■ CHILDREN'S ORTHOPAEDICS

Current concepts of the management of anterior cruciate ligament injuries in children

N. Al-Hadithy,
A. L. Dodds,
K. S. N. Akhtar,
C. M. Gupte

From Imperial College London, London, United Kingdom

Recent reports have suggested an increase in the number of anterior cruciate ligament (ACL) injuries in children, although their true incidence is unknown.

The prognosis of the ACL-deficient knee in young active individuals is poor because of secondary meniscal tears, persistent instability and early-onset osteoarthritis. The aim of surgical reconstruction is to provide stability while avoiding physeal injury. Techniques of reconstruction include transphyseal, extraphyseal or partial physeal sparing procedures.

In this paper we review the management of ACL tears in skeletally immature patients.

Cite this article: *Bone Joint J* 2013;95-B:1562–9.

Mid-substance injuries of the anterior cruciate ligament (ACL) in children and adolescents were traditionally thought to be rare,[1] but a number of recent studies suggest that their incidence is increasing.[2] Possible explanations include raised awareness of the injury, improved imaging techniques, more demanding sporting activities in the young,[3] as well as the increase in obesity leading to increased stresses on the knee ligaments.

Treatment is directed towards restoring stability to the knee while minimising the risk of secondary meniscal and physeal injury from surgery. It used to be thought that surgery should be delayed until skeletal maturity to prevent violation of the physes and consequent disturbance of growth. It is now generally accepted that operative intervention gives a better functional outcome.[4,5] However, in a recent systematic review, Moksnes et al[6] found that studies promoting surgery had widespread methodological flaws. In this paper we review the natural history of ACL injuries in children, as well as their diagnosis and management.

Incidence

There is little information about the incidence of ACL injuries in childhood: the reported rates are mostly drawn from retrospective reviews of children with an acute haemarthrosis or from insurance data.[7] Retrospective reviews of 186 acute haemarthroses of the knee revealed rupture of the ACL in 96 patients (52%).[8-11] Micheli et al[12] noted an increase in reconstructive surgery of the ACL as time progressed; however, this may have been due to a lower threshold for intervention, or to a higher rate of detection. Shea et al[7] reviewed 8215 injury claims from an insurance company that specialised in football injuries, and found that 22% of these involved the knee; of those, 31% were injuries to the ACL. However, insurance claims may not reflect the true incidence, as few sports injuries result in an insurance claim and up to 30% of ACL tears do not occur while playing sport.[13]

Several authors have reported that young female athletes are at a greater risk of sustaining ACL injuries, with a rate three to seven times that of male athletes.[14-16] It has been suggested that the reasons for this include differences in joint laxity, hormones, anatomy (narrow notch width), neuromuscular function and training.[7] Myklebust et al[17] found that 50% of ACL ruptures in elite female athletes occurred during the menstrual phase of their cycle; this, however, conflicts with the findings of Wojtys et al,[18] who found that athletes were most susceptible during the ovulatory phase.

Classification

In skeletally immature patients the collagen fibres of the ACL form a strong connection between the ligament, the perichondrium and the epiphyseal cartilage. The ACL is relatively stronger than the underlying cancellous bone of the unossified tibial eminence. As the patient ages this pattern is reversed, and weaker Sharpey's fibres link the ligament and the ossified bone.[19] Therefore, both mid-substance injuries of the ACL and avulsion fractures of the tibial spine may occur in the skeletally immature knee at different rates, depending on the stage of maturation of the skeleton. This

■ N. Al-Hadithy, BSc(Hons), MSc, MRCS(Eng), Specialist Registrar in Trauma and Orthopaedics
■ A. L. Dodds, MSc, FRCS(Tr & Orth), Specialist Registrar in Trauma and Orthopaedics
■ C. M. Gupte, PhD, FRCS(Tr & Orth), MA(Oxon), Consultant Orthopaedic Surgeon, Senior Lecturer
Imperial College NHS Trust, London W6 8RF, UK.

■ K. S. N. Akhtar, MEd, FRSA, FRCS(Tr & Orth), Clinical Lecturer in Orthopaedic Surgery
Imperial College London, MSK Lab, Charing Cross Hospital, Hammersmith, London W6 8RF, UK.

Correspondence should be sent to Mr C. M. Gupte e-mail: c.gupte00@imperial.ac.uk

doi:10.1302/0301-620X.95B11.31778 $2.00

Bone Joint J
2013;95-B:1562–9.
Received 4 February 2013; Accepted after revision 31 July 2013

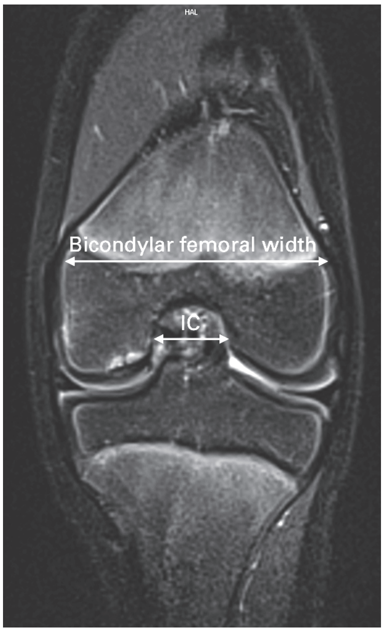

Fig. 1

Coronal MRI scan of the knee showing the intercondylar (IC) and bicondylar femoral widths.

has been substantiated by studies that have found that 80% of avulsion fractures of the tibial spine are in patients aged < 12 years, whereas 90% of mid-substance tears are in patients aged > 12 years.[20,21]

Diagnosis

Injuries of the ACL most commonly occur during sports that require pivoting and rapid deceleration, such as racquet games, football and skiing. The most common mechanism of injury is landing with the foot in external rotation.[22] A history suggestive of a major intra-articular injury includes immediate swelling[23] and a 'popping' sensation may be described by a third of patients.[24] Clinical examination is usually unreliable in the acute phase owing to pain and swelling, particularly in children owing to their lower pain threshold, inability to localise symptoms and increased ligamentous laxity.[25] While older patients may be able to provide a more detailed history and permit clinical examination, younger children are often unable to provide a detailed account of the injury. There is also more physiological laxity in children: even the normal knee in a child or adolescent may allow up to 10 mm of anterior draw.[26] It is imperative therefore that a thorough examination of the contralateral normal knee be performed for comparison.

