance width (A) and length (B) using an arthroscopic ruler.

individual anatomical measurements be double-checked intraoperatively with an arthroscopic ruler prior to finalising the ACLR reconstruction method (figure 3). Understanding each patient's unique anatomy is therefore crucial for anatomical, individualised ACLR as the patient's native knee and ACL anatomy should guide the surgeons towards the most appropriate ACLR for the athlete (ie, graft type, tunnel size, double-bundle vs single-bundle reconstruction).[43]

Graft choice in the elite athlete

The decision behind individualised graft choice should also be based on the elite athlete's particular sport and previous ACLR in case of revisions. For example, the harvesting method of BPTB autograft has been associated with anterior knee pain,[49–51] and thus the use of BPTB autograft for ACLR generally is not recommended in athletes whose sport requires much kneeling, such as wrestlers or judo athletes.[49 50] Similarly, there is a disadvantage for HS ACLR for athletes whose sports rely heavily on their HSs, such as sprinters due to the HS and knee flexion weakness associated with HS ACLR.[49 50 52] An in-depth discussion of ACLR graft choice is beyond the scope of this state-of-the-art review, but there are salient points regarding graft choice in the elite athlete that should be considered by the treating surgeon.

BPTB autograft

Outcomes after ACLR with the use of BPTB have been overall good,[53 54] and BPTB has been the graft of choice for the majority of elite athletes in the USA.[14–18] Recent studies and meta-analyses have found that BPTB autografts have lower failure rates[53 54] and less residual anterior knee laxity and instability compared with HS autografts.[51] Proponents of BPTB also cite the advantages of bone-to-bone healing compared with soft-tissue allografts since bone-to-bone healing is similar to fracture healing and it is faster and stronger than soft-tissue healing.[55] It has also been shown that bone grafts can be healed to the host bone within 6 weeks, whereas soft-tissue grafts take 8–12 weeks to fully incorporate.[56] Most of the complications associated with BPTB are almost exclusively related to the graft harvesting technique, such as patellar fractures, patellar tendon rupture and patellar tendonitis.[57] Anterior knee pain is also a common problem.[49–51] In a meta-analysis of 21 studies, BPTB autografts had an incidence of anterior knee pain of 17.4% vs 11.5% in HS autografts.[51] There is, however, some uncertainty regarding the actual nature of the anterior knee pain as some studies have actually shown no difference in the incidence of anterior knee pain between BPTB autograft and allografts.[58] It has been suggested that anterior knee pain after ACL surgery may be related to loss of motion and poor rehabilitation rather than graft choice.[59]

HS autograft

Given the complications and disadvantages associated with BPTB autografts, HS autograft (semitendinosus and gracilis muscles) is considered a good option for ACLR, for certain patient populations[50]; however, it has most recently been shown that there is increased failure rates when compared with BPTB autografts.[54] Despite the higher failure rates, HS autografts do offer advantages over BPTB autografts, such as greater cross-sectional area, avoidance of the extensor mechanism in the graft harvesting process and being an option for the skeletally immature.[50] Disadvantages include prolonged healing times, unpredictable graft size, knee flexion weakness, bone tunnel widening and higher infection rates.[49 50 60]

In general, if the surgeon believes that HS is the best option for the patient's anatomical, individualised ACLR, then conjunction with a lateral extra-articular tenodesis (LET) may be considered. This is because a recent randomised controlled trial (RCT) showed that the addition of LET to HS autograft ACLR has led to a clinically relevant and statistically significant reduction in graft failure (11% in HS ACLR alone vs 4% HS ACLR+LET, relative risk ratio (RRR) 0.67, 95% CI 0.36 to 0.83, $p<0.001$) and persistent rotatory laxity at 2 years after surgery.[61]

