Knee Surg Sports Traumatol Arthrosc (2010) 18:1445–1451
DOI 10.1007/s00167-009-1041-4

KNEE

No bone tunnel enlargement in patients with open growth plates after transphyseal ACL reconstruction

S. Kopf · J.-P. Schenkengel · G. Wieners · C. Stärke · R. Becker

Received: 17 July 2009 / Accepted: 26 December 2009 / Published online: 3 February 2010

Abstract Bone tunnel enlargement after ACL reconstruction has been described extensively in adults. However, little is known about this phenomenon in patients with open growth plates. Thus, the goals of the current study were to evaluate changes in bone tunnel size in patients with open growth plates after transphyseal ACL reconstruction with suspensory fixation and to correlate tunnel size with clinical outcome after medium-term follow-up. Fourteen patients with open growth plates were included that underwent primary transphyseal ACL reconstruction using hamstrings autografts and suspensory fixation. Mean follow-up time was 7 years. At the time of follow-up, MRIs of the operated knee were performed, and outcome was assessed using KOS-ADLS, Lysholm score, IKDC Subjective Knee Form score, Knee Examination Form score, and KT-1000 measurements. On MRI, the cross-sectional area of the bone tunnels was assessed using special axial cuts perpendicular to the axes of the tunnels. Two orthopaedic surgeons and two radiologists analysed the MRIs. Change in bone tunnel size from surgery to follow-up was calculated. No significant changes in bone tunnel size from surgery to follow-up were found. Regarding outcome measures, KOS-ADLS averaged 95%, Lysholm Score averaged 96 points, IKDC Subjective Knee Form averaged 95%, IKDC Knee Examination Form scores were 8A, 5B, 1C, and KT-1000 measurements averaged 1.8 ± 1.4 mm. No significant correlations were found between tunnel size at follow-up and outcome measures. Based on our study, bone tunnel enlargement does not occur in patients who have open growth plates and undergo ACL reconstruction using suspensory fixation.

Keywords Anterior cruciate ligament (ACL) · Open growth plate · Skeletally immature · Tunnel enlargement · Suspensory fixation

S. Kopf · C. Stärke
Department of Orthopaedic Surgery, Otto-von-Guericke University of Magdeburg, Magdeburg, Germany
e-mail: mail@koepfchen.org

J.-P. Schenkengel · G. Wieners
Department of Radiology, Otto-von-Guericke University of Magdeburg, Magdeburg, Germany

R. Becker (✉)
Department of Orthopaedic Surgery and Traumatology, City Hospital of Brandenburg, Hochstrasse 26, 14770 Brandenburg, Germany
e-mail: roland_becker@yahoo.de

Introduction

In patients with open growth plates, a controversy still exists on the best treatment choice for torn anterior cruciate ligaments (ACL) [24]. Clinical studies have shown poor outcome in conservative treatment of ACL injuries in children and adolescents. Thus, early reconstruction may be recommended in these patients [27, 36]. Several surgical techniques were initiated, e.g. primary sutures, extra-articular tenodesis, transphyseal reconstructions, partial transphyseal reconstructions, and physeal sparing reconstructions [19, 22]. The fixation technique of the graft is crucial to prevent growth disturbances. Fixation hardware or bone plugs in the bone tunnel should not bridge the growth plate, and the bone tunnels should be filled with tendon across the growth plate [29, 39, 44]. Based on these findings, suspensory graft fixation may be recommended today [26, 43]. However, radiological studies in adults revealed a higher predisposition of bone tunnel enlargement in patients with suspensory graft fixation compared to aperture graft fixation [3, 32]. These studies in adults did not find a correlation between tunnel enlargement and clinical outcome, but bone tunnel enlargement after ACL reconstruction has been suggested to play an important role for revision ACL surgery, which is necessary in about 8% of patients after ACL reconstruction [47]. The purpose of the current study was to evaluate the change in bone tunnel size in patients that underwent transphyseal ACL reconstruction with open growth plates and suspensory graft fixation, and to correlate tunnel size with clinical outcome after medium-term follow-up. Towards this end we hypothesized that in patients with open growth plates and suspensory graft fixation, (1) bone tunnel enlargement occurs after a medium-term follow-up, and (2) bone tunnel size does not correlate with clinical outcome after a medium-term follow-up.