Plain radiographs should be used to exclude fractures of the tibial spine or femoral condyles. MRI is the mainstay of diagnosis. Primary and secondary MRI signs in children are similar to those in adults. Primary signs include discontinuity of the ACL, alteration in its course, and abnormal signal within it. Secondary signs include meniscal tears, abnormal orientation of the posterior cruciate ligament (PCL), and a pivot shift lesion, a contusion between the anterolateral femoral condyle and the posterolateral tibial plateau due to rotatory subluxation of the tibia relative to the femur.[27]

Various MRI sequences have been suggested, but should include physeal-specific sequences such as a spoiled gradient echo (SPGR) fat-saturated cartilage sequence to improve sensitivity for primary and secondary signs.[28,29] Kocher et al[25] found the sensitivity of MRI to be 75% and the specificity 94%. However, these figures were lower in children aged < 12 years: this was attributed to less imaging experience with younger patients and their smaller size. Other studies have found similar results.[8,30] Therefore, as with any ancillary diagnostic test, MRI is best used as an adjunct and not instead of a thorough history and clinical examination.

Anatomical risk factors

Palmer et al[31] first advanced the theory that a narrow intercondylar notch may predispose the ACL to injury, as the ligament is progressively stretched over the medial edge of the lateral femoral condyle. Souryal and Freeman[32] found that those with a stenotic intercondylar notch were at a significantly greater risk of ACL injury. Patients with bilateral ACL tears have been reported to have a significantly lower notch width index (NWI: notch width / bicondylar femoral width; Fig. 1) than those without tears,[33] but others have found no correlation between the NWI and the rate of ACL tears.[34] Shelbourne et al[35] explained this discrepancy by suggesting that the NWI cannot be used for standardising people of different heights, as although the absolute notch width does not change, the width of the condyles increases with the height of the patient. Nor, they suggested, is it useful for standardising the genders, as women have different ratios from men. They also found that patients with a narrower notch width had a higher rate of ACL rupture,[35] and this has been supported by other studies.[36] Although it is assumed that a larger notch would house a larger ACL, there have been no studies correlating the dimensions of the ACL with ultimate load.

Associated injuries

Although injuries to the ACL are diagnosed commonly in children, there are few studies documenting the incidence of associated injuries. Meniscal injuries are the most common (as high as 64%[37,38]), with lateral injuries occurring more frequently with acute ACL tears, and medial meniscal tears with chronic tears. Other associated injuries include damage to the medial collateral ligament, chondral injuries and, rarely, femoral fractures.

In a review of 39 patients aged < 14 years, Millett et al[38] found an increased incidence of tears of the medial meniscus at the time of ACL reconstruction if patients were treated > six weeks after their injury. Dumont et al[39] reviewed 370 children who had undergone reconstruction of the ACL and found that those treated > five months after

Table I. Tanner stages of maturity

Tanner stage	Male-specific (genitals)	Female-specific (breasts)	Both genders (pubic hair)
1	Small	No glandular tissue	None
2	Slightly enlargement of scrotum. Penis length unchanged	Breast bud forms	Small amount & fine
3	Further enlargement of scrotum and penis	Enlargement of breast and areola	Coarse and curly extending laterally
4	Further enlargement of scrotum and penis	Projection of areola and papilla to form secondary mound	Adult like hair that crosses pubis
5	Adult size and shape	Adult size and shape	Adult hair extending to medial thigh

injury had a significantly higher rate of tears of the medial meniscus than those treated before this time; lateral meniscal injuries did not progress. They also found that those with tears of the menisci were more likely to have chondral injuries. Chhadia et al[40] confirmed this in a retrospective review of 1252 patients, and also found that there was a significantly lower chance of successful meniscal repair when there had been a longer delay to surgery. This suggests that the patterns of meniscal injury in children with a deficient ACL are similar to those seen in adults.[41]

Several authors have found that associated injuries are more common in older children[39,40]; those aged > 15 years have the highest risk, possibly due to the incidence of high-energy injuries in this age group as a result of their higher weight and level of activity. Dumont et al[39] found that children who weighed > 65 kg had a higher rate of meniscal tears at the time of surgery; this may become even more prevalent as the incidence of childhood obesity continues to increase.

Physeal considerations

The primary concern when operating on the skeletally immature patient is the potential for iatrogenic injury to the physes. The proximal tibial and distal femoral physes contribute 55% and 70% to the growth of their respective bones.[42]

In has been shown in animal models that drill holes measuring 7% to 9% of the cross-sectional area of a physis are sufficient to cause a disturbance of growth.[43] Mäkelä et al[44] found that drill holes involving 3% of the physeal cross-section had no effect on growth in a rabbit model, but if this was increased to 7%, shortening of 5 mm occurred within 24 weeks. In an MRI study of 31 knees, Kercher et al[45] found that drilling tunnels of 8 mm diameter produced a volumetric injury of 2.4% of the femoral physis and 2.5% of the tibial physis in patients aged between ten and 15 years. However, as graft diameter increased from 6 mm to 11 mm in diameter, the volumetric injury increased from 2.3% to 7.8%: this equates to a 1.1% increase in volumetric injury for every 1 mm increase in tunnel diameter.[43]

The orientation of the tunnel also affects the degree of physeal injury: oblique tunnels cause a greater volumetric injury than vertical tunnels. Kercher et al[45] found that increasing the drill angle from 45° to 70° reduced the volume of physis removed by 4.1% to 3.1%. The technique of 'anatomical' ACL reconstruction requires an oblique femoral tunnel (10 o'clock position in the right knee[46]), and therefore increases the risk of physeal injury in a child's knee. The senior author (CMG) therefore adjusts the obliquity of the femoral tunnel depending on the age of the patient, with more oblique tunnels in older adolescents.

