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The tibial attachment of the anterior cruciate ligament in children and adolescents: analysis of magnetic resonance imaging

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Abstract Recent studies have demonstrated that skeletally immature athletes with an ACL injury may require surgical reconstruction if they return to high-demand sports. This study used MRI to compare the anatomy of the ACL in skeletally immature and adult subjects. Measurements were recorded in the sagittal plane for the anterior-posterior dimension of the proximal tibia, and the anterior, center, and posterior limits of the ACL, and the roof inclination angle of the femur. These values were compared to established reference values for adult knee anatomy. In skeletally immature women (*n*=7) the ACL anterior limit, center and posterior limit, and roof inclination angle were 28%, 46%, 63%, and 38°, respectively, compared to 28%, 44%, 60%, and 35° in adult women. In skeletally immature men (*n*=15) the ACL anterior limit, center, posterior limit, and roof inclination angle were 27%, 43%, 59%, and 40°, respectively, compared to 28%, 44%, 59%, and 37° in adult men. In the younger subjects the overall dimensions of the proximal tibia were smaller than that in adults, but the anatomical landmarks for the ACL were proportional. If ACL reconstruction is performed in skeletally immature subjects, the smaller dimensions of the tibia need to be considered, and the use of anatomical landmarks is an important factor in graft placement

Keywords Anterior cruciate ligament · Anatomy · Pediatric · Magnetic resonance imaging · Knee injury

Introduction

The incidence of middle-substance anterior cruciate ligament (ACL) tears in children is unknown, although studies have provided evidence that this injury is now recognized more frequently in children and adolescents [1, 2, 8, 10, 11, 12, 13, 14, 16, 19, 20, 21, 26, 28, 42, 43, 46, 47, 50, 52, 53, 54, 57, 65, 69, 75]. Recent studies of skeletally immature subjects with ACL tears have demonstrated that nonoperative treatment results in poor outcomes, especially in children who return to sports [3, 20, 26, 57].

Historically, ACL reconstruction in children has not been recommended, because of concerns about potential physeal injuries from placement of transphyseal drill holes. Theoretically, these physeal injuries could lead to leg length discrepancy and/or angular deformity [7, 27, 44, 68, 77]. Many studies have advocated physeal-sparing techniques, although these techniques can result in nonanatomical graft placement, which may compromise the long-term stability of the knee [1, 12, 56, 60, 66, 72]. Recent studies have developed algorithms for treating ACL injury in skeletally immature patients, which include surgical reconstruction in carefully selected patients [1, 6, 12, 39, 45, 46, 49, 52, 53, 55, 56, 59, 66, 70].

Successful anterior cruciate reconstruction requires precise anatomical placement of the graft [30, 37]. The anatomy of the insertion of the ACL on the tibial plateau is well defined in the literature for adults [4, 17, 23, 24, 25, 61, 62]. The purpose of this study was to compare the anatomy of the ACL insertion in skeletally immature patients to that in adults.

Materials and methods

A database of children who underwent diagnostic magnetic resonance imaging (MRI) was reviewed. In all selected cases the physeal plates were open, and there were no injuries of the tibial plateau or ACL. The study consisted of 22 patients (mean age 12.4±1.1 years): 15 men (mean age 12.7, range 11–15) and 7 women (mean age 12.3 years, range 12–14). Scan dates ranged from early 1996 to late 1998 (Tables 1, 2).

The methods of Staubli and Rauschning [73] were used to analyze the MRI data and to determine the measurements of the ACL and proximal tibia. Staubli and Rauschning [73] employed magnetic resonance arthrography (MRA) using intra-articular gadopentate dimeglumine. Our patients underwent MRI without the use of intra-articular contrast. The following measurements were taken from the sagittal images, measured at the midpoint of the ACL in the sagittal plane (Fig. 1):

- Total anterior-posterior dimension of the proximal tibia
- ACL anterior limit: distance from the anterior aspect of the tibia, to the anterior fibers of the ACL on the tibia plateau
- ACL center: calculated by determining the midpoint between the ACL anterior and posterior limits
- ACL posterior limit: distance from the anterior aspect of the tibia, to the posterior fibers of the ACL on the tibia plateau
- Roof inclination angle: measured on the sagittal image in which the ACL was best visualized in the intercondylar notch

The values for skeletally immature subjects obtained in our study were compared to the published MRA values for adult men and women, described by Staubli and Rauschning [73] (Fig. 1). Subjects were separated by sex. The anatomical data on adults derived from the study by Staubli and Rauschning [73] did not include standard deviations for the MRA images. Because of this the values for standard deviations are reported here only for skeletally immature subjects.