Methods

Patient selection

Fourteen patients with a mean age of 14.4 years (median 14.5 years, range 11–16 years) at the time of surgery were included that underwent primary transphyseal ACL reconstruction. Radiologically, all patients had open distal femoral and proximal tibial growth plates corresponding to Tanner stage 2 and 3 [12]. Patients with combined ligament injuries, fractures, and without any growth between time of surgery and follow-up were excluded. The mean time from injury to surgery was 7.6 months (median 5 months, range 6 days to 39 months). The fourteen patients included six girls and eight boys, with three right and eleven left knees affected. The average time of follow-up was after 7 years (median 8.3 years, range 23–133 months). The patients grew on average 0.08 m (median 0.04 m, interquartile range 0.02–0.07 m) from surgery to follow-up. Two patients underwent bilateral ACL reconstructions. One patient had open growth plates at the time of both surgeries and the other patient had open growth plates only during the first surgery. In this second patient, only the knee with open growth plates at the time of surgery was included. The Ethical Committee of the Otto-von-Guericke University Magdeburg approved this study (#78-2006). All patients signed informed consent.

Operative technique

Primary arthroscopic single-bundle ACL reconstruction was performed in all patients. Both tibial and femoral tunnels were drilled across the growth plate similar to the transtibial technique in adults. In one patient the graft was passed over-the-top at the femoral side; thus, no femoral bone tunnel measurements were performed. Hamstring autografts were used in all cases (Table 1), and suspensory tibial and femoral fixation was applied. Endobutton™ (Smith&Nephew, St. Petersburg, USA) fixation was used at the femoral site, and staples or sutures around a post were used at the tibial side. In addition to the ACL reconstruction, one lateral and two medial menisci were repaired, and one lateral meniscus was partially resected. Postoperatively, patients underwent full weight bearing, bracing with full extension, and a limited knee flexion to 90° continuously for 6 weeks. No complications were noted after surgery.

Bone tunnel measurements

In order to assess the size of the bone tunnels at follow-up, knee MRIs with special cuts were performed at the time of follow-up (1.5 Tesla scanner, Siemens, Erlangen, Germany). Slice thickness was 4 mm. T1-SE sequences were done with special axial cuts strictly perpendicular to the axes of the bone tunnels (Fig. 1). These perpendicular cuts were chosen to standardize the measurements, to measure the tunnel size independently from the drill angle, and to make the measured tunnel size comparable to the drill bit size that was used during surgery. At these special cuts, the size of the bone tunnels was measured at two different locations: (1) at the bone tunnel aperture and (2) 1 cm deep to the aperture (Fig. 2) [6]. Thus, the tunnel size at the aperture and at 1 cm tunnel depth was measured strictly perpendicular to the axes of the tunnels.

At the above-mentioned locations, the widest tunnel diameter (1. diameter) and the diameter strictly perpendicular to the widest diameter (2. diameter) were measured (Fig. 2). Thereafter, the cross-sectional area (CSA) was calculated by using an ellipse model $\left(A = \frac{\pi}{4} \times \text{diameter1} \times \text{diameter2}\right)$. The change in tunnel size from surgery to follow-up was calculated by subtracting the tunnel size calculated using the MRI measurements from the drill bit size that was reported in the surgical notes.

Clinical outcome

To assess clinical outcome, Knee Outcome Survey-Activities of Daily Living Scale (KOS-ADLS) [4, 15], Lysholm

Table 1 Choice of autografts

Grafts	Number of patients
Semitendinosus—two strands	6
Semitendinosus—four strands	3
Semitendinosus/Gracilis—each two strands	5

