20-Year Outcomes of Anterior Cruciate Ligament Reconstruction With Hamstring Tendon Autograft

The Catastrophic Effect of Age and Posterior Tibial Slope

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Background: No well-controlled studies have compared the long-term outcome of anterior cruciate ligament (ACL) reconstruction with hamstring tendon autograft between adolescents and adults. Increased posterior tibial slopes (PTSs) have been reported in the ACL-injured versus controls, but the effect of PTS on the outcome after reconstruction is relatively unexplored.

Purpose: To compare the prospective longitudinal outcome of ''isolated'' ACL ruptures treated with anatomic endoscopic ACL reconstruction using hamstring tendon autograft over 20 years in adolescent and adult cohorts and to examine factors for repeat ACL injury.

Study Design: Case-control study; Level of evidence, 3.

Methods: A single-surgeon series of 200 consecutive patients undergoing isolated primary ACL reconstruction with hamstring tendon autograft were prospectively studied. Subjects were assessed preoperatively and at 2, 7, 15, and 20 years postoperatively. Outcomes included International Knee Documentation Committee (IKDC) Knee Evaluation, IKDC subjective scores, KT-1000 instrumented laxity testing, and radiological evaluation of degenerative change and medial tibial slope. Twenty-year outcomes were compared between those who underwent surgery at the age of 18 years or younger (adolescent group, n = 39) and those who underwent surgery when older than 18 years (adult group, n = 161).

Results: At 20 years, 179 of 200 subjects were reviewed (89.5%). ACL graft rupture occurred in 37 subjects and contralateral ACL injury in 22 subjects. Of those with intact ACL grafts at 20 years, outcomes were not statistically different between adolescents and adults for the variables of IKDC subjective score ($P = .29$), return to preinjury activity level ($P = .84$), current activity level ($P = .69$), or degree of radiological degenerative change at 20 years ($P = .51$). The adolescent group had a higher proportion of grade 1 ligamentous laxity testing compared with the adult group ($P = .003$). Overall, ACL graft survival at 20 years was 86% for adults and 61% for adolescents (hazard ration, 3.3; $P = .001$). The hazard for ACL graft rupture was increased by 4.8 in adolescent males and 2.5 in adolescent females compared with adults. At 20 years, the ACL survival for adolescents with a PTS of $\geq 12°$ was 22%. The hazard for ACL graft rupture was increased by 11 in adolescents with a PTS of $\geq 12°$ ($P = .001$) compared with adults with a PTS $< 12°$.

Conclusion: Repeat ACL injury after isolated ACL reconstruction is common, occurring in 1 in 3 over 20 years. In the absence of further injury, isolated ACL reconstruction using this technique was associated with good long-term outcomes with respect to patient-reported outcomes and return to sports, regardless of age. However, mild ligament laxity and ACL graft rupture after ACL reconstruction are significantly more common in adolescents, especially adolescent males, compared with adults. PTS of 12° or more is the strongest predictor of repeat ACL injury, and its negative effect is most pronounced in adolescents.

Keywords: ACL; cruciate; knee; tibial slope; juvenile

Anterior cruciate ligament (ACL) injuries are being seen with increasing frequency in the young. Factors contributing to this increase include higher rates of sports participation, sports specialization occurring at a younger age, increasing intensity of training and play, and improved

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rates of diagnosis of ACL injury.[19] It is now accepted that ACL reconstruction should be advocated in the young, even before skeletal maturity, and anatomic transphyseal ACL reconstruction can be safely performed to restore functional stability.[19,26] After ACL reconstruction, there is considerable recent evidence that second ACL injuries occur more frequently in the young.[1,21,29,34,37,51]

The sagittal slope of the tibial plateau has only recently been recognized as a significant contributor to primary ACL injuries.[22,43,46,52] It has been suggested that high sagittal posterior tibial slopes increase the relative anterior translation of the tibia relative to the femur,[17,20] and recent robotic models have demonstrated that this is associated with higher flexion and adduction torques on landing tasks, a known contributor to ACL injuries.[7] It has been reported that the mean tibial slope of ACL-injured individuals is higher than that of uninjured control subjects on both radiographic and magnetic resonance imaging (MRI) measures.[15,46-48] Relatively less attention has been paid to the effect of high tibial slopes on further ACL injuries after ACL reconstruction.[18,49] The combined effect of high tibial slope and a young age on reinjury rates after ACL reconstruction is currently unreported.

While it is accepted that rates of second ACL injury are higher in the young, relatively little is known about differences in clinical, radiographic, and subjective outcomes between adolescents and adults over the long term. In this study, we prospectively followed a cohort of 200 subjects undergoing ACL reconstruction without significant chondral or meniscal injury over a 20-year period. At 20 years, we compared clinical, subjective, and radiographic outcomes of ACL reconstruction between a group who underwent reconstruction as adolescents (aged 18 or younger) and a group who underwent reconstruction as adults (age >18 years) and examined the combined effect of age and tibial slope on repeat ACL injuries. We hypothesised that, over 20 years, adults and adolescents would have equivalent patient-reported and clinical outcomes but that a higher incidence of repeat ACL injury would be seen in adolescents over adults and in those with tibial slopes of 12° or more compared with <12°.

METHODS

Patient Selection

Subjects who underwent ACL reconstruction with hamstring tendon autograft between October 1993 and March 1996 under the care of the senior surgeon were eligible for inclusion (n = 1131 subjects). The following exclusion criteria were applied: (1) associated ligament injury requiring surgical treatment, (2) evidence of significant chondral damage or degeneration, (3) previous meniscectomy, (4) excision of more than one-third of one meniscus at the time of reconstruction, (5) abnormal radiographic findings, (6) any abnormality in the contralateral knee, (7) those seeking compensation for their injuries, and (8) those who did not wish to participate in a research program. The first consecutive 100 males and 100 females who met the inclusion criteria formed the study group. Ethical approval was obtained from a local independent human research ethics committee (St Vincent's Human Research Ethics Committee, Sydney, Australia). Reconstruction was performed once the knee had recovered from the acute trauma of the ACL injury and patients had a pain-free, mobile joint.

Operative Technique

A standardized surgical technique and postoperative rehabilitation protocol was followed for all patients. The technique and rehabilitation regimen has previously been reported in detail.[14,41] This was a "single-incision" endoscopic technique using a 4-strand ipsilateral hamstring autograft. Anatomic femoral tunnel drilling was performed via the anteromedial portal. Graft fixation was achieved with a 7 × 25-mm titanium RCI interference screw in all subjects (Smith & Nephew) in both the femoral and tibial tunnels. Surgery was performed as a outpatient procedure. Subjects were permitted to weightbear as tolerated on crutches immediately after surgery, and no brace was used. An accelerated rehabilitation program was instituted, supervised by a physical therapist, with the aim of achieving full extension by 2 weeks and full range of motion by 6 weeks. At the time of postoperative rehabilitation for these subjects, intensive plyometric, agility, and sports-specific training was not routinely instituted. Return to competitive sport involving jumping, pivoting, or side-stepping was prohibited until 6 months after the reconstruction, after clinical confirmation of ligamentous stability by the surgeon.

