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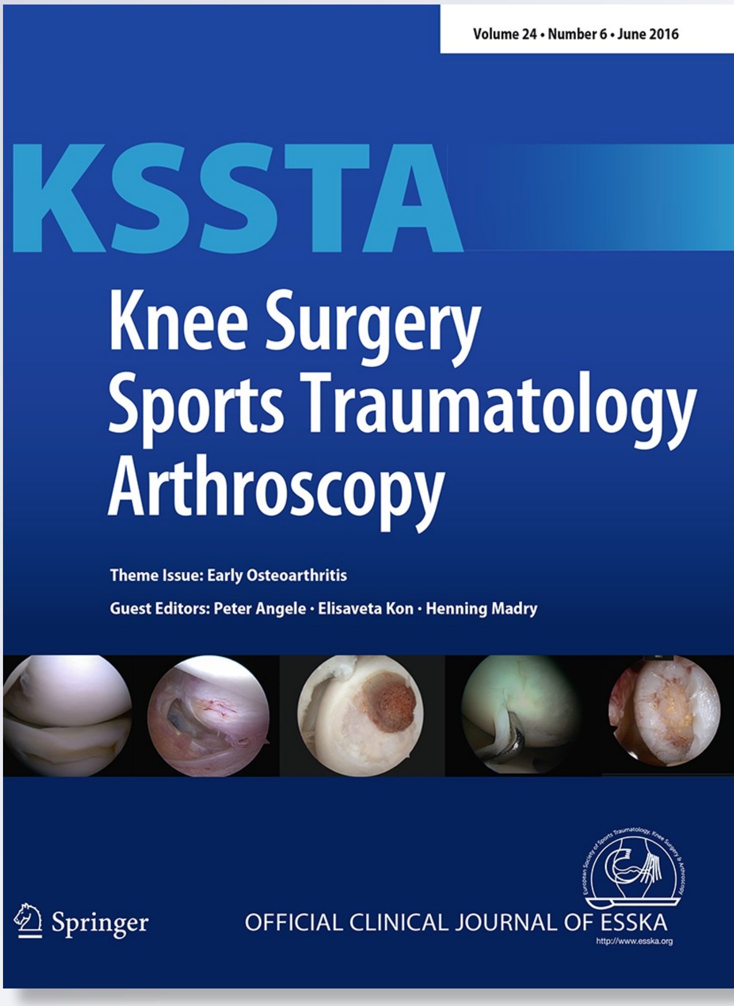

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Abstract
Purpose Instability following non-operative treatment of anterior cruciate ligament (ACL) rupture in young children frequently results in secondary chondral and/or meniscal injuries. Therefore, many contemporary surgeons advocate ACL reconstruction in these patients, despite the challenges posed by peri-articular physes and the high early failure rate. We report a novel management approach, comprising direct ACL repair reinforced by a temporary internal brace in three children.
Methods Two patients (aged 5 and 6 years) with complete proximal ACL ruptures and a third (aged seven) with an associated tibial spine avulsion underwent direct surgical repair, supplemented with an internal brace that was removed after 3 months.
Results Second-look arthroscopy, examination and imaging at 3 months confirmed knee stability and complete ACL healing in all cases. Normal activities were resumed at 4 months, and excellent objective measures of function, without limb growth disturbance, were noted beyond 2 years.
Conclusion ACL repair in young children using this technique negates the requirement and potential morbidity of graft harvest and demonstrates the potential for excellent outcome as an attractive alternative to ACL reconstruction, where an adequate ACL remnant permits direct repair.

Level of evidence IV.

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Keywords Paediatric ACL · ACL repair · Internal bracing

Introduction

Approximately 3.4 % of all anterior cruciate ligament (ACL) injuries occur in skeletally immature patients [22, 35]. This proportion continues to increase as a result of greater clinical awareness, improved availability of diagnostic imaging [8, 23, 40, 43, 45] and a rise in the number of children involved in high-demand sport [1, 11, 34]. Furthermore, incomplete ACL injuries in children may progress to a complete tear with poor functional outcomes and subsequent meniscal and chondral damage, if not surgically reconstructed [2, 21, 25].

Although the optimal management of ACL injuries in adults is established, significant anatomical and physiological differences limit the transference of techniques to the treatment of paediatric ACL injuries, which remain controversial and continue to present a major management challenge. Whilst surgical treatment is now widely accepted to restore stability and prevent sequelae, the timing of surgery, graft choice and tunnel placement are contentious [5, 10, 27]. The challenge associated with the avoidance of physeal damage and consequent growth disturbance has resulted in those who continue to favour non-operative management.