It is also important to consider the speed at which the tunnels are reamed. A greater speed of reaming leads to more heat necrosis and a greater 'penumbra' of physeal injury; consequently, it has been suggested that damage may be minimised by drilling slowly and in short bursts.[47]

Higuchi et al[48] reviewed MRI scans six months after transphyseal reconstructions in ten skeletally immature patients and found narrowing of the growth plate and corticalisation around the drill holes in all patients. Although there was no incidence of growth arrest or disturbance, it is possible that this may occur in patients who have not reached skeletal maturity.

Despite the fact that the size of the tunnel used for ACL reconstruction accounts for only 3% of the cross-sectional area, many surgeons are still reluctant to drill through the physis – there remains debate in the literature about whether transphyseal or physeal-sparing techniques should be used.

Assessment of skeletal maturity

There are various methods of assessing skeletal maturity. These include radiological evaluation, comparison of the patient's height with those of their siblings and parents, and sexual maturity. Radiological evaluation often involves reference atlases of age and gender-matched controls to act as a direct comparison.[49] Tanner staging[50] of sexual maturity is most commonly used in the reviewed literature and is summarised in Table I.

Prevention of injury

Considerable efforts have been made to identify means of preventing ACL injuries. Mandelbaum et al[51] performed a prospective non-randomised study of 1041 female athletes, and compared those undergoing their traditional warm-up *versus* those undergoing a programme of education, stretching, strengthening, plyometrics (jump training) and sport-specific agility drills. They reported reductions in the rate of ACL injury in the study group compared with the controls of 88% and 74% at one and two years, respectively.[51] Specific biomechanical interventions to reduce risk include the avoidance of an extended leg (encouraging the 'knee-over-toe' position), and landing on two-feet after jumping; these have been found to reduce the incidence of ACL tears.[17,52] A recent systematic review of six randomised trials found a 50% reduction in ACL injuries in patients who had undergone neuromuscular and educative interventions.[53]

Management

One of the main controversies in the management of ACL injuries in children is whether reconstruction should take place early to prevent secondary meniscal injury, or whether it should be delayed to prevent iatrogenic injury to the physes.[54]

Non-operative or delayed surgical treatment. Traditional algorithms of management suggest an initial period of conservative treatment until the child is close to the end of growth, accompanied by a reduction in levels of activity, functional bracing and physiotherapy. However, poor outcomes have been noted in patients treated non-operatively. Graf et al[55] reported high rates of meniscal tears in their series of 12 patients, with seven patients developing meniscal tears at a mean of 15 months after initial injury. Mizuta et al[56] had similar results, with only one of 18 patients returning to sport at their pre-injury level. In addition to their reduced level of function, secondary injuries were seen with radiological signs of degenerative changes being present in 60% of patients at four years. In addition there was a high rate of secondary meniscal injuries. Another study found that almost 70% of skeletally immature patients who underwent a three-month physiotherapy rehabilitation programme required reconstruction within five years owing to persistent symptoms.[57] One difficulty encountered with non-operative management, is poor adherence to a reduction in sporting activities, especially for a prolonged period of time.[58]

In one of the only studies that found favourable results in patients managed non-operatively, Woods et al[59] compared 13 adolescents with open physes whose ACL reconstructions were intentionally delayed by 16 months with a group of 116 patients who underwent reconstruction at a mean of 14 weeks after injury. They found no difference between the groups in terms of secondary injuries and long-term functional outcome, and concluded that surgery can be delayed safely if patients wear an ACL brace and abstain entirely from sports. This study, however, did not have matched groups, was retrospective, and the rehabilitation regimes used were not stated.[59]

Patients with a partial ACL tear may benefit from non-operative treatment. Kocher et al[60] reviewed the outcome of 45 skeletally mature and immature patients who underwent a structured course of rehabilitation for a partial tear of the ACL: only 31% needed reconstruction. They suggested that patients under the age of 14 years with a stable knee may be treated non-operatively.

Operative treatment. A variety of reconstructive techniques have been described. Techniques may either be intra- or extra-articular, and may be transphyseal, physeal-sparing or partial transphyseal, and may use additional augments.

1. Transphyseal. Transphyseal repair involves a tunnel being drilled across both the tibial and femoral physes, and has traditionally been approached with caution because of the possibility of growth disturbance. Kocher et al[54] sent questionnaires to 140 surgeons who reported only 15 patients with growth disturbance. In 12 of these, staples, or screws of bone plugs, were passed across the physis, acting as a mechanical block. In two separate studies Lipscomb and Anderson[61] and Koman and Sanders[62] reported single cases of growth disturbance with significant shortening (20 mm) and marked valgus deformity; in both cases fixation passed across the physis, causing a mechanical block. Guzzanti et al[43] and Stadelmaier et al[63] used different animal models but found that soft tissue placed in drill holes prevented the formation of bony bridges, and therefore suggested that intra-articular techniques may be safe.

Many authors have evaluated the use of a transphyseal technique on skeletally immature patients (Table II).[13,47,64-71] Kaeding et al[4] undertook a systematic review of 13 case series and found that both transphyseal and physeal-sparing reconstructions were safe in Tanner[72] stage II and III patients. They reported a lack of studies evaluating the safety of Tanner stage I patients undergoing transphyseal reconstruction. Recently, Frosch et al[5] performed a meta-analysis of 55 studies and found low rates of leg-length discrepancy or angular deformity after early ACL reconstruction. More recently, Liddle et al[65] and Nikolaou et al[71] used the transphyseal method in Tanner stage I and II, and reported no leg-length discrepancy or growth disturbances in their series of 17 and 66 patients, respectively.

In a series with the longest follow-up, Kumar et al[47] reported the outcome of 32 patients with a mean age of 11.3 years who had undergone transphyseal reconstruction, with a mean follow-up of 72.3 months. All but one had a good or excellent outcome; one patient re-ruptured and one had a mild valgus deformity that did not cause any functional disturbance (Table II).