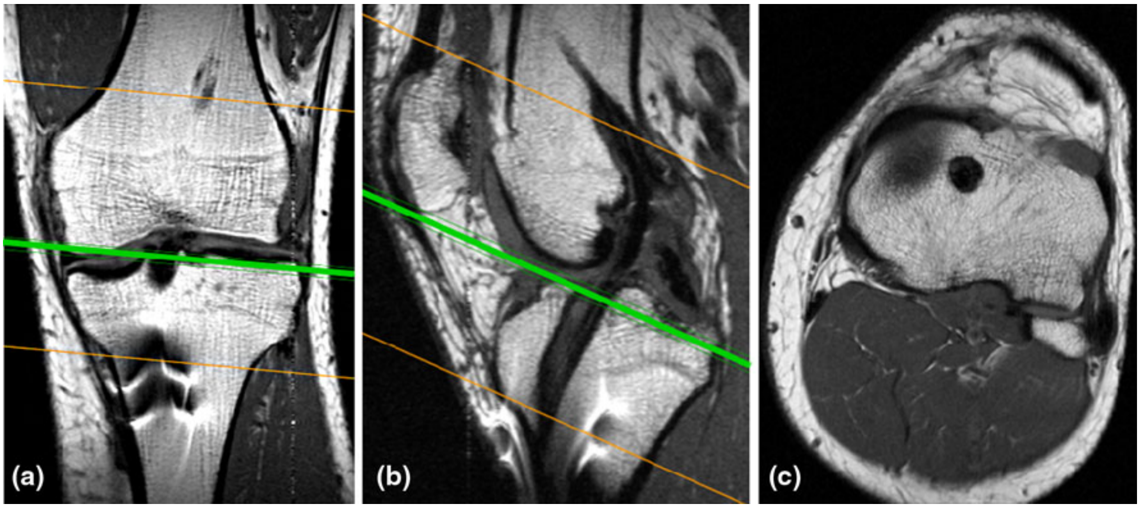

Fig. 1 T1 MRI special transverse cuts strictly perpendicular to the axes of the bone tunnels were used to measure the diameters of the tibial and femoral tunnels. These special cuts were obtained using coronal and sagittal sequences as orientation. **a** Coronal sequence with drawn *lines* of positions of special transverse cuts. **b** Sagittal sequence with drawn *lines* of positions of special transverse cuts. **c** Special transverse cut strictly perpendicular to the tibial bone tunnel

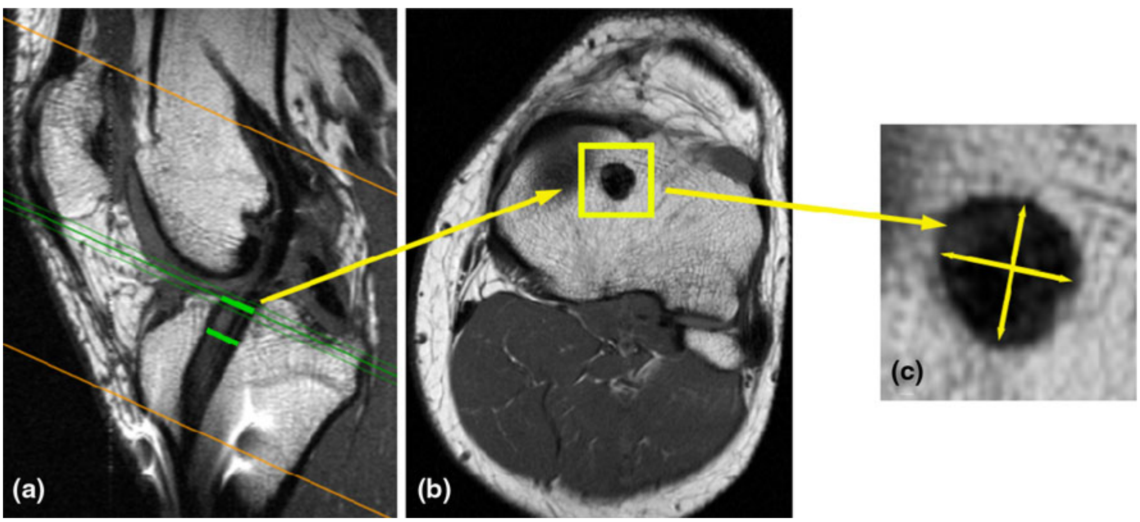

Fig. 2 Measuring points of tibial bone tunnel diameter at the entrance and at a depth of 1 cm (**a**, **b**) achieving the widest diameter and the diameter strictly perpendicular to it (**c**)

Score [45], and International Knee Documentation Committee (IKDC) Subjective Knee Form [14] were completed by the patients at follow-up. Clinical examination included the IKDC Knee Examination Form, and to further quantify the anterior knee laxity, KT-1000 arthrometer measurements were performed (134 N; MEDmetric Corp., San Diego, USA).