QT autograft

The QT autograft has gained popularity as an alternative graft option for primary or revision ACLR due to its versatility. It can be harvested as a full or partial thickness graft with or without a bone block (BB).[23] Compared with a BPTB autograft, QT is longer, wider and has a higher tensile strength and about 50% more mass.[62] Its cross-sectional area is also nearly twice as big as that of a BPTB autograft (figure 2D).[63] Studies have also shown similar patient-reported outcomes with QT when compared with BPTB autograft.[24] Other advantages include less risk of infection compared with HS,[64] less anterior knee pain,[65] less donor site morbidity, less risk of injury to the infrasaphenous branch and low rate of quad strength deficit.[23] It can also be used in the skeletally immature.[66] QT complications include donor site pain (less common than BPTB, however), rectus femoris retraction, bleeding (QT has a rich blood supply) and fractures of the patella after QT harvest with BB.[24 67 68]

A systematic review of QT versus BPTB and HS showed no significant differences in laxity, patient satisfaction or patient-reported outcomes between QT and either BPTB or HS.[67] There were also no differences in knee stability testing (KT-1000, pivot shift rating and Lachman testing).[67] QT can also be used in primary and revision ACLRs based on tunnel size, tunnel position and previous graft used.[23]

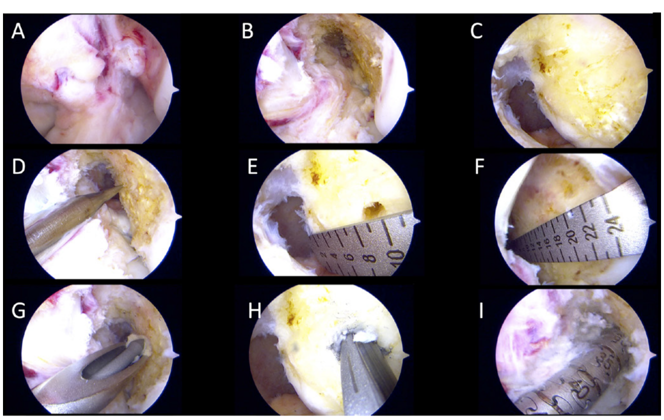


Figure 4 Anatomical single-bundle reconstruction with quadriceps tendon autograft of the left knee. (A) The torn ACL is shown. (B) Anterolateral portal view of the femoral insertion of the ACL is shown after debridement. (C) The femoral insertion site is shown with the camera in the AM portal. The anatomy of the posterior femoral condyle is appreciated. (D) The anatomical femoral insertion of the ACL is marked with an awl. (E) The centre of the planned tunnel is measured to verify if the planned tunnel size will provide a 1–2 mm back wall. (F) The femoral insertion site and the size of the lateral femoral condyle are measured. (G) The flexible guidewire is placed in the planned anatomical ACL femoral insertion. (H) Prior to flexible guidewire drilling, the spot for the tunnel is verified by placing the camera in the AM portal to visualise the lateral femoral condyle and the native ACL femoral insertion. (I) The femoral tunnel is reamed with a flexible reamer over the guidewire in the centre of the native ACL femoral insertion site (posterior to the intercondylar ridge) to its appropriate length. ACL, anterior cruciate ligament; AM, anteromedial.

Allograft

Although there are relative advantages of allografts such as shorter operative times, predictable graft size, no harvest-site morbidity and easier recovery in the postoperative period,[19] the use of allograft is generally not recommended for primary ACLR in elite athletes. Studies have consistently shown that allografts have a higher rerupture rate than autografts in young, athletic individuals.[69] In a recent systematic review, active patients <25 years of age had a 9.6% graft rupture rate with autograft vs 25.0% with allograft.[70] There is also evidence that athletes have an improved RTS rate when undergoing ACLR with autograft rather than allograft.[71] Special circumstances that would potentially justify the use of allograft in an elite athlete would be multiligament knee injuries, revision ACLRs or cases in which autograft tissue is inadequate.[72]

Anatomical reconstruction technique

Knowledge of the ACL anatomy and its surrounding structures is essential for performing anatomical ACLR. A thorough understanding of bony landmarks is thus essential for anatomical placement of the femoral tunnel. More specifically, the surgeon should remember that the intercondylar ridge makes up the most anterior border of the native ACL insertion site and that the bifurcate ridge runs posterior and perpendicular to the intercondylar ridge, dividing the insertion sites for the posterolateral and AM bundles.[73] These are essential to know as bony landmarks can guide anatomical femoral tunnel placement in cases in which the ACL remnant may have dissolved or may have been debrided, such as chronic ACL cases or non-anatomical ACLR revision cases.[73]