2. Physeal sparing. Various intra- and extra-articular methods have been described to avoid the physes. Most involve either all-epiphyseal drilling or the use of an extra-articular 'over-the-top' position on the femoral side with fixation to the tibial metaphysis.

Guzzanti, Falciglia and Stanitski[73] reconstructed the ACL using epiphyseal tunnels and hamstring grafts in eight Tanner stage I patients. None had growth disturbance or instability at a mean follow-up of 69.2 months. Anderson[74] described an all-epiphyseal placement using a parallel lateral femoral epiphyseal tunnel with a tibial tunnel similar to that of Guzzanti et al.[73] The hamstring graft was secured with an Endobutton (Smith & Nephew, Andover, Massachusetts) in the femoral tunnel and an interference screw in the tibial epiphysis. There were no failures in their series of 12 patients with a mean follow-up of 4.1 years. Lawrence et al[75] developed Anderson's[74] technique, but elected to use an interference screw instead of an Endobutton in the femur as it reduced the length of the graft, which they considered would reduce the potential chance of stretching. They had no growth disturbance in their pilot study of

Table II. Reports using the transphyseal technique

Author/s	Patients (n)	Age (yrs)/skeletal maturity*	Graft†	Outcome‡	Mean follow-up (mths)
Kumar et al[47]	32	11.3 (28 T1/2, 4 T3)	Four-strand hamstring	No LLD; 1 re-rupture; 1 valgus deformity	72.3
McCarroll et al[64]	60	Near skeletal maturity	BPBT	No GD; 3 re-ruptures	50
Liddle et al[65]	17	8 T1, 9 T2	Four-strand hamstring	1 re-rupture; 1 valgus deformity	44
Cohen et al[66]	26	13.3	Four-strand hamstring	3 re-ruptures	45
Fuchs et al[67]	10	13.2	BPBT	No LLD; no GD	40
Shelbourne et al[68]	16	7 T3, 9 T4	BPBT	No LLD; no GD	40.8
Aichroth et al[13]	47	13.0	Four-strand hamstring	No GD; 75% satisfactory; 3 re-ruptures	49
Edwards and Grana[69]	21	13.7	Four-strand hamstring (15); BPBT (6)	No LLD; no GD; 2 re-ruptures; 1 persistent laxity	34
Kocher et al[70]	35	14.7 (all T3)	Four-strand hamstring	No LLD; no GD; 2 re-ruptures	43
Nikolaou et al[71]	94	21 T1, 42 T2, 25 T3, 3 T4	Four-strand hamstring	No LLD; no GD; 4 re-ruptures	38

* T, Tanner stage
† BPBT, bone–patella–bone–tendon
‡ LLD, leg-length discrepancy; GD, growth disturbance

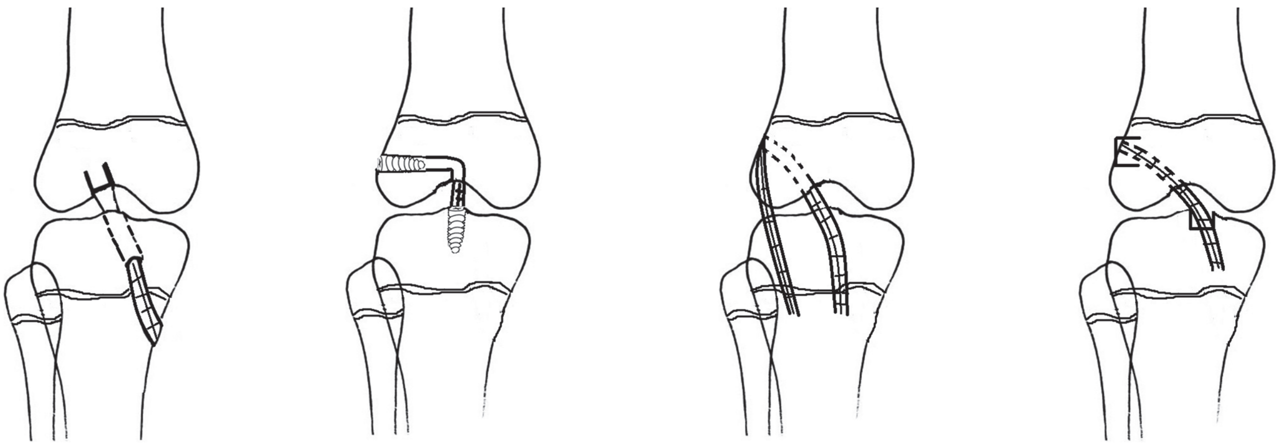

Fig. 2a Fig. 2b Fig. 2c Fig. 2d

Diagrams showing various physeal-sparing techniques. Figure 2a – the extraphyseal technique of Guzzanti et al[73]: after the oblique epiphyseal tunnels are drilled, a staple is fixed into the femoral epiphysis. The proximally detached hamstring tendons are passed through the tibial epiphyseal tunnel and looped around the staple. The staple is then fixed into the femoral epiphysis under tension. The free end of the graft is sutured to the tibial periosteum. Figure 2b – the extraphyseal technique of Lawrence et al[75]: a lateral epiphyseal femoral tunnel and an oblique epiphyseal tibial tunnel (retrograde) are drilled first, ensuring that the physis is avoided. The graft is introduced from the femoral tunnel using a passing suture. The graft is fixed first in the tibia using an inside/out screw. After tensioning, the graft is secured into the femur with an interference screw. Figure 2c – the extraphyseal technique of Janarv et al[57]: the semitendinosus graft is detached proximally. A tibial epiphyseal tunnel is drilled, avoiding the physis and allowing passage of the graft. It is passed in an 'over-the-top' position on the femur and secured into the femoral metaphysis. Figure 2d – the extraphyseal technique of Brief,[76] Parker et al[37] and Bonnard et al[77]: the semitendinosus graft is detached proximally and either passed into the knee under the medial meniscus (Brief) or through a groove fashioned on the anterior tibia (Parker and Bonnard). The graft is then passed in an 'over-the-top' position, and secured into the lateral femur metaphysis.

three patients. One possible disadvantage of these techniques is the acute angle made by the graft when passing through a relatively vertical tibial tunnel into a horizontal femoral tunnel. This may cause fretting of the graft and theoretically increase the risk of rupture.