Patient-Reported Outcome Measures and Clinical Evaluation

Subjects were evaluated preoperatively; at 6 months, 12 months, and annually until 5 years; and then at 7, 15, and 20 years after surgery. Assessment included the International Knee Documentation Committee (IKDC) Knee Ligament Evaluation Form in its early version until the 7-year review[23,27] and then using the updated version at 15 and 20 years.[27] Ligament laxity was assessed with Lachman test, pivot-shift test, and the KT-1000 arthrometer (Medmetric Corp) using the side-to-side difference of manual maximum

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anterior displacement between knees. The single-legged hop test was used for functional assessment.

Radiological Evaluation

Before surgery and at 2, 7, 15, and 20 years after surgery, weightbearing anteroposterior, 30° flexed posteroanterior, patellofemoral, and lateral knee radiographs were performed. All radiographs were assessed by an independent musculoskeletal radiologist (J.L.) for radiographic features of osteoarthritis. Osteoarthritis was graded according to the IKDC radiological grading system,[27] where A is normal, B indicates minimal changes (small osteophytes, slight sclerosis, or flattening of the femoral condyle) and narrowing of the joint space that is just detectable, C indicates moderate changes and joint space narrowing of up to 50%, and D is severe changes such as a joint space <2 mm or narrowing of the joint space >50%. The worst compartment of the medial, lateral, and patellofemoral compartments determines the overall IKDC radiological grade.

Sagittal femoral and tibial osseous tunnel position was measured on lateral knee radiographs, and graft inclination was measured in the coronal plane on anteroposterior radiographs using a method previously described.[39] Ideal radiological tunnel position was defined as the tibial tunnel being 40% to 50% posterior along the tibial plateau in the sagittal plane, femoral tunnel >80% posterior along Blumensaat's line in the sagittal plane, and a graft inclination angle of greater than 15° in the coronal plane.[39]

Sagittal tibial slope was measured by 2 knee fellowship–trained orthopaedic surgeons using OsiRix software on the best available digitized lateral radiograph of the knee using a method previously described.[49] The tibial slope was calculated by measuring the angle between a line drawn tangentially to the medial tibial plateau and the proximal anatomic axis (PAA) of the tibia. The PAA is determined by a line connecting the midcortical diameters of the tibia at a point 5 and 15 cm distal to the knee joint. One assessor repeated the measures after a period of 2 weeks to assess intraobserver reliability.

Statistical Analysis

The outcomes were compared between selected subgroups using the Student t test for continuous measurements (mean KT-1000 arthrometer, radiological tunnel placement) and chi-square tests for categorical variables (IKDC categories, Lachman, pivot-shift test). Changes in mean instrumented laxity testing over time were assessed with paired t tests. Multiple logistic regression was performed to assess the relative contribution of age, sex, and side on the 2- and 20-year ligament laxity testing. Intraobserver and interobserver reliability of the tibial slope measures was assessed with intraclass correlations. Survival of the ACL graft and contralateral ACL was calculated using the Kaplan-Meier survival method with 95% CIs. Survival curves were compared with univariate Cox regression. Factors that approached significance ($P < .10$) on univariate survival analysis were entered into multivariate Cox regression and then eliminated in a stepwise fashion until only the independent significant factors remained. Statistical significance was set at 5%.

RESULTS

Study Group

Overall, 100 male and 100 female consecutive participants undergoing isolated ACL reconstruction with hamstring tendon autograft under the care of the senior surgeon who met the inclusion and exclusion criteria formed the study group. The mean age at surgery was 25.8 years, and 152 patients (76%) had their reconstructions performed within 12 weeks of injury. There were 99 left-sided reconstructions and 101 right-sided reconstructions. At the time of surgery, 176 patients (88%) had intact lateral menisci and 184 (92%) had intact medial menisci. Twenty (10%) had meniscal tears requiring suturing, and 20 (10%) required excision of less than one-third of the meniscus. Mean follow-up was 236 months (range, 212-257 months).

The participant flow is shown in Figure 1. Of the 200 participants recruited to the study, 179 (90%) were reviewed at 20 years. Of the 21 patients not reviewed, 5 refused continuing participation in the study, 8 did not respond to review requests, and 8 were not located. Subjects with intact ACL graft and contralateral ACL completed full IKDC, clinical, and radiographic assessment. Subjects who had a contralateral ACL injury completed subjective review and radiographic assessment only, as IKDC clinical review requires comparison to a "normal" contralateral knee. Of the 37 subjects who sustained an ACL graft rupture, 32 underwent revision ACL reconstruction. All 37 subjects who sustained an ACL graft rupture were excluded from the analysis of full clinical assessment, radiological, and subjective review. For the purposes of the survival analysis, all 200 subjects were included in the analysis; in the case of those lost to follow-up, subjects were included but censored after their last attendance. This model assumes that censored patients are considered to have survival prospects similar to those of the participants who continued to be followed.

Study participants were divided into 2 groups: those who had surgery at the age of 18 or younger (adolescent group, n = 39) and those who were >18 years at the time of surgery (adult group, n = 161). There was a higher proportion of females in the adolescent group, compared with the adult group ($P = .01$). The mean age of the adolescent group was 16 years (range, 14-18), and the mean age of the adult group was 28 years (range, 19-52 years). There were no subjects in this study with open growth plates at the time of surgery.

Patient-Reported Outcomes

At 20 years, there were 163 participants with intact ACL grafts, and patient-reported outcomes were completed on 149 (91%). There were no significant differences between the adolescent and adult groups for patient-reported outcomes at 20 years (Table 1).

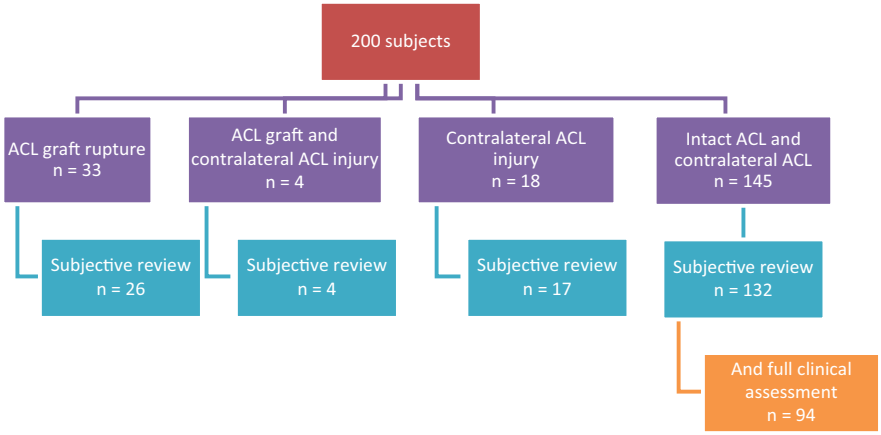

Figure 1. Participant flow. ACL, anterior cruciate ligament.