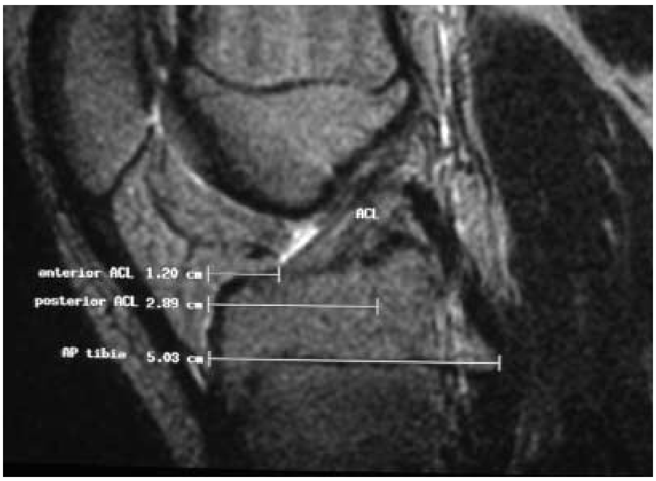

Fig. 1 Total anterior-posterior dimension of the proximal tibia. ACL anterior limit: distance from the anterior aspect of the tibia, to the anterior fibers of the ACL on the tibia plateau: ACL posterior limit: distance from the anterior aspect of the tibia to the posterior fibers of the ACL on the tibia plateau

MRI protocol

Patients were scanned on either a GE Signa LX 1.5 T (Milwaukee, Wis., USA) or a Siemens Symphony 1.5 T (Erlangen, Germany). All images were obtained with the patient in supine position, knee in extension, and externally rotated approximately 15°. T1-weighted spin-echo sagittal images were obtained in all patients (TR range 400–800, TE range 7–20). T2-weighted spin-echo or fast spin-echo fat saturation sagittal, coronal, and axial images were also obtained in each patient (TR range 3000–6000, TE range 85–100). Slice thickness was 3.0 mm and gap width was 1.0 mm. Matrix size was 256×256. The images were then downloaded to an independent workstation for analysis. The T1- and T2-weighted sagittal images were preferred for anatomical measurements. All linear and angular measurements were made with standard workstation tools with values obtained recorded for later analysis. In some patients special cartilage sequences were obtained with reconstruction in the sagittal plane. On the GE Signa these were three-dimensional fast spoiled gradient recall fat suppression sequences and on the Siemens Symphony three-dimensional fast low-angle shot fat suppression sequences.

Radiographic measurement protocol

Measurements of the ACL and tibial plateau were made using an electronic cursor on an AGFA workstation. The anterior-posterior distances were measured by the criterion of Staubli and Rauschning [73] and included the posterior horn of the tibia. This measurement was taken on the sagittal slice that best bisected the ACL (Fig. 1). The distances from the anterior border of the tibia to the anterior and posterior point of ACL insertion were also measured. The roof inclination angle was also measured electronically but on

Fig. 2 Roof inclination angle. The roof inclination angle was measured on the sagittal image in which the ACL was best visualized in the intercondylar notch

the sagittal image in which the ACL was visible in the intercondylar notch (Fig. 2).

Results

Women

In the skeletally immature women in our series the anterior-posterior width of the tibia was 4.83±0.24 cm, compared to adult values of 4.90 cm. The ACL anterior limit was 1.37±0.19 cm (28% of the total width of the tibia) for the skeletally immature, compared to adult values of 1.34 cm (28% of the total width of the tibia). The ACL center was 2.21±0.21 cm (46% of the total width of the tibia) for the skeletally immature, compared to adult values of 2.14 cm (44% of the total width of the tibia). The ACL posterior limit was 3.05±0.34 cm (63% of the total width of the tibia) for the skeletally immature, compared to adult values of 2.94 cm (60.0% of the total width of the tibia). The roof inclination angle was 38.4±1.4° for the skeletally immature, compared to adult values of 35.2° (Table 1).