Micheli et al[12] and Janarv et al[57] proposed a combined intra- and extra-articular technique that used a proximally harvested iliotibial band, which was passed over the lateral femoral condyle, through a notchplasty and fixed directly on to the anterior tibia. They reported no cases of growth disturbance or leg-length discrepancy in 17 patients with a mean age of 11 years.

Brief[76] was concerned about the effects of drill holes, regardless of whether or not they passed through the physes, and described a method that avoided them by passing a hamstring graft under the medial meniscus, through the posterior capsule and on to the lateral femoral metaphysis, where it was secured. This was augmented with an extra-articular iliotibial band tenodesis. Of the nine patients treated, eight felt that the knee was stable and did not have a positive pivot shift: six were able to return to their pre-injury level of sporting activities.[76] All had a grade 1 Lachmann's sign and anterior draw test indicating some stretching of the graft, which occurred within 18 months of their operation and had not progressed by three years.

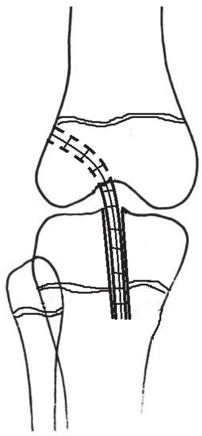

Fig. 3

Diagram showing a partial physeal-sparing technique, involving a transphyseal tibial tunnel being drilled, into an epiphyseal femoral tunnel.

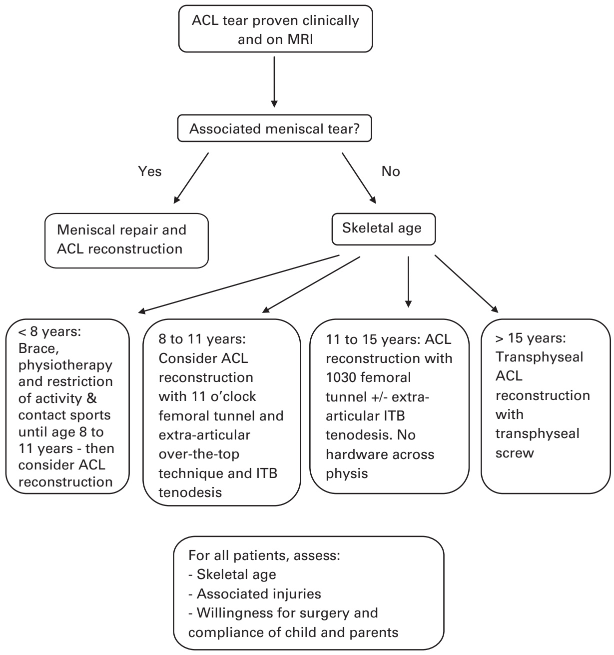

Fig. 4

The senior author's preferred treatment algorithm (ACL, anterior cruciate ligament; ITB, iliotibial band).

Parker et al[37] described six patients in whom a graft was passed through a groove created in the tibial epiphysis and over the top of the lateral femoral condyle before being secured in the proximal tibial metaphysis. One developed arthrofibrosis but none had a disturbance of growth. Bonnard et al[77] used a similar technique in a larger series of 57 patients, with a mean age of 12.2 years and a mean follow-up of five years, and had three re-ruptures but no other complications.

Physeal-sparing procedures are not without risk. Frosch et al[5] found a higher rate of growth disturbance after physeal-sparing procedures (5.9%) than after transphyseal reconstructions (1.9%). Other authors have also reported growth disturbance after physeal-sparing procedures.[78] While the reasons for this are not clear, it may be due to the unfamiliar surgical technique or to thermal injury of the physes from drilling. Techniques that require all-epiphyseal drilling close to the true anatomical position are difficult, and have a small margin for error. Behr et al[79] found that the distance between the proximal ACL and the femoral physis was only 3 mm in the immature skeleton. Even the 'over-the-top' position may violate the distal femoral physis. Figure 2 shows a number of different physeal-sparing techniques.

3. **Partial physeal sparing**. This technique involves passing a graft through a transphyseal tibial tunnel and fixing it to the metaphysis of the lateral femur. This may reduce the risk of growth disturbance, as the femoral physis, which contributes to a greater proportion of lower limb growth, is avoided. Lipscomb and Anderson[61] reported on 24 patients using their partial physeal-sparing method: 16 felt that their knee was normal. One had a growth disturbance (2 cm) that they attributed to a staple crossing the physis. Other authors using the same technique have found no evidence of growth disturbance.[80,81] Figure 3 shows a partial-physeal sparing technique.

Outcomes

In 2012, Moksnes et al[6] published a systematic review of the methodological quality of the literature that advocated surgical treatment. In all, 31 studies were identified that included 966 children. None were randomised controlled trials and most (94%) were retrospective.

They found that most studies had major flaws in methodology, particularly with regards to sample size, study design and description of post-operative rehabilitation protocols. They noted that rehabilitation programmes including exercises, weight-bearing status and post-operative restriction were poorly documented. Most studies were used as a means to document their surgical technique rather than objectively assessing outcomes.

The four studies with the highest methodological scores reported a good functional outcome after reconstruction and a low rate of growth disturbance.

It is generally accepted that the rate of re-rupture is higher in adolescents than in adults. Frosch et al[5] found a re-rupture rate of 4.8% in their meta-analysis of 935 skeletally immature patients, which is higher than the 3.1% failure rate found in adults.[82] However, direct comparisons must be made with caution, as the lower rates reported in adults often reflect a less active patient group. The rate of re-rupture can be as high as 13% in adults who participate in sport at a high level.[83]

Thus, a variety of techniques have been described for reconstruction of the ACL in childhood. Familiarity and comfort of the surgeon with a particular technique is of utmost importance. It is generally agreed that this procedure should only be carried out by specialist surgeons with expertise in both arthroscopic reconstruction of the ACL and children's injuries, in dedicated units with appropriate facilities for rehabilitation. The senior author's (CMG) proposed algorithm for the treatment of these patients is shown in Figure 4.