Standard paediatric ACL reconstruction involves drilling and passing the graft across the open physes. Tunnel positions are compromised because although oblique tunnels are biomechanically favourable, they effectively increase the cross-sectional area of physeal disruption. This problem is exacerbated on the femoral side where the distal physis has an undulating orientation [10, 11, 22]. An alternative surgical treatment for ACL rupture by direct repair and temporary reinforcement with an internal brace, rather than reconstruction, reduces or negates physeal injury and any requirement for graft use. To date this technique has been used in the treatment of three young children with minor modifications: in a 5-year-old girl who sustained an ACL rupture whilst trampolining; in a 6-year-old boy in a skiing accident and in a 7-year-old girl who twisted her knee falling off a playground roundabout (Table 1).

Case report

A 5-year-old girl presented with knee pain and inability to weight bear after landing awkwardly whilst trampolining. Radiographs of the knee confirmed a haemarthrosis and excluded bony avulsion. Magnetic resonance imaging (MRI) was suggestive of an ACL tear, with a suspicion of a partial lateral meniscal tear (Fig. 1). Informed consent was gained to assess the patient's knee under anaesthesia with a view to ACL repair.

Operative procedure

Examination under general anaesthesia (EUA) demonstrated a highly positive Lachman and pivot shift test. Arthroscopy performed through anteromedial (AM) and anterolateral (AL) portals revealed normal chondral surfaces and a partial thickness tear to the upper surface of the lateral meniscus. A complete ACL rupture with an empty lateral wall of the femoral notch was noted with a good remnant present (Fig. 2). A decision was made to proceed to direct ACL repair using the internal brace technique as described by MacKay et al. [32].

The torn ACL was initially mobilised and a suture passing device was used to secure a non-absorbable braided suture through the proximal end of the ACL remnant, enabling its subsequent approximation to the femoral ACL footprint. Two bites of the stump were required for satisfactory purchase. A femoral tunnel was made at the footprint using a calibrated paediatric guide. In order to avoid physeal damage, an all-epiphyseal technique was employed on the femoral side: using a paediatric 'outside to in' jig, a 2.4-mm guide wire was passed from the lateral epiphyseal cortex under fluoroscopic control such that it entered the joint in the centre of the femoral footprint. This was subsequently swapped for a 1.4-mm wire over which a 3.2-mm cannulated drill was used. The tibial tunnel was made using a transphyseal technique starting with a 2.4-mm guide wire within a paediatric guide. This tunnel was directed more centrally and vertically than for an adult procedure to minimise potential injury to the tibial tubercle apophysis whilst maintaining a central entry point within the tibial physis. Looped sutures were passed through each tunnel and into the joint. Both looped passing sutures and the suture attached to the ACL stump were simultaneously retrieved through

Fig. 1 Sagittal MRI of the left knee of the 5-year-old child presenting with ACL rupture and lateral meniscus tear (Case 1)

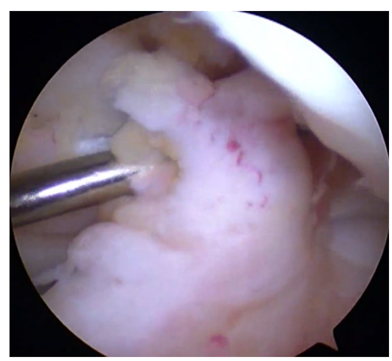

Fig. 2 Arthroscopic image showing ACL rupture with a bare lateral wall of the notch. The ACL remnant is visible

Table 1 Details of three patients included in this report

Case	Age (years)	Gender	Side	Mode of injury	Type of tear	Time to surgery (weeks)	Current follow-up (months)
1	5	Female	Left	Trampoline	Femoral peel-off	5	24
2	6	Male	Right	Skiing	Femoral peel-off	6	12
3	7	Female	Right	Playground	Tibial avulsion	1	21

the AM portal to avoid soft tissue bridging. The internal brace consisted of non-absorbable braided tape (Fiber-Tape, Arthrex, Naples, FL, USA) loaded onto a suspensory cortical fixation device (Tightrope RT), which also served to secure the ACL stump suture. The construct was pulled into the joint through the tibial tunnel and then up into the femoral tunnel using the passing sutures. The suspensory device was deployed under direct vision onto the lateral femoral cortex. The repair was visualised arthroscopically to confirm good approximation of the ACL tissue to its femoral footprint (Fig. 3). A bioabsorbable suture anchor screw was used to secure the distal end of the internal brace within the tibial metaphysis, and the ACL brace construct tension was fine-tuned using the femoral Tightrope.