As discussed previously, another key component to anatomical ACLR that must be kept in mind is that there is variation among individuals in the size and shape of the ACL.[45] Understanding each patient's unique anatomy is crucial for anatomical ACLR as the morphology of the native ACL and of the knee should direct the surgeon towards the most appropriate procedure for the patient (ie, single-bundle or double-bundle reconstruction, graft type and tunnel size).[43] An anatomical femoral tunnel can be drilled using an independent transportal drilling technique via the AM portal or via an outside-in technique. A step-by-step anatomical, single-bundle ACLR with QT autograft is shown in figures 4 and 5.

Rotatory knee instability

There has been a recent increased focus on understanding the anterolateral (AL) structures of the knee and their biomechanical role since the rediscovery of the anterolateral complex (ALC)

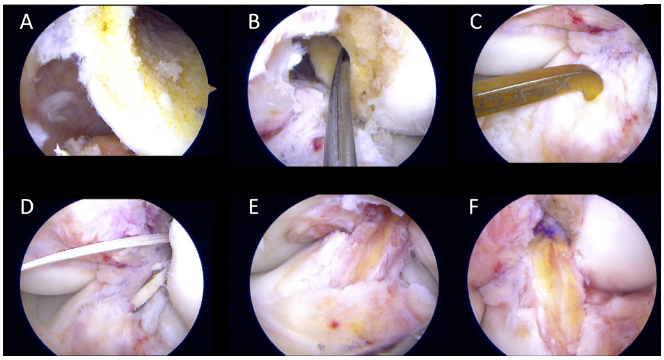


Figure 5 Anatomical single-bundle reconstruction with quadriceps tendon autograft of the left knee (continued). (A) View from the AM portal to verify a 1–2 mm back wall after drilling an anatomical femoral tunnel. (B) View from the AL portal of the anatomical femoral tunnel. (C) The location of the native ACL tibial insertion is localised with the drill guide. (D) The tibial tunnel is drilled in the centre of the native ACL insertion site. (E) The final result after passing the graft, viewed from the AL portal. (F) The final result after passing the graft, viewed from the AM portal. AL, anterolateral; AM, anteromedial.

in the literature.[74] Given the association between ACL tear and AL rotatory instability likely due to injury of the lateral soft-tissue envelopes,[75] the addition of a lateral extra-articular tenodesis (LET) to the intra-articular reconstruction was proposed with the aim to better address residual rotatory knee laxity.[76] In both cadaveric and time-zero in vivo studies, the addition of a LET resulted in a superior reduction of AP and rotational laxity compared with isolated intra-articular procedures[77]; however, the clinical relevance of these studies has not been fully clarified yet.

Given that the structure and function of the ALC has created some controversy since its 'rediscovery', the ALC Consensus Group was formed from experts in the field in order to produce consensus statements regarding the anatomy and biomechanical properties of the ALC as well as indications for LET.[76] A consensus statement worth highlighting is that currently, clinical evidence is lacking to support LET as an augmentation procedure to ACLR and that possible indications for LET could be revision cases, high-grade pivot shifts, generalised ligamentous laxity and young patients returning to pivoting activities.[76]

In elite athletes, there are some outcomes data on ACLR with the addition of LET. In an analysis of a series of patients that included a large proportion of elite athletes, those treated with a combined ACL plus a LET (in the form of a modified Lemaire, figure 6) had a reduced prevalence of rotational instability in the early-stage postsurgical period (mean of 6.3 month postsurgery) in comparison to the isolated ACLR group.[78] The ACLR+LET group also did not show any loss of motion despite the increased restraint.[78] In a 20-year minimum follow-up study, a group of patients engaged in cutting sports who underwent an over-the-top ACLR coupled with LET had satisfactory results in laxity control, without the development of lateral knee osteoarthritis.[79]