In conclusion, it seems that paediatric ACL injuries are occurring more commonly in recent years. Although most surgeons recommend early surgical treatment in an attempt to prevent secondary meniscal tears, the ideal treatment remains controversial owing to the lack of high-quality studies. There is currently inadequate data on the ideal techniques of operation, the timing of surgery and rehabilitation regimes. Both transphyseal and physeal-sparing techniques have been advocated, but these should only be carried out in dedicated units with the appropriate expertise in surgery and rehabilitation.

Supplementary material

Two tables giving the details of studies reporting on i) physeal-sparing and ii) partial-physeal sparing techniques are available with the electronic version of this article on our website www.bjj.boneandjoint.org.uk

No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

This article was primary edited by A. Ross and first-proof edited by J. Scott.

References

1. **Rang M.** *Children's fractures*. Philadelphia: JB Lippincott, 1974.
2. **Mohtadi N, Grant J.** Managing anterior cruciate ligament deficiency in the skeletally immature individual: a systematic review of the literature. *Clin J Sport Med* 2006;16:457–464.
3. **Utukuri MM, Somayaji HS, Khanduja V, Dowd GS, Hunt DM.** Update on paediatric ACL injuries. *Knee* 2006;13:345–352.
4. **Kaeding CC, Flanigan D, Donaldson C.** Surgical techniques and outcomes after anterior cruciate ligament reconstruction in preadolescent patients. *Arthroscopy* 2010;26:1530–1538.
5. **Frosch KH, Stengel D, Brodhun T, et al.** Outcomes and risks of operative treatment of rupture of the anterior cruciate ligament in children and adolescents. *Arthroscopy* 2010;26:1539–1550.
6. **Moksnes H, Engebretsen L, Risberg MA.** The current evidence for treatment of ACL injuries in children is low: a systematic review. *J Bone Joint Surg [Am]* 2012;94-A:1112–1119.
7. **Shea KG, Pfeiffer R, Wang JH, Curtin M, Apel PJ.** Anterior cruciate ligament injury in pediatric and adolescent soccer players: an analysis of insurance data. *J Pediatr Orthop* 2004;35:623–628.
8. **Eiskjaer S, Larsen ST.** Arthroscopy of the knee in children. *Acta Orthop Scand* 1987;58:273–276.
9. **Bomberg BC, McGinty JB.** Acute haemarthrosis of the knee: indications for diagnostic arthroscopy. *Arthroscopy* 1990;6:221–225.
10. **Bergstrom R, Gillquist J, Lysholm J, Hamberg P.** Arthroscopy of the knee in children. *J Pediatr Orthop* 1984;4:542–545.
11. **Stanitski CI, Harvell JC, Fu F.** Observations on acute knee haemarthrosis in children and adolescents. *J Pediatr Orthop* 1993;13:506–510.
12. **Micheli LJ, Metzl JD, Di Canzio J, Zurakowski D.** Anterior cruciate ligament reconstructive surgery in adolescent soccer and basketball players. *Clin J Sports Med* 1999;9:138–141.
13. **Aichroth PM, Patel DV, Zorrilla P.** The natural history and treatment of rupture of the anterior cruciate ligament in children and adolescents: a prospective review. *J Bone Joint Surg [Br]* 2002;84-B:38–41.
14. **Harmon KG, Ireland ML.** Gender differences in noncontact anterior cruciate ligament injuries. *Clin Sports Med* 2000;19:287–302.
15. **Powell JW, Barber-Foss KD.** Sex-related injury patterns among selected high school sports. *Am J Sports Med.* 2000;28:385–391.
16. **Arendt E, Dick R.** Knee injury patterns among men and women in collegiate basketball and soccer: NCAA data and review of literature. *Am J Sports Med* 1995;23:694–701.
17. **Myklebust G, Engebretsen L, Braekken IH, et al.** Prevention of anterior cruciate ligament injuries in female team handball players: a prospective intervention study over three seasons. *Clin J Sports Med* 2003;13:71–78.
18. **Wojtys EM, Huston LJ, Lindenfeld TN, Hewett TE, Greenfield ML.** Association between the menstrual cycle and anterior cruciate ligament injuries in female athletes. *Am J Sports Med* 1998;26:614–619.
19. **Herring JA.** *Tachdijian's pediatric orthopaedics*. Third ed. Philadelphia: Saunders, 2002:2354.
20. **Vaquero J, Vidal C, Cubillo A.** Intra-articular traumatic disorders of the knee in children and adolescents. *Clin Orthop Relat Res* 2005;432:97–106.
21. **Kellenberger R, von Laer L.** Nonosseous lesions of the anterior cruciate ligaments in children and adolescents. *Prog Pediatr Surg* 1990;25:123–131.
22. **Olsen OE, Myklebust G, Engebretsen L, Bahr R.** Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. *Am J Sports Med* 2004;32:1002–1012.
23. **Stanitski CL.** Anterior cruciate ligament injury in the skeletally immature patient: diagnosis and treatment. *J Am Acad Orthop Surg* 1995;3:146–158.
24. **Dorizas JA, Stanitski CL.** Anterior cruciate ligament injury in the skeletally immature. *Orthop Clin North Am* 2003;34:355–363.
25. **Kocher MS, DiCanzio J, Zurakowski D, Micheli LJ.** Diagnostic performance of clinical examination and selective magnetic resonance imaging in the evaluation of intraarticular knee disorders in children and adolescents. *Am J Sports Med* 2001;29:292–296.
26. **Flynn JM, Mackenzie W, Kolstad K, et al.** Objective evaluation of knee laxity in children. *J Pediatr Orthop* 2000;20:259–263.
27. **Lee K, Siegel MJ, Lau DM, Hildebolt CF, Matava MJ.** Anterior cruciate ligament tears: MR imaging based diagnosis in a pediatric population. *Radiology* 1999;213:697–704.
28. **Disler DG, McCauley TR, Kelman CG, et al.** Fat-suppressed three-dimensional spoiler gradient echo MR imaging of hyaline cartilage defects in the knee: comparison with standard MR imaging and arthrscopy. *AJR Am J Roentgenol* 1996;167:127–132.
29. **Crema MD, Roemer FW, Marra MD, et al.** Articular cartilage in the knee: current MR imaging techniques and application in clinical practice and research. *Radiographics* 2011;31:37–61.
30. **Ure BM, Tiling T, Röddecker K, Klein J, Rixen D.** Arthroscopy of the knee in children and adolescents. *Eur J Pediatr Surg* 1992;2:102–105.
31. **Palmer I.** On the injures to the ligaments of the knee joint: a clinical study. *Acta Chir Scand Suppl* 1938;53:1–28.
32. **Souryal TO, Freeman TR.** Intercondylar notch size and anterior cruciate injuries in athletes: a prospective study. *Am J Sports Med* 1993;21:535–539.
33. **Souryal TO, Moore HA, Evans JP.** Bilaterality in anterior cruciate ligament injuries: associated intercondylar notch stenosis. *Am J Sports Med* 1988;16:449–454.
34. **Herzog RJ, Silliman JF, Hutton K, Rodkey WG, Steadman JR.** Measurements of the intercondylar notch by plain film radiography and magnetic resonance imaging. *Am J Sports Med* 1994;22:204–210.
35. **Shelbourne KD, Davis TJ, Klootwyk TE.** The relationship between intercondylar notch width of the femur and the incidence of anterior cruciate ligament tears: a prospective study. *Am J Sports Med* 1998;26:402–408.
36. **Domzalski M, Grzelak P, Gabos P.** Risk factors for anterior cruciate ligament injury in skeletally immature patients: analysis of intercondylar notch width using Magnetic Resonance Imaging. *Int Orthop* 2010;34:703–707.
37. **Parker AW, Drez D, Cooper JL.** Anterior cruciate ligament injuries in patients with open physes. *Am J Sports Med* 1994;22:44–47.
38. **Millett PJ, Willis AA, Warren RF.** Associated injuries in pediatric and adolescent anterior cruciate ligament tears: does a delay in treatment increase the risk of meniscal tear? *Arthroscopy* 2002;18:955–959.
39. **Dumont GD, Hogue GD, Padalecki JR, Okor N, Wilson PL.** Meniscal and chondral injuries associated with pediatric anterior cruciate ligament tears. *Am J Sports Med* 2012;40:2128–2133.
40. **Chhadia AM, Inacio MC, Maletis GB, et al.** Are meniscus and cartilage injuries related to time to anterior cruciate ligament reconstruction? *Am J Sports Med* 2011;39:1894–1899.