Statistical analysis

Wilcoxon signed ranks test was used to evaluate whether or not there was a statistical difference in tunnel CSA from surgery to follow-up. Spearman's rank correlation coefficients were calculated to investigate the correlation between bone tunnel size and clinical outcome. The intraclass correlation coefficient (ICC) was performed to rate the reliability, using an absolute agreement and a two-way random effect model, in which subjects and raters are considered random effects. A *post hoc* sample size estimation was performed (power of 90%). Alpha level for statistical significance was set at $P < 0.05$. Data are given as mean (median, interquartile range) and, if reasonable, the range is also presented. SPSS 18 (Statistical Product and Service Solutions Inc., IL, USA) and Stata 11 (StataCorp, TX, USA) were used for statistical analyses.

Results

The averaged results of the four observers of the MRI measurements at follow-up are summarized in Table 2. The average CSA of the drill bit used during surgery was 43.2 mm^2 (median 38.5 mm^2, interquartile range = 38.5–50.3 mm^2) [average diameter of 7.4 mm (median 7 mm, interquartile range = 7–8 mm)]. The changes in bone tunnel sizes from surgery to follow-up are summarized in Table 3. No significant tunnel size changes were observed from surgery to follow-up (Table 2). The average ICC was 0.73 ± 0.16. Of note, all ACL grafts were intact at the time of follow-up.

Regarding clinical outcome, the KOS-ADLS averaged 95% (median 96%, interquartile range 93–100%). In the subsection "Symptoms," the average score was 95% (median 99%, interquartile range 90–100%), while in the subsection "Activity," the average score was 95% (median 97%, interquartile range 92–100%). The Lysholm Score averaged 96 points (median 100 points, interquartile range 93–100 points). Of the 14 subjects, 11 patients were rated as excellent (>91 points) and three patients as good (84–90 points) according to the Lysholm score. The mean score of the IKDC Subjective Knee Form was 95 points (median 96 points, interquartile range 92–98 points). The IKDC Knee Examination Form was categorized eight times as A, five times as B, and once as C. The subject categorized as C was done so because of a ++ (clunk) pivot shift. Despite this result, this patient scored 97 points on the IKDC Subjective Knee Form, 100 points in the Lysholm score, and 91% in the KOS-ADLS.

An average side-to-side difference of 1.8 mm (median 1.5 mm, interquartile range 1–3 mm) was measured with the KT-1000 arthrometer. All patients demonstrated a normal range of motion with a mean knee flexion angle of 155.7° (median 160.0°, interquartile range 151.3–165.0°) and extension angle of 0.4° (median 0.0°, interquartile range 0.0–0.0°). Clinical evaluation showed no leg deformity.

No significant correlations were found between the clinical outcome data (KOS-ADLS, Lysholm score, IKDC Subjective Knee Form and Knee Examination Form, KT-1000 measurements) and the CSA of the tibial and femoral tunnels (Table 4).

Discussion

The most important finding of the current study was that no significant bone tunnel enlargement was found in patients with open growth plates and suspensory fixation after medium-term follow-up. This finding rejected our first hypothesis. These results contrast findings in adults, where bone tunnel enlargement after ACL reconstruction has been extensively described, especially with suspensory fixated grafts [13, 32, 38, 42].

Different reasons have been given to explain tunnel enlargement after ACL reconstruction, including mechanical causes such as bungee cord effect and windshield wiper effect [46], biological causes such as synovial fluid [7] and inflammatory cytokines in the bone tunnel [48], aggressive rehabilitation, heat exhaustion because of drilling, and immune response to the graft [18]. Almost all fixation techniques and grafts types have been noted to be accompanied by the phenomenon of bone tunnel enlargement in the tibia and femur [32, 38]. However, hamstring grafts placed in the cancellous bone area and fixed suspensorily were more likely to develop this phenomenon [9, 38].