Modified operative procedure

Two additional children (aged six and seven) have subsequently been treated using an all-epiphyseal technique with 2.4-mm-diameter intra-epiphyseal femoral and tibial tunnels: a looped shuttling suture was passed into the joint through each tunnel and retrieved through the AM portal cannula. The loop of the femoral suture was cut, resulting in two snare sutures: one snare was used to retrieve the ACL repair sutures back through the femoral tunnel; the other snare was attached to the tibial looped suture and pulled out of the joint through the tibial tunnel. This suture was then used to advance the internal brace construct from the lateral femoral cortex, through the femoral tunnel, into the joint and down into the tibial tunnel. Narrower tunnels could be employed with this modification as there was no longer a requirement to pass the suspensory device through the bone tunnels. Only a diameter of 2.4 mm was required to accommodate the sutures and suspensory tape, resulting in removal of less than half the total volume of bone—a particular advantage in these small children.

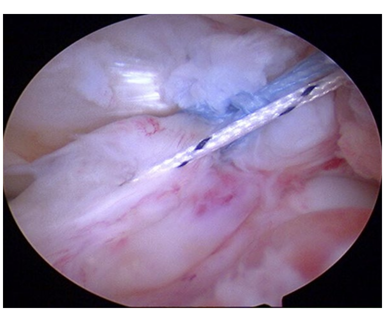

Fig. 3 Arthroscopic image following direct ACL repair using non-absorbable sutures (*blue*) reinforced with an internal brace (*white-striped suture*)

Post-operative course

Post-operative radiographs confirmed correct fixation positioning (Fig. 4), and the knee was immobilised in extension for 4 weeks to facilitate direct healing before commencing active knee flexion.

Outcome scores (KOOS-Child, Lysholm and Tegner) were collected pre-operatively and at up to 2 years post-operatively. Standard post-operative objective laxity testing was precluded because the children's legs were too small to fit within our arthrometer. We therefore measured the pivot shift phenomenon and anteroposterior translation using a triaxial accelerometer at 1 year (KiRa, OrthoKey, Lewes, DE, USA) [6, 38], in comparison with the uninjured contralateral knee. Each measurement was taken three times. Statistical analysis was performed using GraphPad Prism 6 (GraphPad Software Inc, La Jolla, CA, USA).

Results

All patients demonstrated a stable knee with negative Lachman and pivot shift tests at EUA 3 months post-operatively. Repeat arthroscopy in all cases revealed undamaged articular cartilage, no synovitis or persisting meniscal lesion and a healed ACL that was firmly attached to the lateral wall

Fig. 4 Post-operative imaging: **a** anteroposterior and **b** lateral post-operative radiographs confirm implant positioning and fixation. The cortical fixation device is fully seated in direct contact with the thick uncalcified periosteum

of the notch (Fig. 5). Appropriate ACL tension was demonstrated throughout a full range of knee motion with no evidence of impingement. The temporary internal brace and bone fixation devices were removed without difficulty, and further intra-operative examination confirmed knee stability. Subsequent MRI confirmed a taut, healed and well-vascularised ACL in all patients. They returned to all normal activities without limitations at 4 months and remain with stable knees with no detectable clinical or radiological leg growth disturbance beyond 2 years (Fig. 6). Outcome scores demonstrated significant improvements at up to 2 years compared with pre-operative evaluation (Table 2). Objective laxity testing for anteroposterior and pivot shift stability using a triaxial accelerometer demonstrated no significant difference between the operated and contralateral uninjured knee (Table 3).

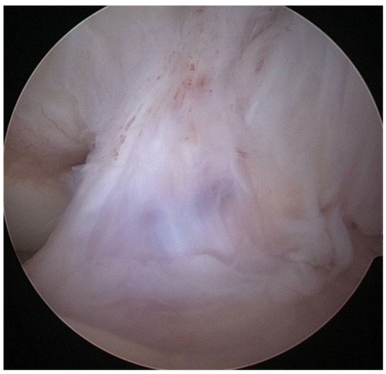

Fig. 5 Arthroscopic image at 3 months post-ACL repair, following removal of the internal brace, showing healed ACL with new tissue obscuring the suture fixation