TABLE 1
Selected Demographics and Comparison of Patient-Reported Outcome Measures for Adolescent and Adult Groups[a]

	Adolescent	Adult	*P* Value
No. of subjects with intact ACL at 20 years	24	139	
No. of subjects reviewed at 20 years	23 (96)	126 (91)	
No. of females	17 (74)	57 (45)	.01
No. of right knees	14 (61)	66 (52)	.453
Mean graft diameter, mm	6.8	6.8	.531
Mean sagittal tibial slope, deg	8.6	8.9	.584
IKDC subjective score/100 at 20 years, mean	87	89	.292
Regular activity level at 20 years			
Strenuous/very strenuous	14 (61)	77 (61)	.691
Moderate	6 (26)	30 (24)	
Light	3 (13)	19 (15)	
Return to preinjury level of sport at any time	18 (78)	101 (80)	.835
Current knee-related decrease in activity level	5 (22)	20 (16)	.489
Current knee function, mean/10	8.7	8.9	.671
No or minimal kneeling difficulty	18 (78)	101 (80)	.904

[a]Data provided as n (%) unless otherwise noted. IKDC, International Knee Documentation Committee.

Clinical Assessment

Clinical examination with the IKDC evaluation requires comparison to a normal contralateral knee. Clinical IKDC evaluation was performed at 20 years on 97 of the 145 (67%) participants with an intact ACL graft and contralateral ACL.

IKDC Evaluation

The IKDC evaluation includes subcategories of effusion, range of motion, ligament evaluation, and overall IKDC grade. The percentage of subjects with a normal IKDC grade for each IKDC subcategory is shown in Figure 2. There was no significant difference between the adolescent and adult groups for the variables of effusion and range of motion. When compared with adults, significantly fewer adolescents had a normal ligament evaluation (P = .003) and overall IKDC evaluation (P = .07).

If those with an ACL graft rupture are attributed with an abnormal grade, then the proportion of patients with a normal or nearly normal overall IKDC grade at 20 years was 15 of 31 (48%) in the adolescent group and 77 of 98 (79%) in the adult group (P = .006).

Ligament Evaluation

The adolescent group had a significantly lower proportion of subjects with normal laxity on pivot-shift testing (P = .003), instrumented laxity (P = .03), and overall IKDC ligament grade (P = .002) (Figure 3). The comparison of adolescent and adult laxity testing is shown over time in Figure 4. The mean manual maximum side-to-side difference in KT-1000 instrumented testing was 2.6 mm (SD, 1.7) in the adolescent group and 1.2 mm in the adult group (P = .02).

Multiple logistic regression was performed to assess the relative contribution of age, sex, and side on the 20-year

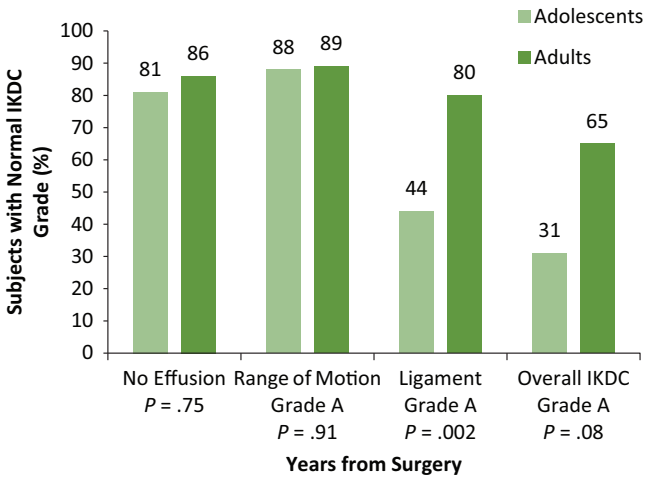

Figure 2. Percentage of adolescents and adults with ''normal'' subgroup and overall International Knee Documentation Committee (IKDC) grades at 20 years.

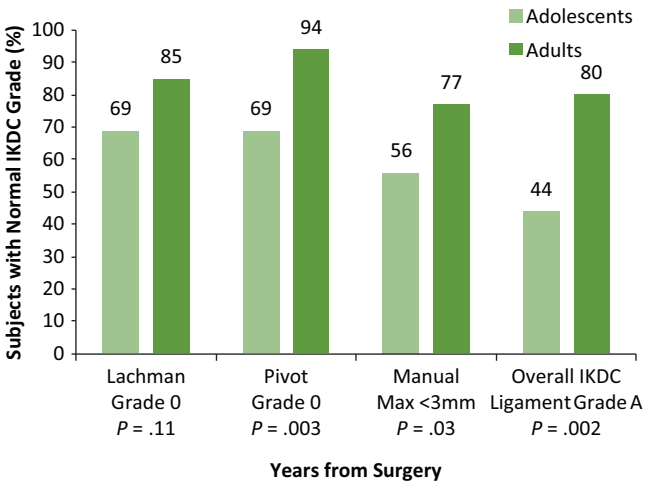

Figure 3. Percentage of adolescents and adults with ''normal'' International Knee Documentation Committee (IKDC) ligament grades at 20 years.

IKDC ligament laxity grade. The results are shown in Table 2. Ligament laxity testing performed at 2 years after surgery was also examined with the same multiple regression analysis. At 2 years, greater ligamentous laxity was associated with female sex (odds ratio [OR], 4.0; 95% CI, 2.0-8.0; P = .001), not adolescents (OR, 1.7; 95% CI, 0.7-4.1; P = .23) or right knees (OR, 1.5; 95% CI, 0.7-2.9; P = .27).

Single-Legged Hop Test

Hop testing was performed on 82 patients at 20 years. Eight patients did not complete hop testing due to pregnancy or injury to other joints. Overall, 9 of 15 adolescents (60%) and 56 of 67 adults (84%) were able to hop within 90% distance of their contralateral limb at 20 years (P = .08).

Radiological Assessment

Assessment of radiological degenerative change was assessed with the IKDC radiological grade. A total of 99 adults and 22 adolescents had radiographs available for evaluation at 20 years. The worst compartment of the medial, lateral, and patellofemoral compartments determines the overall IKDC radiological grade. Preoperatively and at 2 years, no patient had an abnormal radiological examination. No significant difference was found in the incidence of radiological osteoarthritis between the adolescent and adult groups at 20 years (P = .283). Moderate to severe radiological degenerative change was evident in 20 of the 121 subjects (17%) at 20 years. The results are shown in Table 3.

