Original Article

Posterior Cruciate Ligament and Patellar Tendon Can Predict Anterior Cruciate Ligament Size for Planning During ACL Reconstruction in Pediatric Patients

Nicholas A. Strada, M.D., Emil Stefan Vutescu, M.D., Mohammadali Mojarrad, M.D., Ryan Harrington, M.D., Sebastian Orman, M.D., Peter Evangelista, M.D., and Aristides I. Cruz Jr., M.D., M.B.A.

Purpose: To establish correlations between the anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), and patellar tendon in normal pediatric knees to inform surgical planning for ACL reconstruction graft size. **Methods:** Magnetic resonance imaging scans of patients ages 8 to 18 years were assessed. Measurements included ACL and PCL length, thickness, and width, and ACL footprint thickness and width at the tibial insertion. Interrater reliability was assessed with a random set of 25 patients. Pearson correlation coefficients were used to assess the correlation between ACL, PCL, and patellar tendon measurements. Linear regression models were used to test whether the relationships differed by sex or age. **Results:** Magnetic resonance imaging scans of 540 patients were assessed. Interrater reliability was high for all measurements except PCL thickness at midsubstance. Sample equations for estimating ACL size are as follows: ACL length = 22.61 + 1.55*PCL origin width (R^2 = 0.46; 8- to 11-year-old male patients), ACL length = 12.37 + 0.58*PCL length + 2.29*PCL origin thickness − 0.90*PCL insertion width (R^2 = 0.68; 8- to 11-year-old female patients), ACL midsubstance thickness = 4.95 + 0.25*PCL midsubstance thickness + 0.04*PCL insertion thickness − 0.08*PCL insertion width (R^2 = 0.12; 12- to 18-year-old male patients), and ACL midsubstance width = 0.57 + 0.23*PCL midsubstance thickness + 0.07*PCL midsubstance width + 0.16*PCL insertion width (R^2 = 0.24; 12- to 18-year-old female patients). **Conclusions:** We found correlations between ACL, PCL, and patellar tendon measurements that can be used to create equations that predict ACL size in various dimensions based on PCL and patellar tendon measurements. **Clinical Relevance:** There is a lack of consensus on the ideal ACL graft diameter for pediatric ACL reconstruction. The findings from this study can assist orthopaedic surgeons to individualize ACL graft size for specific patients.

Treatment of anterior cruciate ligament (ACL) rupture in skeletally immature patients presents a unique challenge. While nonoperative treatment may be successful for some patients with partial ACL injuries, complete tears have been associated with persistent instability and subsequent meniscus and chondral injuries.[1] For this reason, surgical techniques in pediatric and adolescent anterior cruciate ligament reconstruction (ACLR) have gained popularity, and the number of skeletally immature patients undergoing

From the Warren Alpert Medical School of Brown University, Providence, Rhode Island, USA.

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Address correspondence to Nicholas A. Strada, M.D., 222 Station Plaza N Suite 305, Mineola, NY 11501, U.S.A. E-mail: nicholas.a.strada@gmail.com

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ACLR has increased. Between 1994 and 2006, the number of ACLRs performed in patients younger than 15 years increased by 924%.[2]

In the setting of an ACL injury, the size of the ligament before rupture is unknown without the availability of prerupture imaging. This poses a challenge when it comes to determining the appropriate graft size for ACLR. Although evidence supporting a recommended graft size is limited, a generally accepted graft diameter for the adult population is 8 mm.[3-5]

However, there is less literature on the appropriate graft size for the pediatric population.

Studies have suggested that smaller grafts are associated with greater revision rates. Some place this number at 8 mm, whereas others suggest it may be slightly larger at 8.5 mm diameter.[3,4] This is supported by others who suggest that even small increases of 0.5-mm increments, up to 10 mm, might be beneficial.[5] Some studies have found that increased graft sizes also have had better pain and functional outcomes, in addition to lower revision rates.[6] In contrast, a graft that is too large may increase complications, with at least one study showing that larger grafts in pediatric patients are associated with an increased risk of arthrofibrosis.[7]

Estimating the native ACL size on preoperative imaging would ideally inform graft size during surgery and make it possible to individualize ACL graft size to each patient. If the size of the ruptured ACL could be accurately estimated based on imaging and measurement of the surrounding structures like the intact posterior cruciate ligament (PCL) and intact patellar tendon, then it may be possible that a more individualized surgical plan could be in place for the proper graft size. The purpose of this study is to establish correlations between the ACL, PCL, and patellar tendon in normal pediatric knees to inform surgical planning for ACLR graft size. Our hypotheses are that correlations would exist between the ACL, PCL, and patellar tendon and that equations could be created that predict ACL size in the setting of a rupture.