Higher level of evidence studies have recently been published to help better understand the indications and clinical outcomes after extra-articular procedures. In a prospective comparative study of 502 young patients participating in pivoting sports, the rates of graft failure in the groups who underwent HS ACLR with an extra-articular procedure were 2.5 and 3.1 times less than those who underwent isolated BPTB or HS ACLR

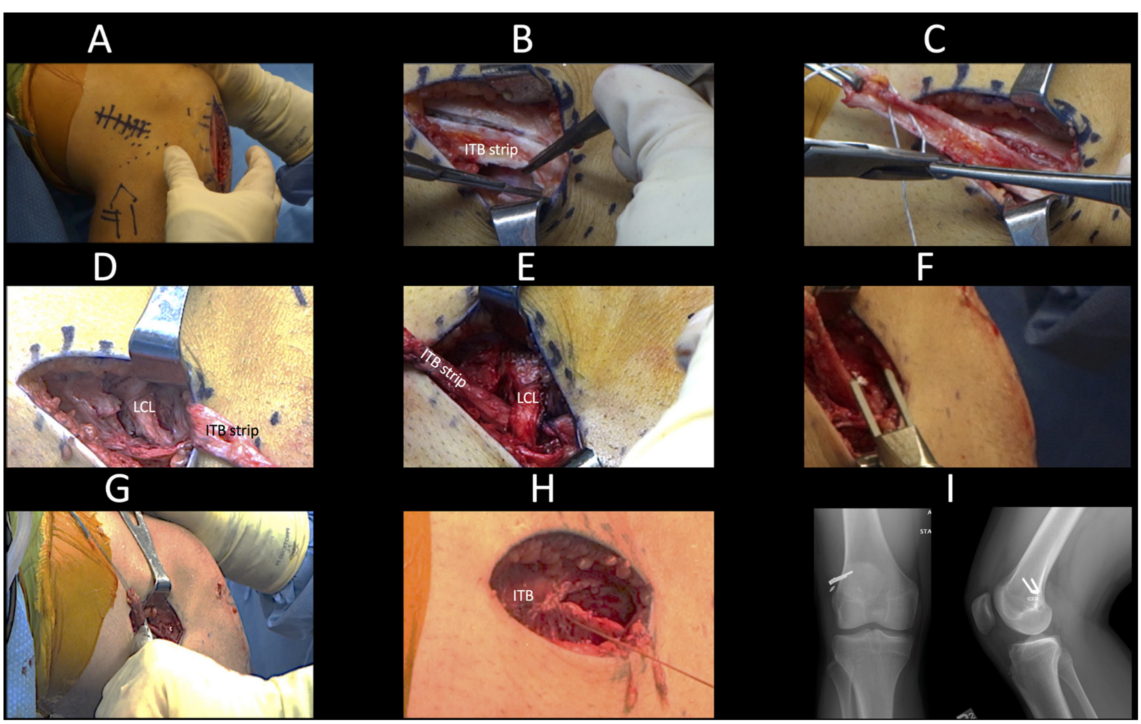


Figure 6 Modified LET technique. (A) The lateral incision is planned centred on the distal ITB. The surgeon's thumb is localising Gerdy's tubercle. (B) A full thickness 10×80 mm strip of the central one-third of the ITB is dissected. (C) The proximal end of the ITB strip is secured with non-absorbable sutures. (D) The LCL is identified. (E) The ITB strip is shuttled deep to the LCL. (F,G) A staple is used to secure the ITB strip to the lateral femur epicondyle with the appropriate amount of tension. (H) The ITB defect is closed proximally, but a portion is left open distally to no overtension the repair. (I) Anteroposterior and lateral X-rays after an ACLR+LET procedure demonstrating the appropriate location of the staple. ACL, anterior cruciate ligament; AM, anteromedial; ITB, iliotibial band; LCL, lateral collateral ligament; LET, Lemaire lateral extra-articular tenodesis.