Radiological Tunnel Placement

Radiological tunnel placement was determined in 191 of the 200 patients. The mean sagittal femoral tunnel placement was 84% posterior (SD, 7%), the mean sagittal tibial tunnel placement was 47% (SD, 6%), and the mean graft

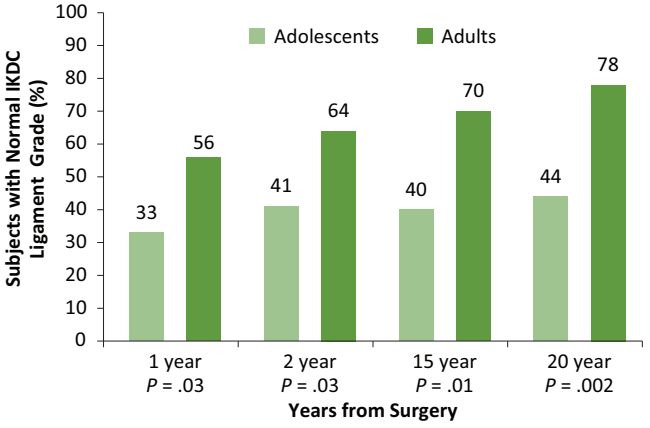

Figure 4. Percentage of adolescents and adults with ''normal'' overall International Knee Documentation Committee (IKDC) ligament grade over time.

angle was 18° (SD, 5°). The ideal tunnel position has been defined as being a sagittal tibial tunnel 40% to 50% anterior, sagittal femoral tunnel 80% to 90% posterior, and coronal graft inclination greater than 17°.[9,39] Ideal tunnel position was evident in 43 of the 191 subjects' radiographs (23%). There was no significant difference between adolescents and adults with respect to sagittal femoral tunnel position (P = .68), sagittal tibial tunnel position (P = .288), or graft angle (P = .387). The tunnel position could be assigned ideal in 7 of the 39 adolescents (18%) and in 36 of the 152 adults (24%; P = .444).

Radiological Tibial Slope

Measurement of radiological tibial slope was possible in 182 of the 200 subjects using lateral radiographs.

TABLE 2
Results of Regression Analysis: The Relationship Between 20-Year IKDC Laxity Grade and Age, Sex, and Side of Reconstruction[a]

Factor	Adjusted OR	95% CI	*P* Value
Age 18 years or younger	4.6	1.4-14.7	.010
Female sex	1.2	0.4-3.3	.710

[a]IKDC, International Knee Documentation Committee. OR, odds ratio.

Measurement was performed by 2 orthopaedic fellows, and 1 orthopaedic fellow repeated the measurements 2 weeks apart. The interobserver reliability was 0.64 (intraclass correlation), and the intraobserver reliability was 0.75 (intraclass correlation). This represents substantial reliability according to the guidelines of Landis and Koch.[31] The mean tibial slope was 8.9° (SD, 2.9°). There was no significant difference between adults and adolescents for mean tibial slope (mean 8.6 for adolescents and mean 8.9 for adults; $P = .672$); 37 subjects (20%) (inclusive of 9 adolescents, 26%) had a tibial slope of 12° or more, and 147 (80%) had a tibial slope of <12°. Tibial slope measures were distributed in a similar pattern for adults and adolescents (Figure 5).

ACL Graft Rupture

Over 20 years, 15 of the 39 adolescents (38%) and 22 of the 161 adults (14%) sustained a rupture of the ACL graft ($P = .001$). The Kaplan-Meier survival for ACL reconstruction in all patients was 93% at 2 years, 89% at 5 years, 85% at 10 years, 83% at 15 years, and 80% at 20 years. Survival of the ACL graft was examined with univariate Cox regression as a factor of age <18 years, sex, tibial slope, radiological tunnel placement, and family history of ACL injury (Table 4). Independent factors that were significantly associated with ACL graft rupture on univariate regression analysis (age and tibial slope) are demonstrated with Kaplan-Meier survival curves in Figures 6 to 9 and included in a stepwise multiple regression analysis to determine the relative contribution of each variable. On multiple regression analysis, ACL graft survival was significantly affected by the factor of age <18 years at the time of reconstruction (hazard ratio, 3.3; 95% CI, 1.7-6.4; $P = .001$) and a posterior tibial slope of 12° or more (hazard ratio, 3.1; 95% CI, 1.5-5.9; $P = .001$).

Contralateral ACL Rupture

Contralateral knee ACL rupture occurred in 5 of the 39 adolescents (13%) and 17 of the 161 adults (11%) ($P = .59$). Three adolescents and 1 adult suffered both a contralateral ACL and ACL graft rupture. Details of univariate analysis of contralateral ACL survival at 20 years are presented in Table 5, and the Kaplan-Meier survival curve for tibial slope is shown in Figure 8. Independent factors that trended toward significance ($P < .10$) with contralateral ACL rupture on univariate regression analysis (family history of ACL injury and tibial slope) were included in a stepwise multiple regression analysis to determine the relative contribution of each variable. On multiple regression analysis, contralateral ACL injury was significantly affected only by the factor of posterior tibial slope of 12° or more (hazard ratio, 7.3; 95% CI, 3-18; $P = .001$).

TABLE 3
Comparison of IKDC Radiological Grade for Adolescent and Adult Groups at 20 Years[a]

	Adolescent, n (%)	Adult, n (%)	*P* Value
No. of subjects	22	99	
Grade A	17 (77)	56 (57)	.283
Grade B: minimal changes	3 (14)	25 (25)	
Grade C: joint space narrowing of up to 50%	2 (9)	12 (12)	
Grade D: include a joint space of less than 2 mm or >50% joint space narrowing	0 (0)	6 (6)	

[a]IKDC, International Knee Documentation Committee.

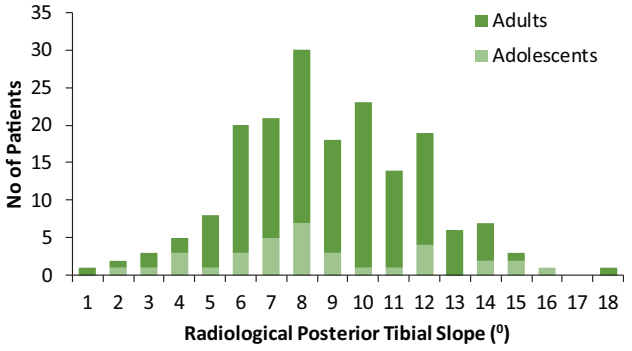

Figure 5. The distribution of tibial slope in adults and adolescents.