Methods

This study was approved by the Lifespan - Rhode Island Hospital IRB 2, CMTT/PROJ: 405119. Data were drawn from a set of magnetic resonance images (MRIs) of pediatric patients with normal knee anatomy. From this set, MRIs of patients ages 8 to 18 years were selected and reviewed retrospectively. For each MRI, the corresponding patient's chart was reviewed for demographic data, including sex, height, weight, body mass index, race, and ethnicity, which were recorded when available. The laterality of the knee also was documented.

To assess the reliability of measurements between multiple readers, a random sample of 25 MRIs was drawn from those selected for the study. The same 25 MRIs were assessed by 3 radiologists, and the interrater reliability was determined (M.M., R.H., P.E.).

ACL length was measured in the craniocaudal dimension on the sagittal view. ACL thickness was measured in the anteroposterior dimension on sagittal images and in the transverse dimensions on axial images at the origin, midsubstance, distal aspect, and tibial footprint. PCL length was measured in craniocaudal dimension on the sagittal view. PCL thickness was measured in the anteroposterior dimension on sagittal images and in the transverse dimensions on axial images at the origin, midsubstance, distal aspect, and tibial footprint. Patellar tendon thickness was measured in the anteroposterior dimension on sagittal images and in the transverse dimension on axial images at the midsubstance.

Example patellar tendon measurements are shown in Figure 1A, ACL measurements in Figure 1B, PCL measurements in Figure 1C, and ACL footprint measurements in Figure 1D. These are displayed together in Figure 2. After confirming interrater reliability, the 540 MRIs were divided equally among 4 readers and all measurements were collected.

Statistical Analysis

Data were imported into SAS, version 9.4 (SAS Institute Inc., Cary, NC) for data management and analysis. Pearson correlation coefficients were calculated to understand the correlations between ACL measurements and PCL and patellar tendon measurements. The strength of the associations was compared by examining the absolute value of the correlation coefficients. Bidirectional stepwise regression was used to estimate formulas for the ACL measurements as a function of patellar tendon and PCL measurements. In the first step, patellar tendon and PCL measurements with a $P < .05$ in univariable models were entered together into a single multivariable model. Measurements with a $P > .10$ in the multivariable model were removed, starting with the variables with the greatest P values. This process finished when all variables in the multivariable model had $P < .10$. These criteria were chosen since it led to parsimonious regression models that had the least amount of change in the R-squared value from the full model. Since sex and age were significantly related to the ACL measurements and moderated the effects of the patellar tendon and PCL measurements on ACL measurements, separate equations were estimated for 8- to 11-year-old female patients, 12- to 18-year-old female patients, 8- to 11-year-old male patients, and 12- to 18-year-old male patients.

Results

A total of 1,059 MRIs were identified; of these, 540 met the inclusion criteria. The study included 140 MRIs of patients ages 8 to 12 years, as well as 200 male