Table 2 Bone tunnel size at follow-up [mean (median, interquartile range)]

	CSA [mm^2]	Widest diameter [mm]	Perpendicular diameter [mm]
Tibia—at aperture	46.9 (44.0, 33.1 to 61.5)	8.2 (8.0, 7.0 to 9.7)	7.1 (7.1, 6.1 to 7.9)
Tibia—at 1 cm depth	43.3 (44.2, 32.1 to 49.6)	7.9 (8.0, 6.8 to 8.4)	6.9 (7.1, 6.0 to 7.6)
Femur—at aperture	40.3 (42.4, 34.0 to 46.8)	7.8 (7.8, 7.3 to 8.6)	6.4 (6.7, 5.7 to 7.0)
Femur—at 1 cm depth	33.1 (34.2, 20.1 to 39.2)	7.1 (7.1, 6.3 to 8.1)	5.8 (5.7, 4.5 to 6.4)

Table 3 Changes in bone tunnel CSA and diameter from surgery to follow-up [mean (median, interquartile range)]

	CSA [mm^2]	1. diameter [mm]	2. diameter [mm]	*P*-value
Tibia—at aperture	3.8 (2.7, −7.7 to 13.6)	0.9 (0.8, 0.0 to 2.2)	−0.3 (−0.3, −1.2 to 0.3)	0.49
Tibia—at 1 cm depth	0.2 (−1.9, −6.3 to 5.4)	0.5 (0.4, 0.0 to 0.9)	−0.4 (−0.7, −1.1 to 0.3)	0.73
Femur—at aperture	−3.9 (−5.4, 14.9 to 7.5)	0.5 (0.5, −0.6 to 1.6)	−1.0 (−1.1, −2.2 to 0.2)	0.31
Femur—at 1 cm depth	−11.1 (−14.1, −24.4 to 1.8)	−0.3 (−0.3, −1.3 to 1.1)	−1.6 (−1.8, −2.6 to −0.6)	0.09

The *P*-value shows whether the tunnel size (CSA) was significantly different from surgery to follow-up ($\alpha < 0.05$)

Table 4 Correlations between tunnel size and clinical outcome data

		KT-1000	IKDC subjective knee form	Lysholm score	KOS-ADLS	IKDC knee examination form
CSA at tibial tunnel aperture	Spearman's ρ	0.143	0.299	0.339	−0.029	0.183
	Sig. (2-tailed)	0.658	0.298	0.236	0.922	0.532
CSA at tibial 1 cm tunnel depth	Spearman's ρ	0.051	0.483	0.464	0.085	0.103
	Sig. (2-tailed)	0.874	0.080	0.095	0.773	0.727
CSA at femoral tunnel aperture	Spearman's ρ	0.328	0.103	0.045	−0.221	0.517
	Sig. (2-tailed)	0.324	0.739	0.884	0.468	0.071
CSA at femoral 1 cm tunnel depth	Spearman's ρ	0.063	−0.379	−0.272	−0.448	0.540
	Sig. (2-tailed)	0.854	0.201	0.369	0.124	0.057

The increased bone tunnel enlargement after ACL reconstruction using suspensory fixation might be because of increased graft motion in the bone tunnel. This increased graft motion would explain the findings of a cadaveric study that showed more anterior-posterior translation and internal rotation with suspensory fixation compared to aperture fixation [16].

However, bone tunnel enlargement increases in vivo through the first 6 months post surgery, and afterwards it decreases slightly without reaching initial tunnel size [6, 35]. In contrast to these findings in adults, in the current study bone tunnel enlargement was not found and one reason might be the high potential of bone growth in patients with open growth plates compared to adults [30, 41].

To evaluate the possible correlation between the tunnel size at follow-up and the clinical outcome, well-known outcome measures were used such as the Lysholm score, KOS-ADLS, IKDC Subjective Knee Form and Knee Examination Form, and KT-1000. The results of the questionnaires and the IKDC Knee Examination Form were similar to other studies evaluating the outcome of ACL reconstruction in patients with open growth plates [1, 10, 20, 22, 28, 31, 40] and slightly superior compared to most of the results in adults [2, 5]. The KT-1000 arthrometer measurements showed an increased antero-posterior knee laxity of 2 mm in the operated knee, which is similar to studies in immature patients regardless of physeal sparing or partial transphyseal techniques [1, 11]. As in previously published adult studies, no significant correlations were found between the above-mentioned outcome measures and the tunnel size at follow-up in our patients with open growth plates. These results confirmed our second hypothesis. This may have occurred because tunnel size does not affect outcome, or the study may not have contained a sufficient number of subjects to detect a correlation. Additionally, the assessment forms have not been validated for children and adolescent yet; thus, it remains questionable whether the results of subjective assessments of children, adolescents, and adults are comparable [37].