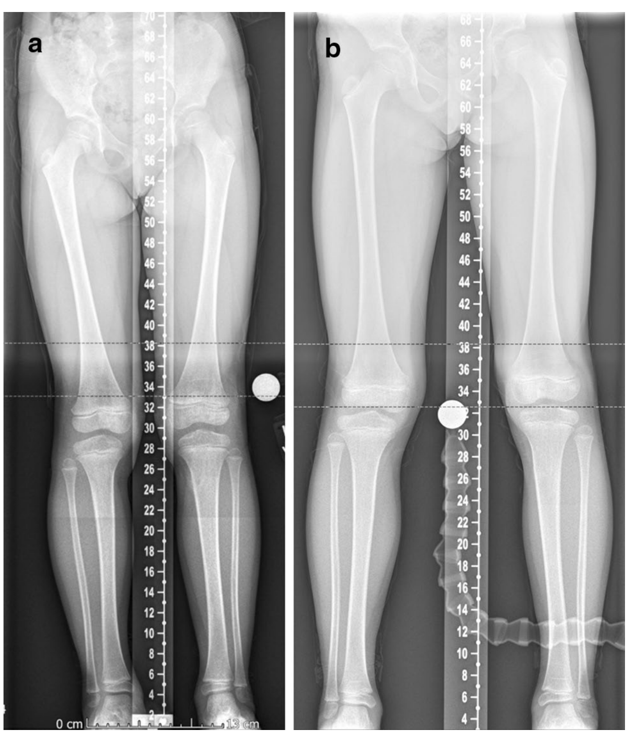

Fig. 6 Long-leg radiographs taken **a** 12 and **b** 24 months post-operatively, confirming equal leg lengths without angular deformity or physeal growth arrest

Discussion

This study demonstrates a new, safe technique in the surgical treatment of young children with ACL injuries with encouraging short-term results. Additional procedures were not required, other than planned removal of the internal brace construct, and no leg length discrepancy or malalignment has been noted. ACL repair in young children using this technique is an attractive alternative to ACL reconstruction. The advantages of repairing the patient's native ACL include maintenance of proprioception and the absence of donor site morbidity. In addition, the requirement to harvest autograft or allograft, and concerns regarding adequate graft dimensions are eliminated.

Support for both operative and non-operative management of skeletally immature patients with ACL ruptures exists, with the majority of recent data leaning towards surgical intervention [41]. Kocher et al. [25] advocated initial immobilisation and restricted weight bearing for the treatment of partial ACL ruptures in children, followed by physiotherapy focusing on hamstring strengthening and a brace during sporting activity. Despite this, 31 % of the non-operated patients required subsequent surgical intervention due to instability or recurrent injury. A systematic review identified only one study where no difference in outcome between operative and non-operative management for complete ACL tears was reported [48, 49]. The authors attributed this to strict adherence of complete abstention from sport and continuous bracing in the non-operative group. Compliance with non-operative management is often difficult in this physically active demographic [10, 37], and with the increasing frequency of ACL ruptures in skeletally immature patients combined with the risk of meniscal and chondral injuries associated with persistent instability, the pendulum has now swung towards operative intervention [28, 44].

Treatment goals for a patient of any age with an ACL injury comprise: the recovery of a stable functional knee; prevention of further intra-articular damage; and expeditious return to daily activities and sport [41]. Timing of surgical intervention is critical; early ACL reconstruction in children (within 6 weeks) is associated with improved results and threefold fewer medial meniscal tears, [36] whereas delayed operative intervention leads to higher

Table 2 Outcome scores and range of movement (ROM) up to latest follow-up for the patients

Case	KOOS-Child		Lysholm		Tegner		ROM (°)	
	Pre-op	Current	Pre-op	Current	Pre-op	Current	Pre-op	Current
1	47.6	95	65	100	1	6	−5 to 130	−3 to 145
2	44.6	92.8	42	100	2	4	−10 to 150	−8 to 150
3	67.3	98.8	58	100	3	7	0 to 145	−5 to 145

Table 3 Objective clinical laxity testing using the KiRa accelerometer at latest follow-up. Each test was performed in triplicate

Case	Pivot shift a_{range} ± SD (m/s^2)			Lachman ± SD (mm)		
	Operated	Contralateral	*p*	Operated	Contralateral	*p*
1	7.8 ± 1.0	8.9 ± 1.0	0.28	7.7 ± 0.6	7.2 ± 0.3	0.27
2	7.1 ± 0.3	7.3 ± 1.0	0.80	9.9 ± 0.2	10.2 ± 0.7	0.54