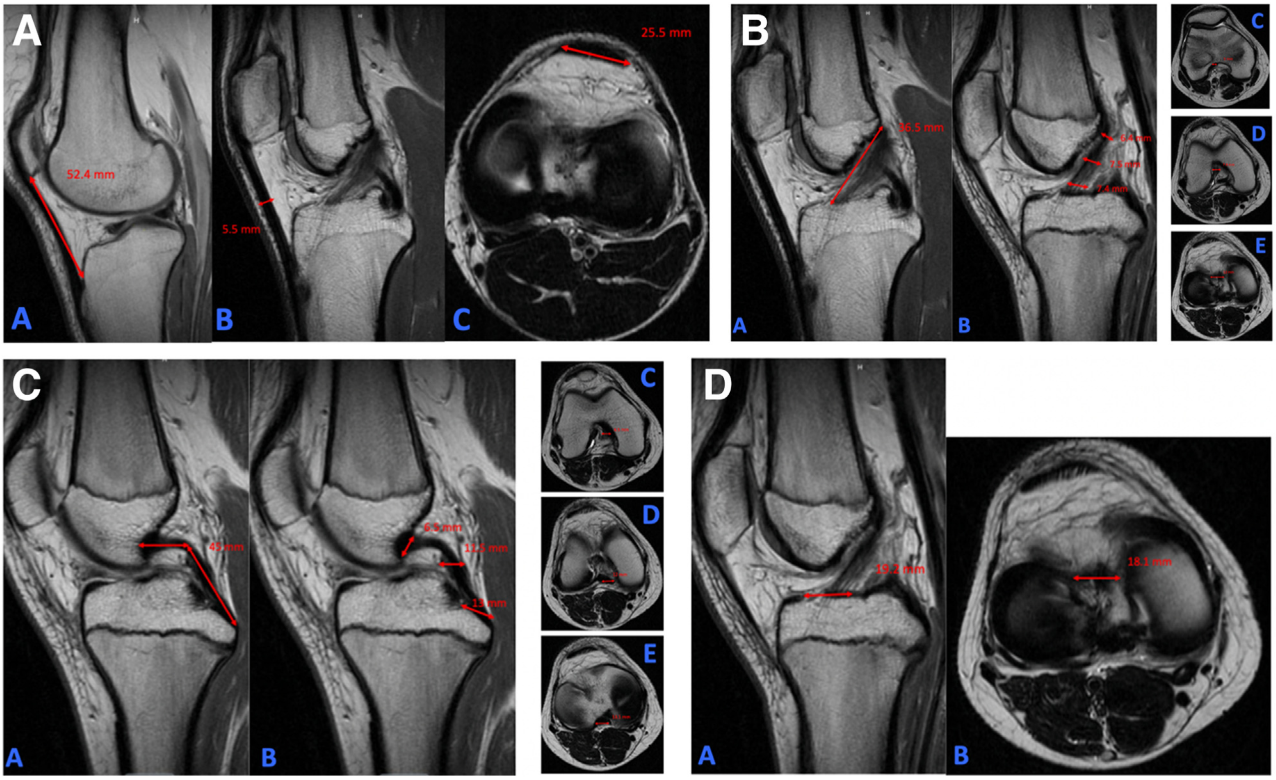

Fig 1. (A) Patellar tendon measurements. A, Patellar tendon length measured from the inferior pole of the patella to the superior lip of the tibial tubercle. B, Patellar tendon thickness measured on the sagittal view at the middle of the tendon. C, Patellar tendon width measured on the axial view at the middle of the tendon. (B) ACL measurement. A, ACL length measured from the most posterosuperior point on the femoral origin to the most anterior point on the tibial insertion. B, ACL thickness measured on the sagittal view at 3 points (origin, midsubstance, and insertion). ACL width measured on the axial view at 3 points: C, origin; D, midsubstance; and E, insertion. (C) PCL measurement. A, PCL length measured from adding 2 lines. One line from the most anterior point on the femoral origin to the PCL crimp, and the other line from the PCL crimp to the most posterior point on the tibial insertion. B, PCL thickness measured on the sagittal view at 3 points (origin, midsubstance, and insertion). PCL width measured on the axial view at 3 points: C, origin; D, midsubstance; and E, insertion. (D) ACL footprint measurement. A, ACL footprint thickness measured on the sagittal view from the most anterior to most posterior point of the tibial footprint. B, ACL footprint width measured on the axial view at the tibial insertion. (ACL, anterior cruciate ligament; PCL, posterior cruciate ligament.)

patients ages 13-18 years and 200 female patients ages 13-18 years. Demographic data for 540 patients are shown in Table 1. Interrater reliability was high for all measurements except PCL thickness at midsubstance. Interrater reliability is shown in Table 2. Correlations between each measurement were determined, and using these correlations, equations were created that predict each ACL variable based on PCL and patellar tendon measurements. The most useful of these equations were determined to be those that could predict ACL length, ACL midsubstance thickness, and ACL midsubstance width.