Other Subsequent Surgery/Complications

Seventy-five subjects underwent further knee surgery. Revision ACL reconstruction was performed on 32 of the 37 subjects who sustained an ACL graft rupture. Contralateral ACL reconstruction was performed on 17 patients. Subsequent meniscectomy was performed in 14 subjects on the ipsilateral knee and 6 on the contralateral knee. Osteotomy was performed in 2 subjects. Three underwent excision of cyclops lesion, 1 underwent excision of tibial ganglion and screw, and 1 underwent removal of loose body. There were no deep infections or postoperative thrombosis in this series.

DISCUSSION

In this study, we compared the outcomes in adolescents and adults after isolated endoscopic ACL reconstruction

TABLE 4
Univariate Analysis of Anterior Cruciate Ligament (ACL) Graft Survival at 20 Years[a]

Factor and Category	n	No. of ACL Graft Ruptures	ACL Graft Survival, y					Hazard Ratio	95% CI	*P* Value[b]
			2	5	10	15	20			
All subjects	200	37	93	89	85	83	80			
Age at ACL reconstruction										
Adolescent	39	15	85	77	72	64	61	3.3	1.7-6.3	**.001**
Adult	161	22	96	93	89	88	86			
Age and sex										
Male adolescent	13	7	77	77	62	54	46	4.8	1.8-12.7	**.001**
Female adolescent	26	8	88	77	77	69	69	2.6	1.0-6.5	**.048**
Male adult	87	12	97	92	88	87	86	1.0	0.4-2.3	.995
Female adult	74	10	96	95	90	89	87	Reference		
PTS, deg										
12 or more	37	14	84	72	67	67	62	3.0	1.6-5.9	**.001**
<12	147	23	96	93	89	86	84			
Age and PTS										
Adolescent and PTS 12° or more	9	7	78	44	33	33	22	11.1	4.5-27.5	**.001**
Adolescent and PTS <12°	26	8	92	85	81	73	69	2.7	1.2-6.5	**.02**
Adult and PTS 12° or more	28	7	93	85	78	74	74	2.3	0.9-5.7	.07
Adult and PTS <12°	119	15	97	95	91	90	88	Reference		
Family history of ACL rupture										
Yes	42	11	90	86	79	74	74	1.7	0.9-3.6	.127
No	146	24	95	92	88	86	85			
ACL graft diameter, mm										
<7	92	21	92	85	82	80	83	1.7	0.9-3.2	.126
7 or more	107	16	95	94	89	86	85			
Radiological tunnel placement										
"Non-ideal"	148	29	95	89	84	82	79	1.1	0.5-2.4	.848
"Ideal"	43	8	93	93	88	88	84			

[a]ACL, anterior cruciate ligament; PTS, posterior tibial slope.
[b]Boldface indicates statistical significance ($P < .05$).

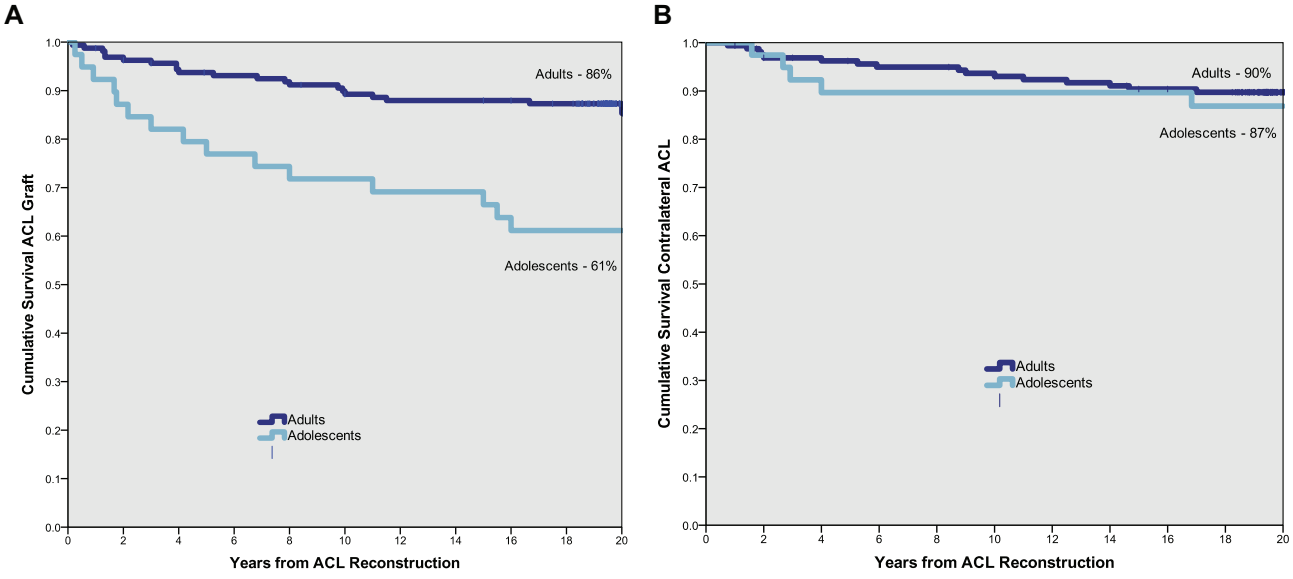

Figure 6. Cumulative survival of the reconstructed anterior cruciate ligament (ACL) and contralateral ACL according to age.

with hamstring tendon autograft and interference screw fixation over 20 years. We found that patients who were adolescents at the time of ACL reconstruction (aged 18 or younger) had significantly greater clinical laxity and a higher rate of ACL graft rupture compared with their adult counterparts. No significant differences were found