Box 1 Key articles on anterior cruciate ligament reconstruction in the elite athlete

1. Erickson BJ, Harris JD, Fillingham YA, *et al*. Orthopaedic Practice Patterns Relating to Anterior Cruciate Ligament Reconstruction in Elite Athletes. *Am J Orthop (Belle Mead NJ)*. 2015;44(12):E480–5.
2. Waldén M, Hägglund M, Magnusson H, Ekstrand J. ACL injuries in men's professional football: A 15 year prospective study on time trends and return-to-play rates reveals only 65% of players still play at the top level 3 years after ACL rupture. *Br J Sports Med*. 2016;50(12):744–50. doi:10.1136/bjsports-2015–0 95 952.
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4. Mai HT, Chun DS, Schneider AD, *et al*. Performance-Based Outcomes after Anterior Cruciate Ligament Reconstruction in Professional Athletes Differ between Sports. *Am J Sports Med*. 2017;45(10):2226–32. doi:10.1177/0363546517704834.
5. Silvers-Granelli HJ, Bizzini M, Arundale A, Mandelbaum BR, Snyder-Mackler L. Does the FIFA 11+Injury Prevention Programme Reduce the Incidence of ACL Injury in Male Soccer Players? *Clin Orthop Relat Res*. 2017;475(10):2447–55. doi:10.1007/s11999-017-5342-5.
6. Guenther D, Irarrázaval S, Albers M, *et al*. Area of the tibial insertion site of the anterior cruciate ligament as a predictor for graft size. *Knee Surgery, Sport Traumatol Arthrosc*. 2017;25(5):1576–82. doi:10.1007/s00167-016-4295-7.
7. Samuelsen BT, Webster KE, Johnson NR, Hewett TE, Krych AJ. Hamstring Autograft vs Patellar Tendon Autograft for ACL Reconstruction: Is There a Difference in Graft Failure Rate? A Meta-analysis of 47 613 Patients. *Clin Orthop Relat Res*. 2017;475(10):2459–68. doi:10.1007/s11999-017-5278-9.
8. Sheean AJ, Musahl V, Slone HS, *et al*. Quadriceps tendon autograft for arthroscopic knee ligament reconstruction: Use it now, use it often. *Br J Sports Med*. 2018;52(11):698–701. doi:10.1136/bjsports-2017–0 98 769.
9. Rothrauff BB, Jorge A, de Sa D, Kay J, Fu FH, Musahl V. Anatomic ACL reconstruction reduces risk of post-traumatic osteoarthritis: a systematic review with minimum 10 year follow-up. *Knee Surgery, Sport Traumatol Arthrosc*. 2019;28(4):1072–84. doi:10.1007/s00167-019-05665-2.
10. Getgood AMJ, Bryant DM, Litchfield R, *et al*. Lateral Extra-articular Tenodesis Reduces Failure of Hamstring Tendon Autograft Anterior Cruciate Ligament Reconstruction: 2 Year Outcomes From the STABILITY Study Randomised Clinical Trial. *Am J Sports Med*. 2020;48(2):285–97. doi:10.1177/0363546519896333.

reconstruction, respectively, at 2 years of follow-up.[80] In a recent randomised clinical trial of patients younger than 25 years involved in pivoting sports or with a high-grade pivot shift at baseline evaluation, the addition of a LET to a single-bundle HS ACLR significantly reduced the graft rupture rate and persistent rotatory laxity at a 2-year follow-up compared with isolated ACLR.[61] These results, therefore, suggest that in elite athletes, the addition of a LET should always be considered when using HS autografts—particularly when the athlete is young and has a high-grade knee rotatory laxity.