The measurements most strongly correlated with each ACL variable were as follows: ACL length was most strongly correlated with PCL length ($r = 0.57$, $P < .0001$); ACL midsubstance thickness was most strongly correlated with PCL insertion thickness ($r = 0.27$, $P < .0001$); ACL midsubstance width was most strongly correlated with PCL midsubstance thickness ($r = 0.31$, $P < .0001$) and patellar midsubstance thickness ($r = 0.33$, $P < .0001$); ACL origin thickness was most strongly correlated with PCL midsubstance thickness ($r = 0.26$, $P < .0001$); ACL origin width was most strongly correlated with PCL insertion width ($r = 0.49$, $P < .0001$); ACL insertion thickness was most strongly correlated with PCL insertion thickness ($r = 0.27$, $P < .0001$); and ACL insertion width was most strongly correlated with PCL midsubstance width ($r = 0.39$, $P < .0001$). Correlations are shown in Table 3.

Some correlations were moderated by sex and/or age as follows: the correlation between ACL and PCL length, as well as between ACL and PCL insertion thickness, was moderated by sex and age; the

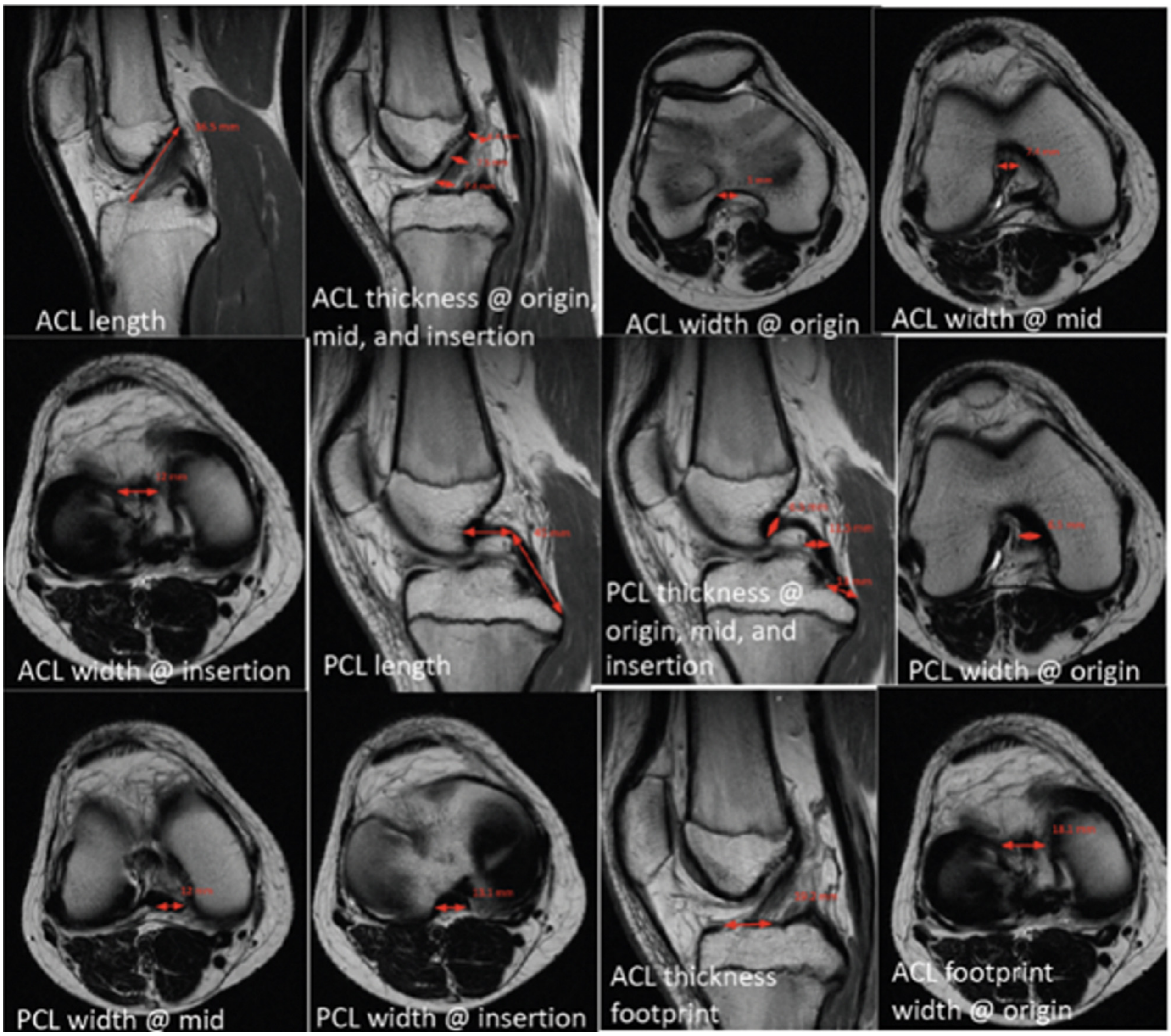

Fig 2. Top row left to right: ACL length measured on sagittal view; ACL thickness — AP dimension at origin (femur), midpoint and insertion (tibia) measured on sagittal view; ACL width at ACL origin on femur — transverse dimension on axial plane view; ACL width at ACL midpoint — transverse dimension on axial plane view. Middle row left to right: ACL width at ACL tibia insertion — transverse dimension on axial plane view; PCL length — measured on sagittal view — by adding 2 lines, one from origin to the PCL crimp and from PCL crimp to the tibia insertion; PCL thickness — AP dimension at origin (femur), midpoint and insertion (tibia) measured on sagittal view; PCL width at PCL origin on femur — transverse dimension on axial plane view. Bottom row left to right: PCL width at PCL midpoint — transverse dimension on axial plane view; PCL width at PCL tibia insertion — transverse dimension on axial plane view; ACL thickness footprint — AP dimension on sagittal view; ACL footprint width at ACL origin on femur — transverse dimension on axial plane view. (ACL, anterior cruciate ligament; AP, anteroposterior; PCL, posterior cruciate ligament.)

correlation between ACL and PCL midsubstance thickness, as well as between ACL and PCL midsubstance width, was moderated by sex; and the correlation between ACL and PCL insertion width was moderated by age.