Men

In the skeletally immature men in our series the anterior-posterior width of the tibia was 4.98±0.56 cm, compared to adult values of 5.37 cm. The ACL anterior limit was 1.38±0.21 cm (28% of the total width of the tibia) for the skeletally immature, compared to adult values of 1.52 cm (28% of the total width of the tibia). The ACL center was 2.16±0.27 cm (43% of the total width of the tibia) for the skeletally immature, compared to adult values of 2.37 cm (44% of the total width of the tibia). The ACL posterior limit was 2.94±0.35 cm (59% of the total width of the tibia) for the skeletally immature, compared to adult values of 3.21 cm (59% of the total width of the tibia). The roof inclination angle was 40.1±3.1° for the skeletally immature, compared to adult values of 36.8° (Table 2).

The ACL landmarks for adult patients (anterior limit, center, and posterior limit) were compared to those obtained for the skeletally immature patients (Fig. 3). Although the overall dimensions of the skeletally immature patients are smaller than those of the adult patients, the ACL landmarks occur at proportionally similar anatomical regions as those in adults.

Discussion

The results of our study demonstrate that skeletally immature knees have similar proportional ACL attachment anatomy as that of adults (Fig. 3). The absolute dimensions of the proximal tibia are smaller in younger patients, and this anatomical difference needs to be considered if ACL reconstruction is planned in skeletally immature patients. When adjusted for size, the ACL anterior limits, center, and posterior limit are similar when comparing adults to skeletally immature individuals.

The results of this study demonstrate some variation in the anatomical parameters of the ACL attachment. Anatomical variation is to be expected in studies of this type due to differences between subjects and the inherent limitations of this measurement technique. MRI images for the knee usually generate sagittal widths of 3.0–4.5 mm. In most cases the ACL can be visualized on two or perhaps three sequential images, and the best image was selected for measurement. Because of the width of the sections

Table 1 Women

Subject no.	Age (years)	Sex	AP tibia measured mid-ACL	Width of ACL attachment site	Distance from anterior tibia to anterior fibers of ACL	Percent tibial plateau anterior to ACL	Distance from anterior tibia to mid-ACL	Distance from anterior tibia to mid-ACL	Percent of anterior tibia to mid-ACL	Distance from anterior tibia to posterior fibers of ACL	Distance from anterior tibia to posterior fibers of ACL	Percent tibial plateau anterior to posterior fibers of ACL	Roof inclination angle where ACL is visible in the notch
1	12	F	4.72	1.81	1.31	28	1.86	2.22	47	2.4	3.12	66	39
2	12	F	4.59	1.12	1.36	30	1.64	1.92	42	1.91	2.48	54	36
3	12	F	4.93	1.44	1.26	26	1.67	1.98	40	2.08	2.70	55	40
4	12	F	4.97	2.05	1.42	29	2.05	2.45	49	2.67	3.47	70	39
5	13	F	5.24	1.41	1.78	34	2.12	2.48	47	2.45	3.19	61	40
6	14	F	4.81	1.95	1.25	26	1.86	2.22	46	2.46	3.20	66	39
7	14	F	4.56	1.98	1.21	27	1.83	2.20	48	2.45	3.19	70	38
Mean	12.7		4.83	1.68	1.37	28	1.86	2.21	46	2.35	3.05	63	38
SD	1.0		0.24	0.35	0.19	3	0.18	0.21	3	0.26	0.34	7	1
Staubli averages	41.5		4.90		1.34	28			44			60	35