Postoperative rehabilitation and RTS

Due to the prolonged time away from competition, ACL injury can be a threat for the athlete's career. Consequently, RTS can be a challenging topic for the elite athlete and surgeons. Two key goals of the RTS strategy are the achievement of a preinjury level of sport[81] and the prevention of secondary ipsilateral or contralateral ACL injury.[82] While more than 90% of athletes returned to competitions within a year after ACLR, only about two-thirds of athletes were engaged at the same level of sport 3 years after RTS.[2] The rate of subsequent ACL surgery ranged from 5% to 12%,[8] and most of the secondary injuries tended to occur early in the RTS period and in the contralateral knee.[83] Notably, the secondary injury rate was significantly higher in younger athletes, nearly 25%.[84]

Many factors that may have an influence on RTS have been identified in literature. Therefore, an analysis of preoperative, surgical and postoperative variables and their relationships must be considered in targeting the recovery pathway of elite athletes.[85] Regarding the preoperative variables, elite sport level, younger age and male gender have been positively associated with RTS.[81] Considering the surgical factors, ACL revisions are associated with a lower RTS rate.[86] Although there is great variability in graft choice and surgical technique,[13–18] in general, outcomes with the use of BPTB autograft are overall better than HS autograft.[51 53 54 87] This is also the case in elite athletes as a recent cohort study reported a lower reinjury risk in level 1 athletes who underwent BPTB ACLR versus those who underwent HS reconstruction.[87] It should also be noted that concomitant injuries such as the presence of a knee cartilage injury or a meniscal tear are associated with a decrease in RTS.[88] Regarding associated procedures, longer time to return to preinjury levels and higher incidence of adverse effect were reported among elite football players who underwent associated lateral meniscectomy, compared with players who underwent associated medial meniscectomy.[89] Furthermore, elite players with associated meniscectomy had a significantly shorter career compared with both uninjured and ACL-isolated patients.[90]

In addition to preoperative and surgical variables, postoperatively, performance on tests such as the one-legged hop and having a positive psychological response have been shown to have an influence in returning to a preinjury level of sport.[81] In line with the concept of anatomical, individualised ACLR, the individualised recovery pathway was introduced with the aim to obtain a fast and complete RTS while avoiding reinjury.[91] Following time-based criteria, a minimum of at least 9 months between reconstruction and RTS is recommended,[82] respecting the graft biological healing timeline. However, in order to return

Box 2 Validated outcome measures and classifications for return to sport

- International Knee Documentation Committee (IKDC) objective.
- IKDC subjective.
- Lysholm score.
- Tegner Activity Score.
- Muscle strength (80% of contralateral limb).
- One-legged hop test.
- Sports-specific drills.

Box 3 Key issues of individualised graft selection for anterior cruciate ligament reconstruction (ACLR)

Bone–patellar tendon–bone autograft
- Considered 'gold standard' by many.
- Should be used only in the skeletally mature.
- Avoid in sports with kneeling (ie, wrestling and judo).
- Can be used in patients with narrow notches or small tibial anterior cruciate ligament (ACL) insertions.

Hamstring (HS) autografts
- Improved results when performed in conjunction with LET.[61]
- Can be used in skeletally mature or immature.
- Avoid in sports that rely heavily on HSs (ie, sprinters).
- Can be used in ACLs with large footprints.
- Can be used for single-bundle or double-bundle reconstructions.

Quadriceps tendon autografts
- Can be used with or without bone block (BB).
- Can be used in skeletally mature or immature (if no BB used).
- Can be used in ACLs with large footprints.
- Can be used for single-bundle or double-bundle reconstruction.
- Can be performed in athletes who kneel (ie, wrestling and judo) or in those who rely on HSs (ie, sprinters).
- Excellent revision option.

Allografts
- Documented high failure rates in young athletes.
- Can be used in multiligament knee injuries, revision ACLR or when other autograft tissues are inadequate.

Box 5 Tips and tricks for anatomical anterior cruciate ligament reconstruction

- Completely debride the femoral anterior cruciate ligament (ACL) insertion and visualise the back wall.
- Use an arthroscopic awl to mark anatomical ACL femoral insertion. Verify this by placing the camera in the anteromedial (AM) portal to visualise the back wall of the lateral femoral condyle. Use a ruler to verify there will be sufficient back wall based on the chosen reamer size.
- Use an AM drilling technique with a flexible guidewire and reamer.
- Prior to reaming, verify the flexible guidewire is in the anatomical ACL femoral insertion by placing camera in the AM portal.
- Drill tibial tunnel at the footprint of the native tibial ACL insertion. Ream to the appropriate size so that the chosen graft can restore 50%–80% of the tibial footprint.