Equations for measurements in each age and sex group are shown in Table 4, with the most important of these equations, as determined by the senior author (A.I.C.), highlighted in Table 5. Although multiple anatomic measurements were made and can be predicted using these equations, the most clinically relevant equations are likely those that predict ACL length, ACL midsubstance thickness, and ACL midsubstance width, as shown in Table 5. This is because although other measurements like insertion thickness or width might still be able to be determined in the setting of ACL rupture, it is the length, midsubstance width, and midsubstance thickness that remain unmeasurable in a

Table 1. Demographic Data From 540 Patients Ages 8-18 Years Old

Demographics	Mean (SD) or n (%)
Age, y	14.4 (2.6)
Sex	
Male	251 (46.5)
Female	289 (53.5)
Laterality	
Left	258 (47.8)
Right	280 (51.9)
Unsure	2 (.04)
Race	
White	442 (81.9)
Black/African American	21 (3.9)
Other	35 (6.5)
Unknown	42 (5.8)
Height	5′5"
Weight	150.4 (47.1)
BMI	24.91 (6.24)

BMI, body mass index.

Table 2. Interrater Reliability for All Measurements

Measurements	Interrater Reliability [95% confidence interval]
ACL width @ origin	0.932 [0.9565, 0.889]
ACL thickness @ midsubstance	0.809 [0.902, 0.684]
ACL width @ midsubstance	0.943 [0.971, 0.907]
ACL thickness @ insertion	0.913 [0.955, 0.856]
ACL width @ insertion	0.856 [0.924, 0.771]
ACL tibial footprint thickness	0.895 [0.946, 0.829]
ACL tibial footprint width	0.951 [0.975, 0.920]
PCL thickness @ origin	0.951 [0.975, 0.920]
PCL width @ origin	0.829 [0.910, 0.725]
PCL thickness @ midsubstance	0.273 [0.609, -0.134]
PCL width @ midsubstance	0.844 [0.919, 0.743]
PCL thickness @ insertion	0.812 [0.903, 0.690]
PCL width @ insertion	0.825 [0.910, 0.713]
Patellar thickness @ midsubstance	0.792 [0.892, 0.660]
Patellar width @ midsubstance	0.888 [0.943, 0.816]

ACL, anterior cruciate ligament; PCL, posterior cruciate ligament.

patient with a completely torn ACL. Therefore, it is these 3 variables that could benefit from an equation as presented previously and that might be of the most use to the practicing orthopaedic surgeon.

An example of how to use the equations correctly is shown in Figure 3. Here, the equations for ACL length in a 10-year-old male patient are used. To solve for ACL length, the PCL origin width is measured and entered into the equation. A PCL origin width of 5.1 mm gives a predicted ACL length of 30.52 mm.