rates of meniscectomy and lower subjective outcome scores [19]. However, ACL reconstruction in patients with open physes results in a threefold increase in re-rupture rates when compared to the adult population [7, 31]. Smaller graft diameter has been suggested as a cause of failure [33], and mature hamstring allograft has been advocated as a solution [39]. Unfortunately, unrelated allograft tissue has a higher failure rate in primary paediatric ACL reconstruction [4, 13, 47]. Parental donated allograft provides biologically active tissue of greater diameter and is associated with better post-operative outcomes and failure rates, although the associated donor site morbidity to the uninjured parent is undesirable [17]. Perhaps the biggest challenge in these patients is the avoidance of iatrogenic physeal damage, potentially causing unilateral growth arrest, limb length discrepancy and angular deformity [25]. The distal femoral physis is particularly vulnerable due to its irregular contour and high proliferative potential. Utilisation of anatomical landmarks and fluoroscopy is recommended in order to achieve anatomical reconstruction whilst avoiding physeal damage [3, 50]. Transphyseal tibial drilling is of lesser concern as this tunnel is situated centrally within the physis and usually requires removal of less than 3 % of the physeal volume [24]. Up to 7 % of physeal volume can safely be removed if soft tissue graft material alone is placed across the physis [42], although it is critically important to avoid securing fixation devices crossing the physis [9], incomplete filling of the tunnel with graft [42], excessive graft tensioning [12] and the use of bone patella tendon bone graft due to the potential formation of an osseous bridge [20]. The vast majority of angular deformities and growth disturbances have been associated with bone plugs or fixation devices deployed across the physis [26]. Despite these risks, transphyseal ACL reconstruction is frequently performed in skeletally immature patients with good outcomes, no or minimal growth disturbance and a high rate of return to previous activity levels [27, 30, 46]. A number of physeal-sparing reconstruction techniques have been proposed in an effort to avoid impaired growth. The extra-articular Macintosh technique [14, 16] and subsequent modifications have demonstrated good results in various studies with no growth deformities [48]. More contemporary intra-articular procedures, using single or both physeal-sparing techniques, have been described with both methods yielding good results [18, 29, 48]. A meta-analysis of 55 studies (935 patients) for ACL surgery in skeletally immature patients revealed a 1.8 % risk of growth disturbance and re-rupture risk of 3.8 % with a significantly higher risk 0.34 % of angular deformity in the physeal-sparing, transosseous group when compared to the transphyseal transosseous group [15]. Physeal damage has been attributed to the deleterious effects of drilling parallel to the physis, including thermal injury, or from a pressure effect of the implant [48]. The internal bracing was electively removed in all cases presented here after 3 months to mitigate any tethering which could impair physeal growth.

Surgical repair of the ACL is an alternative to reconstruction in the pre-adolescent, avoiding a number of potential pitfalls, including the morbidity of parental allograft harvest and inadequacy of autogenous graft. However, it requires sufficient ACL remnant. Excellent outcomes have been observed thus far, and the technique continues to evolve: a reduction of tunnel diameter from 3.5 to 2.4 mm is significant in this demographic and improves the likelihood of all-epiphyseal reconstruction. Furthermore, the modified procedure circumvents the requirements for inter-osseous passage of suspensory fixation and arthroscopic knot tying. Additionally, any failure of this technique does not preclude future ACL reconstruction by conventional means, and although a second procedure is necessary for the removal of the FiberTape construct, conventional reconstruction options are still available. In addition to three paediatric cases described here, 16 adults with femoral ACL peel-off injuries have been treated in this way, with good early results.

This study has several limitations: as the technique is novel, only three patients are described with heterogeneous clinical presentations, arthroscopic findings and operative technique. Although laxity assessment using triaxial accelerometer data has been validated in adults, this has not to our knowledge been performed in children. Our values for both pivot shift and anteroposterior translation are higher (for operated and normal knees) than those documented for adults, but this may be due to constitutional increased joint mobility present in children. The short follow-up period excludes early failure and growth disturbance, but a longer course is required to assess longevity of this technique into adulthood. Nevertheless, this study demonstrates the potential benefits afforded by new instrumentation, materials and techniques and offers an attractive alternative to ACL reconstruction in children.

Conclusion

Knee instability following ACL rupture in skeletally immature patients can be treated with repair and temporary internal bracing rather than reconstruction, with similar short-term outcomes, if sufficient residual ACL remnant tissue is available.

Acknowledgments We acknowledge Professor Gordon MacKay who provided the initial description of the internal brace.

Compliance with ethical standards

Conflict of interest AJW is a consultant for Arthrex.

Appendix

Videos demonstrating the operative procedure of the first two cases can be found at:

https://www.vumedi.com/video/acl-repair-using-the-internal-brace-in-a-5-year-old/.

http://academy.esska.org/esska/2014/video.library.2014/113073/adrian.wilson.acl.repair.in.a.6.year.old.using.the.internal.brace.technique.html?f=p19l4405m10.

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