Table 2 Men

Subject no.	Age (years)	Sex	AP tibia measured mid-ACL	Width of ACL attachment site	Distance from anterior tibia to anterior fibers of ACL	Percent tibial plateau anterior to ACL	Distance from anterior tibia to mid-ACL	Distance from anterior tibia to mid-ACL	Percent of anterior tibia to mid-ACL	Distance from anterior tibia to posterior fibers of ACL	Distance from anterior tibia to posterior fibers of ACL	Percent tibial plateau anterior to posterior fibers of ACL	Roof inclination angle where ACL is visible in the notch
1	11	M	4.78	1.47	1.26	26	1.68	2.00	42	2.1	2.73	57	40
2	11	M	3.55	1.07	0.92	26	1.23	1.45	41	1.53	1.99	56	37
3	11	M	4.37	1.65	1.21	28	1.71	2.04	47	2.2	2.86	65	44
4	11	M	5.25	1.79	1.47	28	1.99	2.37	45	2.51	3.26	62	37
5	12	M	4.71	1.45	1.19	25	1.61	1.91	41	2.03	2.64	56	41
6	12	M	5.23	1.74	1.51	29	2.01	2.38	46	2.5	3.25	62	44
7	12	M	5.62	1.63	1.62	29	2.06	2.44	43	2.5	3.25	58	41
8	12	M	5.23	1.22	1.69	32	1.97	2.30	44	2.24	2.91	56	44
9	12	M	5.46	1.51	1.47	27	1.88	2.22	41	2.29	2.98	55	41
10	13	M	4.81	1.56	1.40	29	1.84	2.18	45	2.28	2.96	62	42
11	13	M	5.57	1.60	1.52	27	1.96	2.32	42	2.4	3.12	56	44
12	13	M	4.70	1.59	1.10	23	1.59	1.90	40	2.07	2.69	57	37
13	13	M	4.59	1.60	1.31	29	1.78	2.11	46	2.24	2.91	63	40
14	14	M	5.62	1.72	1.61	29	2.09	2.47	44	2.56	3.33	59	33
15	15	M	5.25	1.89	1.36	26	1.93	2.31	44	2.5	3.25	62	40
Mean	12.3		4.98	1.6	1.38	28	1.8	2.16	43	2.3	2.94	59	40
SD	1.2		0.56	0.2	0.21	2	0.2	0.27	2	0.3	0.35	3	3
Staubli Averages	35.4		5.37			28		2.37	44		3.21	59	37

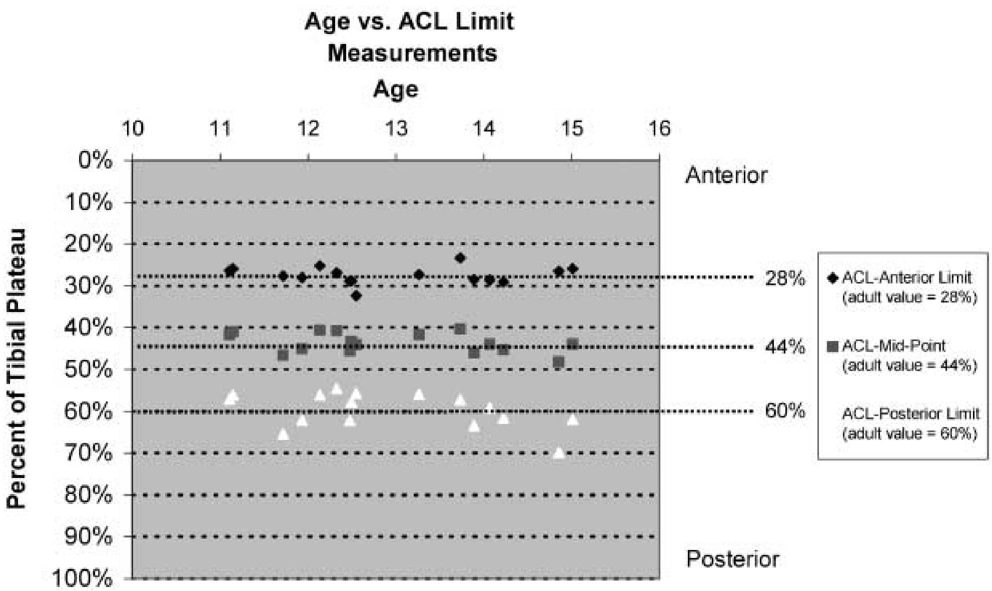

Fig. 3 Age vs. ACL limit measurements (males)

used for imaging, the generated image might not have been provided the most accurate image of the limits of the ACL, leading to measurement variability between subjects. This problem becomes more notable in younger subjects, as the overall dimensions of the knee decrease. Although our study analyzed patients older than 10 years, we noted that it is difficult to obtain more than one or two adequate sagittal images that represents the ACL in patients less than 10 years of age.

Although there are limitations to using the MRI to obtain anatomical data, this modality facilitates anatomical studies in pediatric patients. Gross anatomical studies on young patients are difficult to perform because the availability of specimens in these age groups is very limited.

Staubli and Rauschning [73] have provided anatomical studies of the ACL in adult patients. These studies used anatomical specimens and MRI analysis to define the anatomy of the ACL. Howell and coworkers [29, 30, 31, 32, 33, 34, 35, 36, 37] have emphasized the importance of tibial tunnel placement to prevent graft impingement on the intercondylar notch. In particular, the work of these individuals and others has helped define the precise anatomical placement of ACL grafts, which is a prerequisite to successful ACL reconstruction [41].