Discussion

In this study, we found that correlations exist between the ACL, PCL, and patellar tendon in normal pediatric knees, and that equations can be created that predict ACL size based on the intact PCL and patellar tendon. Although multiple anatomic measurements were made and can be predicted using these equations, the most clinically relevant equations are likely those that predict ACL length, ACL midsubstance thickness, and ACL midsubstance width, as shown in Table 5. This is because although other measurements such as insertion thickness or width might still be able to be determined in the setting of ACL rupture, it is the length, midsubstance width, and midsubstance thickness that remain unmeasurable in a patient with a completely torn ACL. Therefore, it is these 3 variables that could benefit from an equation as presented previously and that might be of the most use to the practicing orthopaedic surgeon.

The literature on the ideal graft size in the pediatric population remains inconclusive, with multiple studies attempting to determine a reliable value by examining revision rates and re-rupture rates, and looking at pain and function outcome scores [3-6,8] Most have concluded that smaller graft sizes have poorer outcomes; however, a larger graft size might not always be better, as Su et al.[7] found that an increase of graft diameter by 1 mm was associated with a 3.2-fold increase in arthrofibrosis in a pediatric cohort.

There are various radiographic studies that have examined ACL measurements and certain correlations. Patient height and MRI also are offered as ways to predict graft diameter preoperatively.[8] In an MRI study, de Oliveira et al.[9] found the mean thickness of the ACL to be 4.5 mm in the sagittal plane and 4.3 mm in the frontal plane, and they also found that the thickness had a positive correlation with the lateral femoral condyle and intercondylar distance. There was no relationship between ACL thickness and age or height. In a study by Kupczik et al.,[10] the average diameter of the ACL was 4.8 mm, the mean length was 38 mm, the origin ranged from 9.7 to 15.4 mm, and the mean insertion was 13.3 mm. Average diameter of the semitendinosus was 4.38 mm, and the mean gracilis diameter was 3.42 mm. The quadriceps diameter was reported as 7.67 mm, length was 35.34 mm, and patellar tendon diameter was reported as 4.5 mm, with a length of 26.62 mm.[10] Mohd Asihin et al.[11] found that the hamstring combined cross-sectional area and thigh circumference predict autograft size when using preoperative ultrasound. Janssen et al.[12] found that hamstring autograft size can be predicted in White patients because gracilis and semitendinosus graft lengths were related to height.

Another study, by Davis et al.,[13] attempted to establish a correlation between the intercondylar notch width of the femur to the width of the ACL and PCL. The authors found a statistically significant correlation ($r = 0.87$) between the notch width and ACL width, as well as between notch width and PCL width ($r = 0.75$), with a mean ACL width of 5.7 ± 1.1 mm in female patients, 7.1 ± 1.2 mm in male patients, and a PCL