In addition to the above-mentioned standard outcome measures, growth disturbances and leg malalignment are important aspects for the outcome of patients with open growth plates after ACL reconstruction. In the current study, none of these complications were observed despite drilling across the growth plates. This might be due to suspensory fixation without bridging the growth plate with hard fixation devices, appropriate drill bit sizes, and appropriate graft tensioning. Previous studies have described growth disturbances caused by hard fixation devices (e.g. bone plugs or screws) that crossed the growth plate [21, 23, 25]. Additionally, animal studies found unfilled bone tunnels [39], graft tensioning with high loads [8, 34], and bone tunnels through the growth plate that exceeded a certain size as causes for growth disturbances [33]. The critical size of the bone tunnel relative to the growth plate to avoid growth disturbances was reported as 13% of the transverse diameter (medial-to-lateral width) and 3% of the CSA. Studies in animals and humans that respected the above-mentioned findings did not find growth disturbances after transphyseal ACL reconstruction [17, 39, 40]. Thus, based on our experience and the experiences of others [22], it seems to be sufficient to use a transphyseal technique and a suspensory fixation for ACL reconstruction in patients with open growth plates and Tanner stage 2–3.

This study has some limitations. Regarding the measurement of the bone tunnel size, CT scans would be superior, but high exposure to roentgen radiation causes ethical difficulties. However, MRI was found useful in other studies evaluating bone tunnel diameter [7]. Furthermore, bone tunnel size at surgery was recorded from the surgical notes, which has been also the standard method in several previously published studies. Additionally, a recent CT study showed that the drill bit size used during surgery is almost similar to the size of the bone tunnel measured immediately after surgery [13]. Moreover, no control group with another treatment option was established. However, a control group may not be necessary because tunnel size at follow-up was compared to tunnel size at the time of surgery. Our sample size is limited; however, patients with open growth plates at the time of ACL reconstruction are rare and our *post hoc* sample size analysis revealed that up to 10,370 patients would be necessary to find a significant difference in bone size from surgery to follow-up. Nevertheless, to our knowledge this was the first study evaluating bone tunnel size change in combination with a clinical assessment using transphyseal tunnel drilling after a mean follow-up time of 7 years.

Conclusions

Bone tunnel enlargement was not observed in patients with open growth plates that underwent ACL reconstruction using suspensory fixation and thus, there might be a decreased concern in revision surgeries about tunnel enlargement in these patients. Additionally, there did not seem to be a correlation between clinical outcome and tunnel size in these patients.

Acknowledgments We wish to thank M. Röpke, M.D. and W. Nebelung, M.D. for their support.

Conflict of interest No potential conflict of interest declared.