to sports efficiently, combining time from ACLR with subjective and objective criteria represents a useful approach to managing the RTS process.[92] The criteria-based rehabilitation concepts allow for time-optimised progress on the basis of defined criteria, such as clinical assessment, performance tests and subjective outcomes.[91] Clinical factors are crucial in the return-to-activity period (between surgery and the start of sport-specific rehabilitation) and must be assessed also in the RTS phase (between start of sport-specific rehabilitation and return-to-team phase). The main clinical criteria are presence of swelling, recovery of range of motion, the assessment of articular laxity and patient-reported score.[93] Regarding rehabilitation factors, higher postoperative quadriceps strength and fewer episodes of instability were correlated with a higher RTS rate.[94] Recovery from the neuromuscular impairment of surgery is also important for RTS.[95] Functional tests and lower isokinetic strength measurements have been developed to aid in the RTS decision making, and many rehabilitations protocol have been proposed.[96 97] However, the ideal RTS test battery has not been established yet.[98] The most commonly reported functional test were the hop test and the strength assessment test,[98] which were generally reported in Limb Symmetry Index, of which values higher than 85% were considered in normal range.[99] Furthermore, during the sport-specific rehabilitation training and before the return to team, qualitative movement pattern evaluation associated with a complete on field rehabilitation programme should be encouraged. The purpose of this is to assess neuromuscular control in high-speed specific athletic tasks.[97]

Psychological factors could also have an important influence on the athlete's ability to return to sport.[100] Kinesiophobia (fear of reinjury or movement), self-efficacy and depression could affect the athlete during the rehabilitation. In fact, one of the most debilitating psychological factors affecting clinical outcomes following ACLR is clinically diagnosed depression, which has been identified preoperatively in nearly 40% of ACLR candidates.[100] Therefore, it is recommended to identify and address psychological factors during the recovery process to better prepare the athlete to return to competition.[100] Interventions

Box 4 Essential measurements for anatomical, individualised anterior cruciate ligament reconstruction (ACLR)

- Anteroposterior (AP) length of tibial ACL insertion at its midsubstance on sagittal MRI.
- Medialateral length of tibial ACL insertion at its midsubstance on coronal MRI.
- Intercondylar notch width on axial MRI.
- Determine preoperatively the cross-sectional area of the available grafts so that the chosen graft for ACLR can restore 50%–80% of the native ACL's tibial insertion (TI) site.[47]
- Verify measurements intraoperatively with an arthroscopic ruler.
- Single-bundle ACLR with a graft of large diameter or double-bundle reconstruction is recommended when the AP TI site is >14 mm and the intercondylar notch width is >14 mm.

Box 6 Major pitfalls

- Not appreciating high-grade rotatory knee instability
- Not hyperflexing the knee when using the flexible reamer can lead to short femoral tunnels.
- Not being perfectly centred when harvesting a quadriceps tendon with a bone block can increase the risk of patella fracture.
- Performing a one-approach-fits-all ACLR (ie, bone–patellar tendon–bone ACLR in kneeling athletes) can lead to suboptimal outcomes.
- Not setting of appropriate expectations on the timeline for return to sport in elite athletes (closer to 9–12 months).

Box 7 Future perspectives

- Long-term and larger-scale studies are needed to reveal the effectiveness of anterior cruciate ligament injury prevention programmes.
- Anatomical, individualised anterior cruciate ligament reconstruction (ACLR) has the potential of improving ACLR outcomes in the elite athlete, but larger scale studies with long follow-ups are needed
- Research on failure rates using different tendon autografts.
- Need for defining indications for lateral extra-articular associated procedures.

such as relaxation, guided imagery, behaviour counselling, goal setting and coping modelling have shown mixed results but overall seem promising.[100] No studies appear to have investigated the use of medication to address psychological factors following ACLR.[100] Further research is thus needed to better understand which interventions are the most effective in having the patient RTS at a high level and at which time during the rehabilitation phase they should be implemented (preoperatively or throughout postoperative rehabilitation).[100]