Table 3. Correlation Coefficients for All Measurements

	ACL Length	ACL Origin Thickness	ACL Origin Width	ACL Midsubstance Thickness	ACL Midsubstance Width	ACL Insertion Thickness	ACL Insertion Width	ACL Footprint Thickness	ACL Footprint Width
Patellar length	r = 0.11	r = 0.12	r = 0.26	r = 0.03	r = 0.15	r = 0.03	r = 0.20	r = −0.06	r = −0.01
	P = .01	*P* = .01	*P* < .0001	*P* = .50	*P* = .00	*P* = .50	*P* < .0001	*P* = .17	*P* = .79
Patellar midsubstance thickness	r = −0.04	r = 0.26	r = 0.34	r = 0.23	r = 0.33	r = 0.15	r = 0.38	r = 0.24	r = 0.05
	P = .41	*P* < .0001	P = <0.0001	*P* < .0001	*P* < .0001	*P* = .00	*P* < .0001	*P* < .0001	*P* = .23
Patellar midsubstance width	r = 0.19	r = 0.10	r = 0.17	r = 0.16	r = 0.18	r = 0.15	r = 0.24	r = 0.17	r = 0.08
	P < .0001	*P* = .02	*P* < .0001	*P* = .00	*P* < .0001	*P* = .00	*P* < .0001	*P* < .0001	*P* = .07
PCL length	r = 0.57	r = 0.17	r = −0.09	r = 0.18	r = 0.07	r = 0.22	r = −0.03	r = 0.27	r = 0.25
	P < .0001	*P* < .0001	*P* = .05	*P* < .0001	*P* = .12	*P* < .0001	*P* = .47	*P* < .0001	*P* < .0001
PCL origin thickness	r = 0.14	r = 0.18	r = 0.06	r = 0.17	r = 0.13	r = 0.19	r = 0.03	r = 0.21	r = 0.07
	P = .00	*P* < .0001	*P* = .15	*P* = .00	*P* = .00	*P* < .0001	*P* = .52	*P* < .0001	*P* = .12
PCL origin width	r = 0.35	r = −0.01	r = −0.23	r = 0.16	r = -0.02	r = 0.19	r = −0.11	r = 0.17	r = 0.10
	P < .0001	*P* = .78	*P* < .0001	*P* = .00	*P* = .68	*P* < .0001	*P* = .01	*P* < .0001	*P* = .02
PCL midsubstance thickness	r = 0.11	r = 0.26	r = 0.23	r = 0.22	r = 0.31	r = 0.18	r = 0.25	r = 0.26	r = 0.03
	P = .01	*P* < .0001	*P* < .0001	*P* < .0001	*P* < .0001	*P* < .0001	*P* < .00001	*P* < .0001	*P* = .48
PCL midsubstance width	r = −0.03	r = 0.12	r = 0.40	r = 0.01	r = 0.25	r = −0.09	r = 0.39	r = 0.03	r = 0.04
	P = .47	*P* = .00	*P* < .0001	*P* = .85	*P* < .0001	*P* = .05	*P* < .0001	*P* = .55	*P* = .32
PCL insertion thickness	r = −0.05	r = 0.17	r = 0.16	r = 0.27	r = 0.24	r = 0.27	r = 0.16	r = 0.28	r = 0.07
	P = .22	*P* < .0001	*P* = .00	*P* < .0001	*P* < .0001	*P* < .0001	*P* = .00	*P* < .0001	*P* = .10
PCL insertion width	r = −0.13	r = 0.06	r = 0.49	r = −0.13	r = 0.24	r = −0.21	r = 0.38	r = −0.21	r = −0.06
	P = .00	*P* = .20	*P* < .0001	*P* = .00	*P* < .0001	*P* < .0001	*P* < .0001	*P* < .0001	*P* = .19

ACL, anterior cruciate ligament; PCL, posterior cruciate ligament.