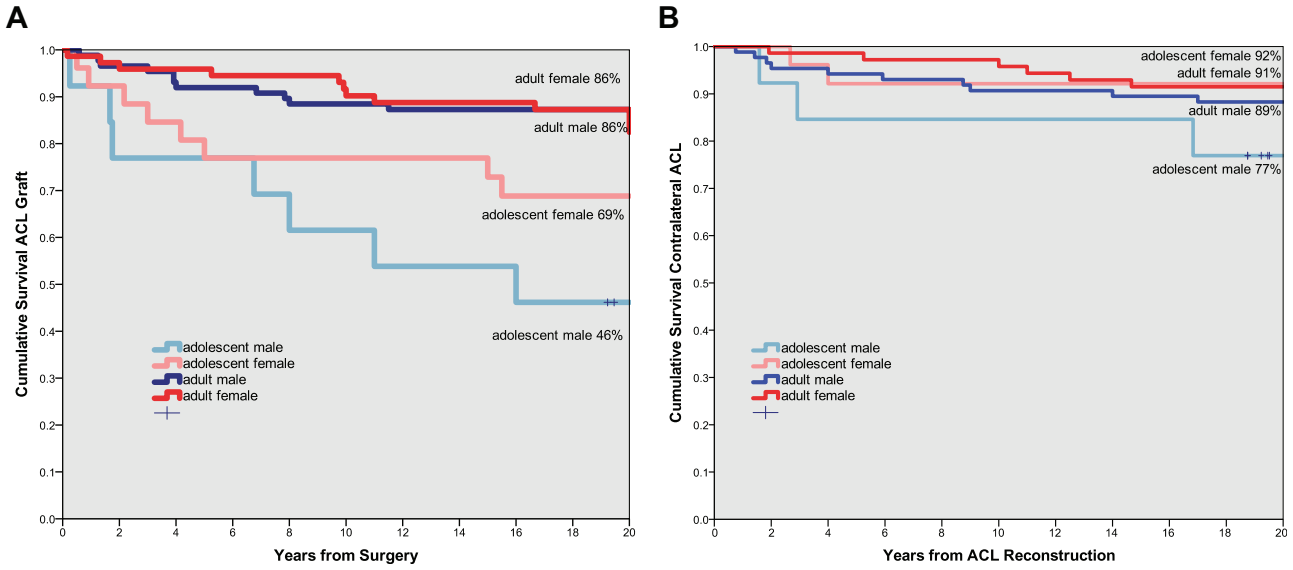

Figure 7. Cumulative survival of the reconstructed anterior cruciate ligament (ACL) according to age and sex.

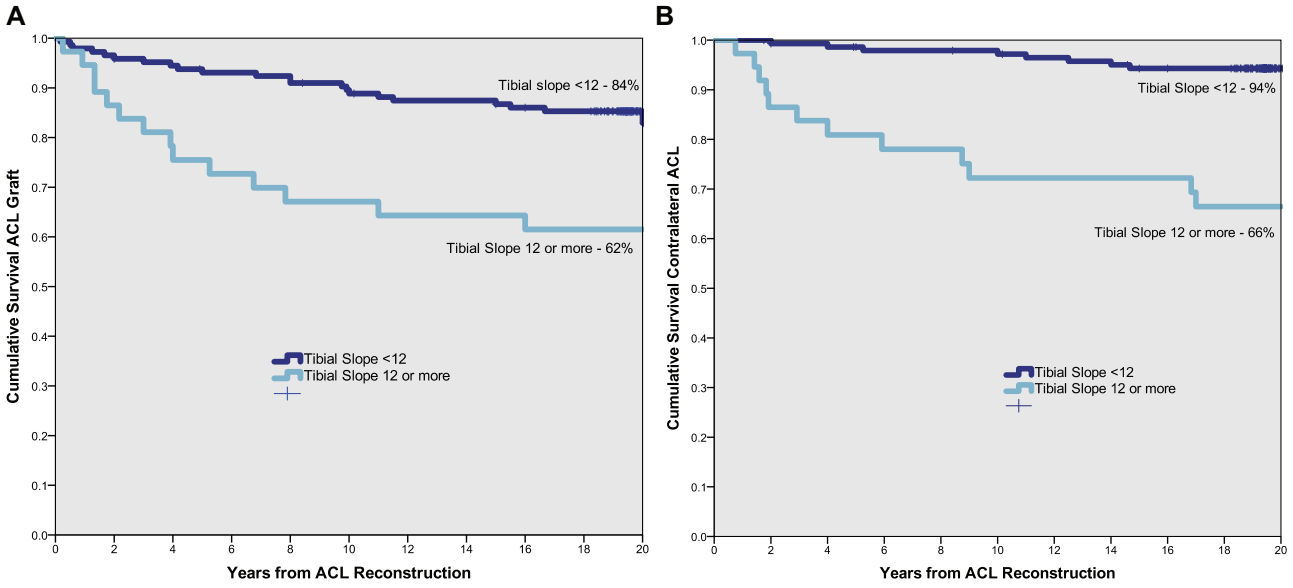

Figure 8. Cumulative survival of the reconstructed anterior cruciate ligament (ACL) and contralateral ACL according to radiographic sagittal tibial slope.

between adults and adolescents for activity level, patient-reported outcomes, radiological osteoarthritis, or functional assessments. While both young age and posterior tibial slope $\geq$12° were independent predictors of second injury, the combined effect of these factors on ACL graft rupture was marked.

High posterior tibial slope had a catastrophic effect on further ACL injury, especially in the adolescent cohort and in the first few years after surgery. Adolescents with a tibial slope of $\geq$12° were 11 times more likely to rupture their ACL graft and 7 times more likely to rupture their contralateral ACL than were adults with tibial slopes of <12°. The steep incline of the survival curve shown in Figure 9 demonstrates that these injuries occur within the first few years after an ACL reconstruction, with more than half of the adolescents sustaining a graft rupture within 5 years. Adults with a posterior tibial slope of more than 12° were 7 times more likely to injure their contralateral ACL and trended toward a higher rate of graft rupture that did not reach statistical significance (P = .07) compared with adults with a posterior tibial slope of <12°. While these findings are alarming, it must be realized that tibial slopes of more than 12° are seen in only about 20% of the study cohort. So, for the vast majority of the population, the rate of repeat ACL injury is conversely low over 20 years. High posterior tibial slopes may be responsible for those rare patients for

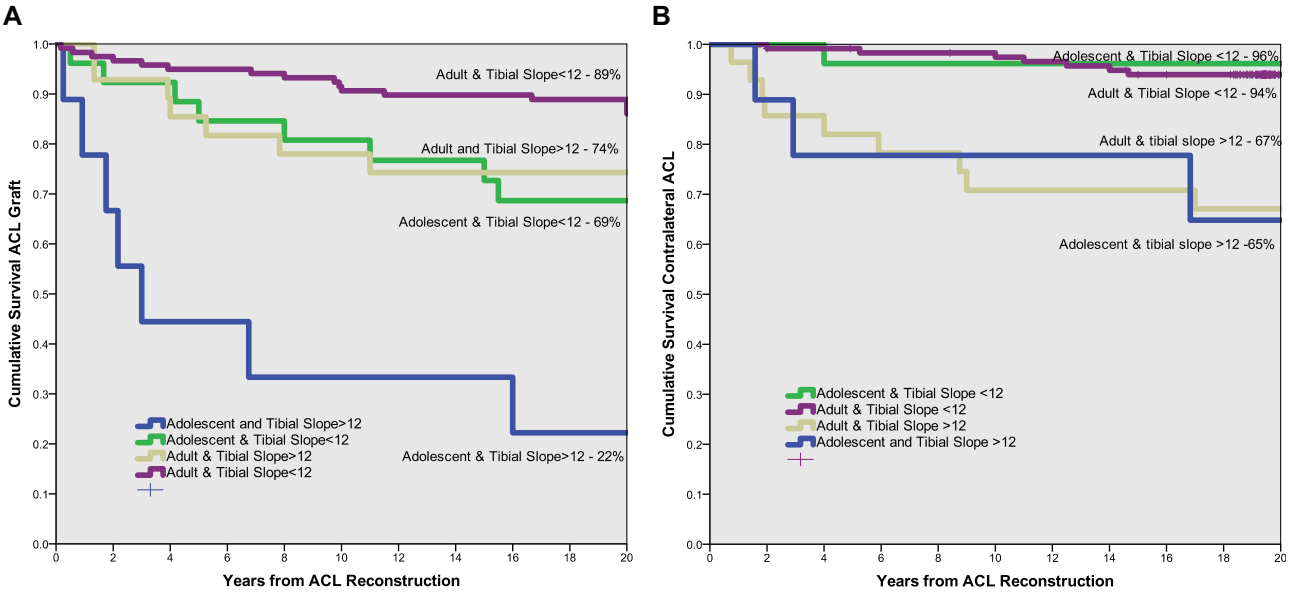

Figure 9. Cumulative survival of the reconstructed anterior cruciate ligament (ACL) and contralateral ACL according to age and radiographic sagittal tibial slope.