Geographical differences

Some of the main differences that need to be kept in mind when discussing ACLR in the elite athlete are that there are geographical differences in the types of professional and collegiate sports played in different regions of the world. Association football or soccer is by far the most popular sport in the world. Based on revenue alone, it could be argued that American football is the most popular sport in the USA. Furthermore, American football is also rarely played in other countries at elite levels. Thus, it should be of no surprise that the athletic demands and athletic build of American football players versus soccer players are quite different. It is therefore difficult to group international ACLR outcomes without taking the type of sport into consideration—hence the argument for an anatomical, individualised ACLR in the elite athlete.[46] Additionally, not all ACL injuries can be treated the same as there is further evidence that the type of sport played may influence preinjury RTS rates and reinjury rates. As discussed earlier, out of all professional sports leagues in the USA, NFL athletes had the worst outcomes after ACLR, whereas NHL athletes fared the best.[12]

Another major international difference is that athletic scholarships are common in the USA, whereas in many other countries, they are rare or non-existent—particularly for women. Consequently, team physicians in the USA have to treat elite student athletes and not just elite athletes. When it comes to injury in collegiate athletics, both athletes and physicians must abide by the NCAA rules and regulations, particularly when scholarships are at stake. Additionally, given the increased number of female student athletes in the USA, collegiate team physicians in the USA need to be comfortable managing ACL injuries in women elite athletes as three of the four sports with the highest ACL injury rates in the NCAA were women's sports: gymnastics, soccer and basketball.[4] Lastly, although allograft is generally not recommended for ACLR in the elite athlete, allografts are not as widely available in other countries outside of the USA.[19]

CONCLUSIONS AND FUTURE PERSPECTIVES

The management of ACL injury in the elite athlete is a challenging endeavour, given its implications on the athletes' longevity, contractual or scholastic obligations and revenue-generating-potential. Unfortunately, if current trends continue,[1–4] ACL injuries are expected to keep rising unless the implementation of effective ACL injury prevention strategies takes place. Although more long-term data are needed, there is evidence supporting the use of ACL injury prevention programmes[25–28] and prophylactic bracing[29–31] to reduce ACL injury incidence. Despite a high RTS rate in elite athletes, few athletes attain RTS to the same level of performance, and their careers may be more short-lived.[2 8–12] A possible explanation for this is the increased variability in ACLR techniques, portal drilling, graft choices, patient's anatomy,and demands of each particular sport.[13–18] Given the advent of anatomical, individualised ACLR, it remains to be seen if ACLR outcomes improve in the elite athlete with modern techniques, but early data show encouraging results.[43–48] In addition to anatomical individualised surgery, it is likely that, in the near future, there may be a decrease in the use of HS autograft ACLR, given its inferior results,[53 54] and a rise in QT autograft, given its versatility and good outcomes.[23 24 62 67] A prospective RCT by the Stability group has shown that the addition of LET has promise in improving ACLR outcomes in patients with high-grade rotatory knee instability after HS autograft ACLR.[61] The Stability group is now currently developing the protocols for a second, prospective RCT in which outcomes after ACLR will be evaluated in patients undergoing BPTB or QT ACLR with or without LET. We thus encourage surgeons treating elite athletes to stay up-to-date in the ACLR literature, and to publish their outcomes as RTS to the same level should be the goal for every athlete—elite or not—undergoing ACLR.

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Acknowledgements We thank Freddie H Fu, MD, for providing copies of his research articles, as well helping us in the development of some of our images.

Contributors RAB and VM: manuscript writing and conception, editing, figures, literature review, final manuscript approval. SZ: manuscript writing (rehab and rotatory instability), editing, literature review and final manuscript approval. RK: manuscript writing (international perspectives), editing, literature review and final manuscript approval.

Funding The authors have not declared a specific grant for this research from any funding agency in the public, commercial or not-for-profit sectors.

Competing interests None declared.

Patient consent for publication Not required.

Provenance and peer review Commissioned; externally peer reviewed.

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