41. **Bellabarba C, Bush-Joseph CA, Bach BR Jr.** Patterns of meniscal injury in the anterior cruciate-deficient knee: a review of the literature. *Am J Orthop* 1997;26:18–23.

42. **Ogden J.** Radiologic aspects. In: *Skeletal injury in the child.* Philadelphia: Saunders, 1990:65–96.

43. **Guzzanti V, Falciglia F, Gigante A.** The effect of intra-articular ACL reconstruction on the growth plates of rabbits. *J Bone Joint Surg [Br]* 1994;76-B:960–963.

44. **Mäkelä EA, Vainionpää S, Vihtonen K, Mero M, Rokkanen P.** The effect of trauma to the lower femoral epiphyseal plate: an experimental study in rabbits. *J Bone Joint Surg [Br]* 1988;70-B:187–191.

45. **Kercher J, Xerogeanes J, Tannenbaum A, Al-Hakim R, Black JC, Zhao J.** Anterior cruciate ligament reconstruction in the skeletally immature: an anatomical study utilizing 3-dimensional magnetic resonance imaging reconstructions. *J Pediatr Orthop* 2009;29:124–129.

46. **Loh JC, Fukuda Y, Tsuda E, et al.** Knee stability and graft function following anterior cruciate ligament reconstruction: comparison between 11 o'clock and 10 o'clock femoral tunnel placement. 2002 Richard O'Connor Award paper. *Arthroscopy* 2003;19:297–304.

47. **Kumar S, Ahearne D, Hunt DM.** Transphyseal anterior cruciate ligament reconstruction in the skeletally immature: follow-up to a minimum of sixteen years of age. *J Bone Joint Surg [Am]* 2013;95-A:1.

48. **Higuchi T, Hara K, Tsuji Y, Kubo T.** Transepiphyseal reconstruction of the anterior cruciate ligament in skeletally immature athletes: an MRI evaluation for epiphyseal narrowing. *J Pediatr Orthop B* 2009;18:330–334.

49. **Greulich WW, Pyle SI.** *Radiographic atlas of skeletal development of the hand and wrist.* Second ed. Stanford: Standford University Press, 1971.

50. **Tanner JM.** The development of the reproductive system. In: *Growth at adolescence.* Second ed. Oxford: Blackwell Scientific, 1962;28–39.

51. **Mandelbaum BR, Silvers HJ, Watanabe DS, et al.** Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. *Am J Sports Med* 2005;33:1003–1010.

52. **Mandelbaum BR, Silvers H, Watanabe D, et al.** ACL prevention strategies in the female athlete and soccer: implementation of a neuromuscular training program to determine its efficacy on the incidence of ACL injury [Abstract]. *AOSSM* 200194–95.

53. **Gagnier JJ, Morgenstern H, Chess L.** Interventions designed to prevent anterior cruciate ligament injuries in adolescents and adults: a systematic review and meta-analysis. *Am J Sports Med* 2013;41:1952–1962.

54. **Kocher MS, Saxon HS, Hovis WD, Hawkins RJ.** Management and complications of anterior cruciate ligament injuries in skeletally immature patients: survey of the Herodicus Society and The ACL Study Group. *J Pediatr Orthop* 2002;22:452–457.

55. **Graf BK, Lange RH, Fujisaki CK, Landry GL, Saluja RK.** Anterior cruciate ligament tears in skeletally immature patients: meniscal pathology at presentation and attempted conservative treatment. *Arthroscopy* 1992;8:229–233.