whom multiple ACL injuries occur, despite an anatomic ACL reconstruction and appropriate rehabilitation, with which many ACL surgeons and therapists may be anecdotally familiar.

The body of literature substantiates that mean tibial slopes are higher in primary ACL-injured individuals than in uninjured controls.[15,46-48,52] After ACL reconstruction, there are fewer studies that examine tibial slope; nevertheless, the findings of a positive association with further injury are consistent.[12,49] What is less clear is how to best manage those active individuals who have a very high posterior tibial slope. A recent study of 1090 cadaveric tibiae reported that the mean osteological posterior slope of the medial tibial plateau is 7° and the lateral tibial plateau is 5°.[50] Some authors have recently advocated correction of "pathological" tibial slopes (defined as >12°) in athletes with multiple ACL injuries using anterior closing-wedge osteotomies at the time of revision ACL reconstruction.[16,18,44] However, the reported outcome of this procedure is limited to 2 series, with 5[44] and 9[16] subjects in each, followed for a minimum of 2 years. Both studies report no recurrent instability or further ACL injuries, but these limited data are currently insufficient to support this approach. The alarming finding of only a 22% ACL graft survival for adolescents with tibial slopes of 12° or more warrants careful consideration, and our findings raise many questions we cannot answer. When examining this cohort previously, we concluded that more consistent anatomic tunnel placement would improve outcomes.[9,39] Whether further modifications to the surgical technique or advice regarding return to sports should be considered, or even whether the ACL reconstruction is indicated in this cohort, remains open to debate. The solution to this difficult clinical problem remains unsolved.

Despite the strong association between posterior tibial slope and further injury, we would advise caution in interpreting radiographic tibial slope measures. There is a lack of consistency regarding whether the medial or lateral tibial plateau slope is most relevant, which is the most robust measurement method, and whether radiographs or MRI scans are more reliable.[18] Testing performed in this study demonstrated substantial reliability for both interrater (intraclass correlation, 0.64) and intraobserver (intraclass correlation, 0.75) reliability, but we remain concerned that the radiological method of measuring tibial slope is highly reliant on the quality of the radiograph, the rotation of the tibia,[50] and the experience of the measurer. While tibial slope is certainly a contributing factor to ACL injuries, a more accurate, robust, and relevant measurement method is needed.[52]

Over 20 years, adolescents were 3 times more likely to have an ACL graft rupture than were adults. This is a consistent finding in the literature. Younger age has been identified as a risk factor for ACL graft rupture of a magnitude of 2 to 7 times in large multicenter registries from the United States,[29,34] Sweden,[1,3] Scandinavia,[21] Denmark,[33] and Norway.[38] In a large series of 750 patients, Wiggins et al[51] recently reported that subjects younger than 20 years at the time of ACL reconstruction were 6 times more likely to sustain a graft rupture than were patients 20 years and older over the first 3 years. Young age may well be a proxy for other factors.[51] Although there was no significant difference in reported activity levels between the adolescents and adults at 20 years in our series, others have found that the young returned to sports after rehabilitation harder, faster, and for longer than did their adult counterparts,[10,42] which could also contribute to this elevated risk of injury. Other potential contributors to the elevated risk of injury in adolescents may include a genetic predisposition and anatomic, biomechanical, and neuromuscular considerations of the adolescent knee.

TABLE 5
Univariate Analysis of Contralateral Anterior Cruciate Ligament (ACL) Survival at 20 Years[a]

Factor and Category	n	No. of Contralateral ACL Injuries	Contralateral ACL Survival, y					Hazard Ratio	95% CI	*P* Value[b]
			2	5	10	15	20			
All subjects	200	22	97	95	92	90	89			
PTS, deg										
12 or more	37	12	84	78	72	72	66	7.3	3.0-18.0	**.001**
<12	147	9	99	98	97	94	94			
Age and sex										
Male adolescent	13	3	85	85	85	85	77	2.7	0.7-10.5	.15
Female adolescent	26	2	96	92	92	92	92	0.9	0.2-4.3	.88
Male adult	87	10	95	93	91	89	88	1.2	0.5-3.2	.70
Female adult	74	7	99	97	96	92	92	92		
Age and PTS										
Adolescent and PTS 12° or more	9	3	89	78	78	78	65	7.3	1.9-28.2	**.004**
Adolescent and PTS <12°	26	1	96	96	96	96	96	0.7	0.1-5.4	.70
Adult and PTS 12° or more	28	9	86	82	71	71	67	6.7	2.5-17.9	**.001**
Adult and PTS <12°	119	8	99	99	97	94	94	Reference		
Family history of ACL rupture										
Yes	42	8	93	86	83	81	81	2.2	0.9-5.1	.08
No	146	14	97	96	95	92	91			
Age at ACL reconstruction, y										
18 or younger	39	5	92	90	90	90	87	0.75	0.3-2.0	.589
>18	161	17	97	95	93	90	90			

[a]ACL, anterior cruciate ligament; PTS, posterior tibial slope.
[b]Boldface indicates statistical significance ($P < .05$).

ACL reconstruction in active subjects is frequently performed with the explicit aim of returning to pivoting and jumping sports. Reassuringly, both adolescents and adults over 20 years reported consistently high mean IKDC scores (87 and 89, respectively, at 20 years), a very high proportion reported returning to their preinjury sports (78% and 80%, respectively), and many continued to participate in strenuous sports (61%). These rates of return to sports are higher than reported in some other series. Ardern et al[5] reported that <50% returned to their preinjury level of sport in a survey of 314 subjects, and 65% returned to their preinjury level of sport in a meta-analysis of 7556 subjects.[4] The longer period of follow-up of this series may favor a return to preinjury sport, as well as the selection criteria that include only those without significant meniscal or cartilage injury at the time of surgery. These selection criteria were applied to exclude the confounding negative effects of meniscal and chondral injuries and account for 1 in 3 subjects undergoing ACL reconstruction during the study period. Therefore, this group constitutes the "best-case scenario" after ACL reconstruction, which may account for this cohort's favorable long-term outcomes.