Injury of the ACL is common in adult athletes, and recent studies show that this injury is now being recognized more frequently in young athletes. Although epidemiological information on ACL tears in skeletally immature athletes is limited, the number of articles related to knee injuries in skeletally immature athletes has increased significantly over the past 10 years [1, 2, 3, 8, 10, 12, 13, 14, 16, 19, 20, 21, 26]. A recent review of data on insurance claims for youth soccer programs throughout the United States demonstrated a significant increase in the incidence of ACL tears at the age of 12 years in women and 14 years in men [69]. Improved diagnostic studies and an increase in the awareness of these injuries will lead to increased recognition of this injury in younger athletes.

Several studies of the natural history of nonsurgical treatment of ACL tears in skeletally immature athletes have demonstrated poor outcomes. Studies by Graf et al. [26], McCarrol et al. [52], Muzuta et al. [57], and Pressman et al. [65] have demonstrated problems with recurrent instability, meniscal tears, and osteochondral injuries in untreated ACL tears in young athletes. These problems are especially common in athletes who return to high-demand sports. Advocates of ACL reconstruction in skeletally immature athletes cite the poor outcome in nonsurgically treated athletes who return to sport [2, 20, 26, 57].

The treatment of ACL injuries in young patients has been controversial because of concerns about physeal injuries, which have the potential for angular deformity and lower extremity length inequality [44, 45, 68, 75]. Ford and Key [22] have demonstrated that physeal injury in the distal femur in rabbits can produce significant angular deformity and shortening if the physeal injury occurs at the periphery. They also show that a small centrally located physeal injury is much less likely to produce growth complications. Animal studies by Guzzanti et al. [27], Ono et al. [63], and Edwards et al. [18] have demonstrated the potential for growth abnormalities in the proximal tibial physis, in the absence of physeal arrest. In both studies growth abnormalities occurred after ACL reconstruction in skeletally immature rabbits or beagles.

In contrast to studies demonstrating physeal arrest after ACL reconstruction, a study by Stadelmaier et al. [71] demonstrated that placement of a soft tissue graft into physeal drill holes prevents formation of an osseous bridge across the physis. Janarv et al. [40] has reported similar findings in an animal model. Despite the concerns related to physeal arrest there are very few reports of these complications after ACL reconstruction [7, 15, 44, 45]. Koman and Sanders [44] report a single case of development of distal femoral valgus after hamstring ACL reconstruction. The femoral fixation used in this case consisted of a transfixation pin, which crossed the lateral aspect of the femoral physis. This pin acted as a Blount physeal staple, producing partial arrest of the lateral physis. Lipscomb and Anderson [45] have also reported a physeal complication related to the use of staples. Both of these studies describe physeal arrest complications on the femoral side only.

The treatment of ACL injury in skeletally immature athletes will remain controversial because of the potential for physeal injury. Several preliminary studies have suggested that ACL reconstruction in skeletally immature patients can be performed safely [1, 6, 12, 39, 45, 46, 49, 52, 53, 55, 56, 59, 66, 70]. Additional studies on the efficacy and safety of treatment methods for ACL reconstruction in the young patient will provide additional evidence that ACL reconstruction is safe in younger patients.

Graft placement is an important factor in successful outcome of ACL reconstruction, and the smaller anatomical dimensions must be considered in immature patients. Several studies have demonstrated the importance of graft placement in determining the outcome of ACL reconstructive surgery, including the effect of tunnel position on graft impingement [5, 30, 31, 32, 33, 35, 36, 37, 64, 67, 78], range of motion [9, 74, 76], and final outcome [41, 74]. Adult studies have described the anatomical location of the tibial tunnel with reference to the posterior cruciate ligament and the posterior edge of the anterior horn of the lateral meniscus [38, 48, 58]. Attention to these anatomical landmarks is of importance, especially in skeletally immature individuals with smaller anatomical dimensions of the knee.

Additional research on the natural history and treatment of ACL injuries in skeletally immature athletes is necessary. Injuries of the ACL in skeletally immature athletes are a common problem, and the current algorithms for ACL injury treatment will continue to evolve [1, 2, 6, 7, 12, 15, 21, 39, 46, 47, 49, 51, 52]. Skeletally immature individuals have smaller knee anatomical dimensions than adults, although the anatomy in younger patients is proportionally comparable to that in adults. Future studies will need to further define the appropriate indications for ACL surgical reconstruction in patients with open physes.

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