56. **Mizuta H, Kubota K, Shiraishi M, et al.** The conservative treatment of complete tears of the anterior cruciate ligament in skeletally immature patients. *J Bone Joint Surg [Br]* 1995;77-B:890–894.

57. **Janarv PM, Nyström A, Werner S, Hirsch G.** Anterior cruciate ligament injuries on skeletally immature patients. *J Pediatr Orthop* 1996;16:673–677.

58. **Fehnel DJ, Johnson R.** Anterior cruciate injuries in the skeletally immature athlete: a review of treatment outcomes. *Sports Med* 2000;29:51–63.

59. **Woods GW, O'Connor DP.** Delayed anterior cruciate ligament reconstruction in adolescents with open physes. *Am J Sports Med* 2004;32:201–210.

60. **Kocher MS, Micheli LJ, Zurakowski D, Luke A.** Partial tears of the anterior cruciate ligament in children and adolescents. *Am J Sports Med* 2002;30:697–703.

61. **Lipscomb AB, Anderson AF.** Tears of anterior cruciate ligament in adolescents. *J Bone Joint Surg [Am]* 1986;68-A:19–28.

62. **Koman JD, Sanders JO.** Valgus deformity after reconstruction of the anterior cruciate ligament in a skeletally immature patient: a case report. *J Bone Joint Surg [Am]* 1999;81-A:711–715.

63. **Stadelmaier DM, Arnoczky SP, Dodds J, Ross H.** The effect of drilling and soft tissue grafting across open growth plates: a histologic study. *Am J Sports Med* 1995;23:431–435.

64. **McCarroll JR, Shelbourne KD, Porter DA, Rettig AC, Murray S.** Patellar tendon graft reconstruction for midsubstance anterior cruciate ligament rupture in junior high school athletes: an algorithm for management. *Am J Sports Med* 1994;22:478–484.

65. **Liddle AD, Imbuldeniya AM, Hunt DM.** Transphyseal reconstruction of the anterior cruciate ligament in prepubescent children. *J Bone Joint Surg [Br]* 2008;90-B:1317–1322.

66. **Cohen M, Ferretti M, Quarteiro M, et al.** Transphyseal anterior cruciate ligament reconstruction in patients with open physes. *Arthroscopy* 2009;25:831–838.

67. **Fuchs R, Wheatley W, Uribe JW, et al.** Intra-articular anterior cruciate ligament reconstruction using patellar allograft in the skeletally immature patient. *Arthroscopy* 2002;18:824–828.

68. **Shelbourne KD, Gray T, Wiley BV.** Results of transphyseal anterior cruciate ligament reconstruction using patellar tendon autograft in tanner stage 3 or 4 adolescents with clearly open growth plates. *Am J Sports Med* 2004;32:1218–1222.

69. **Edwards PH, Grana WA.** Anterior cruciate ligament reconstruction in the immature athlete: long-term results of intra-articular reconstruction. *Am J Knee Surg* 2001;14:232–237.

70. **Kocher M, Smith JT, Zoric B, Lee B, Micheli LJ.** Transphyseal anterior cruciate ligament reconstruction in skeletally immature pubescent adolescents. *J Bone Joint Surg [Am]* 2007;89-A:2632–2639.

71. **Nikolaou P, Kalliakmanis A, Bousgas D, Zourntos S.** Intraarticular stabilization following anterior cruciate ligament injury in children and adolescents. *Knee Surg Sports Traumatol Arthrosc* 2011;19:801–805.

72. **Tanner JM, Whitehouse RH.** Clinical longitudinal standards for height, weight, height velocity, weight velocity, and stages of puberty. *Arch Dis Child* 1976;51:170–179.

73. **Guzzanti V, Falciglia F, Stanitski CL.** Physeal-sparing intraarticular anterior cruciate ligament reconstruction in preadolescents. *Am J Sports Med* 2003;31;949-53.:.

74. **Anderson AF.** Transepiphyseal replacement of the anterior cruciate ligament in skeletally immature patients: a preliminary report. *J Bone Joint Surg [Am]* 2003;85-A:1255–1263.

75. **Lawrence JT, Bowers AL, Belding J, Cody SR, Ganley TJ.** All-epiphyseal anterior cruciate ligament reconstruction in skeletally immature patients. *Clin Orthop Relat Res* 2010;468:1971–1977.

76. **Brief LP.** Anterior cruciate ligament reconstruction without drill holes. *Arthroscopy* 1991;7:350–357.

77. **Bonnard C, Fournier J, Babusiaux D, et al.** Physeal-sparing reconstruction of anterior cruciate ligament tears in children: results of 57 cases using patellar tendon. *J Bone Joint Surg [Br]* 2011;93-B:542–547.

78. **Chotel F, Henry J, Seil R, et al.** Growth disturbances without growth arrest after ACL reconstruction in children. *Knee Surg Sports Traumatol Arthrosc* 2010;18:1496–1500.

79. **Behr CT, Potter HG, Paletta GA Jr.** The relationship of the femoral origin of the anterior cruciate ligament and the distal femoral physeal plate in the skeletally immature knee: an anatomic study. *Am J Sports Med* 2001;29:781–787.

80. **Lo IK, Kirkley A, Fowler PJ, Miniaci A.** The outcome of operatively treated anterior cruciate ligament disruptions in the skeletally immature child. *Arthroscopy* 1997;16:627–634.

81. **Bisson LJ, Wickiewicz T, Levinson M, Warren R.** ACL reconstruction in children with open physes. *Orthopedics* 1998;21:659–663.

82. **Spindler KP, Kuhn JE, Freedman KB, et al.** Anterior cruciate ligament reconstruction autograft choice: bone-tendon-bone versus hamstring: does it really matter?: a systematic review. *Am J Sports Med* 2004;32:1986–1995.

83. **Myklebust G, Bahr R.** Return to play guidelines after anterior cruciate ligament surgery. *Br J Sports Med* 2005;39:127–131.