Clinical ligament laxity testing demonstrated greater ligamentous laxity in the adolescent group compared with the adult group at 20 years. However, the magnitude of the difference was small (mean, 1.4 mm), with adolescents demonstrating a higher proportion with mild laxity (grade 1, 3-5 mm) rather than pathological laxity (grade 2). This may account for the finding that this mild laxity did not translate to lower patient-reported outcomes or rates of sports participation in the adolescents. Indeed, others have shown that instrumented laxity and Lachman tests were poor predictors of subjective and functional outcome after ACL reconstruction.[30,32] If when interpreting the overall IKDC grade at 20 years we categorize all subjects who had an ACL graft rupture as abnormal, then at 20 years a normal or nearly-normal overall IKDC grade was seen in 77% of adults and only 48% of adolescents. It can be concluded that adolescents have inferior outcomes to adults after ACL reconstruction over 20 years in this series.

Previous studies have demonstrated a relationship between greater ligamentous laxity and female sex[41] and right-sided reconstructions[14] over short-term follow-up. The adolescent group in this series did have a higher proportion of females compared with the adults, which may bias the results. To address this, we examined the relative contribution of sex, side, and laxity on 20-year laxity testing and found that young age was a stronger predictor of ligamentous laxity (OR, 4.6) than was female sex (OR, 1.2) or side of surgery (OR, 1.3). However, we also repeated multiple regression testing on the 2-year laxity testing data and found that sex was a significant factor for 2-year laxity over young age. Figure 4 demonstrates that adolescents had consistently higher laxity testing, but this achieved statistical significance only at 15- and 20-year reviews. In summary, female sex may predict short-term laxity and young age may predict long-term laxity.

There have been significant advances over the last decade in the field of rehabilitation after ACL reconstruction and in prevention of ACL injuries. While the population studied in this series may be representative of current surgical techniques, they did not receive a rehabilitation program consistent with current practices. A greater understanding of timing of second ACL injuries[8]

and the biology of the remodeling of the ACL graft[13] has altered our practice to advise delaying a return to competitive sports for 12 months after reconstruction. This is in contrast to a 6-month delay in returning to competitive sports that was applied to this study cohort. The advent of far greater understanding and implementation of neuromuscular training, positive movement patterns, landing techniques, sports-specific programs, a focus on plyometrics, and agilities have great potential to positively affect both rates of return to play and rates of second ACL injury.[5,25,35,51] Hewett et al[24] and Myer et al[36] reported that neuromuscular training programs may be most beneficial in adolescents for preventing primary ACL injuries, and these programs have been successfully incorporated into rehabilitation after ACL reconstruction.[35] Given that 44% of the adolescents studied in this series had a second ACL injury over 20 years and that ACL graft rupture was increased by a factor of nearly 5 times in adolescent males and 2.6 times for adolescent females compared with adults, the importance of completing successful criteria-based rehabilitation and returning to sports both at a suitable time and at an optimal level of performance for the adolescent population is imperative. Particular attention to adolescents and those with tibial slopes of 12° or more with regard to education, delaying a return to play, and completing an effective and complete rehabilitation may be warranted to reduce the high rate of reinjury in these populations.

The majority of subjects in this series (60%) displayed no evidence of radiological degenerative change 20 years after their ACL reconstruction. Mild changes were seen in 23%, and moderate to severe radiological osteoarthritis was evident in only 17%. There was no significant difference in radiological grade between the adolescent and adult groups at 20 years ($P = .51$). Since the mean age of study participants was 45 years at the 20-year review, the incidence of osteoarthritis after ACL reconstruction with regard to moderate to severe degenerative change may be considered comparable with the normal population.[45] The prevalence of knee osteoarthritis has been reported in the literature as 26% in the age group 55 to 65 years.[28] Few studies examine ACL reconstruction over 20 years, but Risberg et al[40] recently reported very similar findings of radiographic osteoarthritis observed in the tibiofemoral compartment in 42% and in the patellofemoral compartment in 21%, 20 years after ACL reconstruction in 168 subjects, with a higher prevalence of osteoarthritis evident in those with combined injuries. Higher rates of radiographic osteoarthritis have been reported by others at 14 years after ACL reconstruction with a transtibial approach,[6] and a recent systematic review and meta-analysis of 615 subjects reported moderate to severe radiologic changes evident in 20% 10 years after ACL injury.[2] Our study may reveal lower rates of degenerative change compared with other series, owing to the selection of participants without significant concurrent injuries to the menisci and articular cartilage. Our radiological findings should be interpreted with caution as only 61% of the original cohort completed radiological examination at 20 years. Like other authors,[11] we are unable to conclude that ACL reconstruction prevents osteoarthritis in this series.

The strengths of this study lie in the prospective longitudinal nature over a 20-year period and the very low rates of loss to follow-up. The surgical technique was reproduced by a single experienced surgeon, eliminating multiple operator bias, utilizing a modern ACL reconstruction technique. However, significant limitations should be acknowledged. As previously stated, the population studied represents only those without significant meniscal or articular cartilage injury at the time of surgery, which is associated with considerably worse outcomes and survival.[37] The high proportion of subjects with a second ACL injury to either the reconstructed or contralateral limb meant that clinical examination, which assumes a normal contralateral limb and the primary ACL graft in situ, was invalidated for >25% of the population studied. With respect to follow-up, although 91% of subjects completed self-reported outcomes at 20 years, only 65% attended the full physical clinical assessment, and 61% underwent radiological examination at 20 years, introducing the possibility of bias. However, for the purposes of survival analysis, all subjects were censored at the time of the last examination. In addition, it should be noted that although we compare adolescents and adults in this study, the adolescent cohort is not representative of the juvenile skeletally immature subject, as only 4 subjects were aged <15 years at the time of surgery, and none had open growth plates. Furthermore, the number of subjects in the adolescent group was smaller than in the adult group. Finally, this study was initially designed as a prospective case series of all ACL reconstructions, not specifically designed to compare adolescents and adults. A more robust study design would involve a prospective design with appropriate power and large sample sizes for both cohorts. Despite these limitations, we were able to detect statistically significant and important clinically relevant differences between cohorts.

CONCLUSION

At 20-year evaluation, isolated ACL reconstruction using hamstring tendons autograft is a reliable and reproducible procedure associated with good long-term outcomes. Adolescents had inferior outcomes compared with adults with respect to ACL laxity testing, but the magnitude of this difference was small and had no effect on activity level, patient-reported outcomes, or return to sports. Adolescents, especially male adolescents, had an unacceptably elevated rate of ACL graft rupture compared with adults. Sagittal tibial slope appears to be a strong predictor of both reconstructed and contralateral ACL injury after reconstruction, and its negative effect is even more pronounced in adolescents.

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