References

1. Anderson AF (2004) Transepiphyseal replacement of the anterior cruciate ligament using quadruple hamstring grafts in skeletally immature patients. J Bone Joint Surg Am 86-A(Suppl 1):201–209
2. Asik M, Sen C, Tuncay I, Erdil M, Avci C, Taser OF (2007) The mid- to long-term results of the anterior cruciate ligament reconstruction with hamstring tendons using Transfix technique. Knee Surg Sports Traumatol Arthrosc 15:965–972
3. Baumfeld JA, Diduch DR, Rubino LJ, Hart JA, Miller MD, Barr MS, Hart JM (2008) Tunnel widening following anterior cruciate ligament reconstruction using hamstring autograft: a comparison between double cross-pin and suspensory graft fixation. Knee Surg Sports Traumatol Arthrosc 16:1108–1113
4. Bizzini M, Gorelick M (2007) Development of a German version of the knee outcome survey for daily activities. Arch Orthop Trauma Surg 127:781–789
5. Buchner M, Schmeer T, Schmitt H (2007) Anterior cruciate ligament reconstruction with quadrupled semitendinosus tendon—minimum 6 year clinical and radiological follow-up. Knee 14:321–327
6. Buelow JU, Siebold R, Ellermann A (2002) A prospective evaluation of tunnel enlargement in anterior cruciate ligament reconstruction with hamstrings: extracortical versus anatomical fixation. Knee Surg Sports Traumatol Arthrosc 10:80–85
7. Clatworthy MG, Annear P, Bulow JU, Bartlett RJ (1999) Tunnel widening in anterior cruciate ligament reconstruction: a prospective evaluation of hamstring and patella tendon grafts. Knee Surg Sports Traumatol Arthrosc 7:138–145
8. Edwards TB, Greene CC, Baratta RV, Zieske A, Willis RB (2001) The effect of placing a tensioned graft across open growth plates. A gross and histologic analysis. J Bone Joint Surg Am 83:725–734
9. Fauno P, Kaalund S (2005) Tunnel widening after hamstring anterior cruciate ligament reconstruction is influenced by the type of graft fixation used: a prospective randomized study. Arthroscopy 21:1337–1341
10. Gaulrapp HM, Haus J (2006) Intraarticular stabilization after anterior cruciate ligament tear in children and adolescents: results 6 years after surgery. Knee Surg Sports Traumatol Arthrosc 14:417–424
11. Guzzanti V, Falciglia F, Stanitski CL (2003) Physeal-sparing intraarticular anterior cruciate ligament reconstruction in preadolescents. Am J Sports Med 31:949–953
12. Guzzanti V, Falciglia F, Stanitski CL (2003) Preoperative evaluation and anterior cruciate ligament reconstruction technique for skeletally immature patients in Tanner stages 2 and 3. Am J Sports Med 31:941–948
13. Iorio R, Vadalà A, Argento G, Di Sanzo V, Ferretti A (2007) Bone tunnel enlargement after ACL reconstruction using autologous hamstring tendons: a CT study. Int Orthop 31:49–55
14. Irrgang JJ, Anderson AF, Boland AL, Harner CD, Kurosaka M, Neyret P, Richmond JC, Shelborne KD (2001) Development and validation of the international knee documentation committee subjective knee form. Am J Sports Med 29:600–613
15. Irrgang JJ, Snyder-Mackler L, Wainner RS, Fu FH, Harner CD (1998) Development of a patient-reported measure of function of the knee. J Bone Joint Surg Am 80:1132–1145
16. Ishibashi Y, Rudy TW, Livesay GA, Stone JD, Fu FH, Woo SL (1997) The effect of anterior cruciate ligament graft fixation site at the tibia on knee stability: evaluation using a robotic testing system. Arthroscopy 13:177–182
17. Janarv PM, Wikström B, Hirsch G (1998) The influence of transphyseal drilling and tendon grafting on bone growth: an experimental study in the rabbit. J Pediatr Orthop 18:149–154
18. Jo H, Jun DS, Lee DY, Lee SH, Seong SC, Lee MC (2004) Tibial tunnel area changes following arthroscopic anterior cruciate ligament reconstructions with autogenous patellar tendon graft. Knee Surg Sports Traumatol Arthrosc 12:311–316
19. Kocher MS, Garg S, Micheli LJ (2005) Physeal sparing reconstruction of the anterior cruciate ligament in skeletally immature prepubescent children and adolescents. J Bone Joint Surg Am 87:2371–2379
20. Kocher MS, Garg S, Micheli LJ (2006) Physeal sparing reconstruction of the anterior cruciate ligament in skeletally immature prepubescent children and adolescents surgical technique. J Bone Joint Surg Am 88(Suppl 1 Pt 2):283–293
21. Kocher MS, Saxon HS, Hovis WD, Hawkins RJ (2002) 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 22:452–457
22. Kocher MS, Smith JT, Zoric BJ, Lee B, Micheli LJ (2007) Transphyseal anterior cruciate ligament reconstruction in skeletally immature pubescent adolescents. J Bone Joint Surg Am 89:2632–2639
23. Koman JD, Sanders JO (1999) Valgus deformity after reconstruction of the anterior cruciate ligament in a skeletally immature patient. A case report. J Bone Joint Surg Am 81:711–715
24. Liddle AD, Imbuldeniya AM, Hunt DM (2008) Transphyseal reconstruction of the anterior cruciate ligament in prepubescent children. J Bone Joint Surg Br 90:1317–1322
25. Lipscomb AB, Anderson AF (1986) Tears of the anterior cruciate ligament in adolescents. J Bone Joint Surg Am 68:19–28

26. Matava MJ, Siegel MG (1997) Arthroscopic reconstruction of the ACL with semitendinosus-gracilis autograft in skeletally immature adolescent patients. Am J Knee Surg 10:60–69
27. McCarroll JR, Rettig AC, Shelbourne KD (1988) Anterior cruciate ligament injuries in the young athlete with open physes. Am J Sports Med 16:44–47
28. McIntosh AL, Dahm DL, Stuart MJ (2006) Anterior cruciate ligament reconstruction in the skeletally immature patient. Arthroscopy 22:1325–1330
29. Meller R, Kendoff D, Hankemeier S, Jagodzinski M, Grotz M, Knobloch K, Krettek C (2008) Hindlimb growth after a transphyseal reconstruction of the anterior cruciate ligament: a study in skeletally immature sheep with wide-open physes. Am J Sports Med 36:2437–2443
30. Meyer RA, Meyer MH, Tenholder M, Wondracek S, Wasserman R, Garges P (2003) Gene expression in older rats with delayed union of femoral fractures. J Bone Joint Surg Am 85-A:1243–1254
31. Moksnes H, Engebretsen L, Risberg MA (2008) Performance-based functional outcome for children 12 years or younger following anterior cruciate ligament injury: a two to nine-year follow-up study. Knee Surg Sports Traumatol Arthrosc 16:214–223
32. Nebelung W, Becker R, Merkel M, Ropke M (1998) Bone tunnel enlargement after anterior cruciate ligament reconstruction with semitendinosus tendon using endobutton fixation on the femoral side. Arthroscopy 14:810–815
33. Nordentoft EL (1969) Experimental epiphyseal injuries. Grading of traumas and attempts at treating traumatic epiphyseal arrest in animals. Acta Orthop Scand 40:176–192
34. Ono T, Wada Y, Takahashi K, Tsuchida T, Minamide M, Moriya H (1998) Tibial deformities and failures of anterior cruciate ligament reconstruction in immature rabbits. J Orthop Sci 3:150–155
35. Peyrache MD, Djian P, Christel P, Witvoet J (1996) Tibial tunnel enlargement after anterior cruciate ligament reconstruction by autogenous bone-patellar tendon-bone graft. Knee Surg Sports Traumatol Arthrosc 4:2–8
36. Pressman AE, Letts RM, Jarvis JG (1997) Anterior cruciate ligament tears in children: an analysis of operative versus nonoperative treatment. J Pediatr Orthop 17:505–511
37. Sallis JF (1991) Self-report measures of children's physical activity. J Sch Health 61:215–219
38. Schultz WR, McKissick RC, DeLee JC (2007) Tibial tunnel widening after hamstring tendon anterior cruciate ligament reconstruction: the effect of supplemental aperture fixation with autogenous bone cores. Am J Sports Med 35:1725–1730
39. Seil R, Pape D, Kohn D (2008) The risk of growth changes during transphyseal drilling in sheep with open physes. Arthroscopy 24:824–833
40. Seon JK, Song EK, Yoon TR, Park SJ (2005) Transphyseal reconstruction of the anterior cruciate ligament using hamstring autograft in skeletally immature adolescents. J Korean Med Sci 20:1034–1038
41. Sethe S, Scutt A, Stolzing A (2006) Aging of mesenchymal stem cells. Ageing Res Rev 5:91–116
42. Siebold R (2007) Observations on bone tunnel enlargement after double-bundle anterior cruciate ligament reconstruction. Arthroscopy 23:291–298
43. Simonian PT, Metcalf MH, Larson RV (1999) Anterior cruciate ligament injuries in the skeletally immature patient. Am J Orthop 28:624–628
44. Stadelmaier DM, Arnoczky SP, Dodds J, Ross H (1995) The effect of drilling and soft tissue grafting across open growth plates. A histologic study. Am J Sports Med 23:431–435
45. Tegner Y, Lysholm J (1985) Rating systems in the evaluation of knee ligament injuries. Clin Orthop Relat Res 198:43–49
46. Wilson TC, Kantaras A, Atay A, Johnson DL (2004) Tunnel enlargement after anterior cruciate ligament surgery. Am J Sports Med 32:543–549
47. Wolf RS, Lemak LJ (2002) Revision anterior cruciate ligament reconstruction surgery. J South Orthop Assoc 11:25–32
48. Zysk SP, Fraunberger P, Veihelmann A, Dörger M, Kalteis T, Maier M, Pellengahr C, Refior HJ (2004) Tunnel enlargement and changes in synovial fluid cytokine profile following anterior cruciate ligament reconstruction with patellar tendon and hamstring tendon autografts. Knee Surg Sports Traumatol Arthrosc 12:98–103