Table 4. Equations for ACL Variables by Age and Sex Group

Age/Sex Group	Equations	R-Squared
8- to 11-year-old male patients	ACL footprint thickness = 5.15 + 0.12*PCL length + 0.35*PCL origin width	0.24
	ACL footprint width = 25.26 − 0.10*patellar length − 1.59*patellar mid thickness	0.47
	ACL length = 22.61 + 1.55*PCL origin width	0.46
	ACL origin thickness = 3.21 + 0.26*PCL origin thickness	0.07
	ACL origin width = 1.79 + 0.42*PCL midsubstance thickness	0.14
	ACL midsubstance thickness = 8.64 − 0.32*PCL insertion width	0.44
	ACL midsubstance width = no model	
	ACL insertion thickness = 5.00 − 0.29*patellar midsubstance thickness + 0.14*PCL origin width	0.2
	ACL insertion width = −0.67 + 0.71*patellar midsubstance thickness − 0.52*PCL origin width + 1.33*PCL midsubstance thickness + 0.65*PCL midsubstance width − 1.26*PCL insertion thickness	0.76
8- to 11-year-old female patients	ACL footprint thickness = 19.42 − 0.67*PCL insertion width	0.26
	ACL footprint width = 16.43 − 0.09*patellar length + 0.89*PCL origin thickness + 0.44*PCL origin width − 0.37*PCL insertion width	0.46
	ACL length = 12.37 + 0.58*PCL length + 2.29*PCL origin thickness − 0.90*PCL insertion width	0.68
	ACL origin thickness = 1.25 + 0.04*patellar length + 0.27*PCL origin thickness	0.23
	ACL origin width = 1.35 + 0.15*PCL insertion width	0.23
	ACL midsubstance thickness = 3.23 + 0.09*PCL length − 0.17*PCL insertion width	0.16
	ACL midsubstance width = 0.70 + 0.05*patellar length + 0.29*PCL midsubstance thickness	0.29
	ACL insertion thickness = 7.41 − 0.19*PCL insertion width	0.07
	ACL insertion width = -0.96 + 0.05*patellar length − 0.44*PCL origin thickness + 0.54*PCL insertion width	0.73
12- to 18-year-old male patients	ACL footprint thickness = 14.46 − 0.07*patellar length + 0.85*patellar midsubstance thickness + 0.34*PCL midsubstance thickness − 0.28*PCL insertion width	0.2
	ACL footprint width = -0.88 + 0.45*PCL length	0.03
	ACL length = -0.99 + 0.08*patellar length + 0.14*patellar midsubstance width + 0.69*PCL length − 0.11*PCL insertion thickness	0.44
	ACL origin thickness = 4.58 − 0.11*PCL origin width + 0.23*PCL midsubstance thickness	0.05
	ACL origin width = -0.20 + 0.02*patellar length + 0.28*patellar midsubstance thickness − 0.20*PCL origin width + 0.10*PCL midsubstance width + 0.16*PCL midsubstance thickness + 0.03*PCL insertion thickness + 0.09*PCL insertion width	0.36
	ACL midsubstance thickness = 4.95 + 0.25*PCL midsubstance thickness + 0.04*PCL insertion thickness − 0.08*PCL insertion width	0.12
	ACL midsubstance width = 1.72 + 0.50*patellar midsubstance thickness + 0.18*PCL midsubstance thickness	0.09
	ACL insertion thickness = 7.02 + 0.22*PCL midsubstance thickness − 0.17*PCL insertion width	0.1
	ACL insertion width = 3.27 + 0.76*patellar midsubstance thickness − 0.07*PCL length + 0.21*PCL midsubstance width + 0.12*PCL insertion width	0.12
12- to 18-year-old female patients	ACL footprint thickness = 6.42 + 0.34*PCL midsubstance thickness + 0.44*PCL insertion thickness	0.09
	ACL footprint width = 5.97 − 0.55*patellar midsubstance thickness + 0.29*PCL length + 0.38*PCL origin width − 0.09*PCL insertion width	0.39
	ACL length = 10.94 + 0.42*PCL length + 0.41*PCL origin thickness + 0.51*PCL origin width	0.29
	ACL origin thickness = 2.03 + 0.21*patellar midsubstance thickness + 0.13*PCL insertion thickness + 0.08*PCL insertion width	0.08
	ACL origin width = 1.48 + 0.26*patellar midsubstance thickness − 0.03*PCL length − 0.08*PCL origin width + 0.07*PCL midsubstance width + 0.18*PCL insertion width	0.44
	ACL midsubstance thickness = 2.10 + 0.23*patellar midsubstance thickness + 0.10*PCL origin width + 0.16*PCL insertion thickness	0.08
	ACL midsubstance width = 0.57 + 0.23*PCL midsubstance thickness + 0.07*PCL midsubstance width + 0.16*PCL insertion width	0.24
	ACL insertion thickness = 3.00 + 0.20*PCL origin thickness + 0.13*PCL origin width	0.06
	ACL insertion width = 2.31 − 0.09*PCL length + 0.39*PCL midsubstance thickness + 0.27*PCL midsubstance width + 0.25*PCL insertion width	0.31

ACL, anterior cruciate ligament; PCL, posterior cruciate ligament.

Table 5. Most Clinically Important Equations

Age/Sex Group	Equations	R-Squared
8- to 11-year-old male patients	ACL length = 22.61 + 1.55*PCL origin width	0.46
	ACL midsubstance thickness = 8.64 − 0.32*PCL insertion width	0.44
8- to 11-year-old female patients	ACL length = 12.37 + 0.58*PCL length + 2.29*PCL origin thickness − 0.90*PCL insertion width	0.68
	ACL midsubstance thickness = 3.23 + 0.09*PCL length − 0.17*PCL insertion width	0.16
	ACL midsubstance width = 0.70 + 0.05*patellar length + 0.29*PCL midsubstance thickness	0.29
12- to 18-year-old male patients	ACL length = −0.99 + 0.08*patellar length + 0.14*patellar midsubstance width + 0.69*PCL length − 0.11*PCL insertion thickness	0.44
	ACL midsubstance thickness = 4.95 + 0.25*PCL midsubstance thickness + 0.04*PCL insertion thickness − 0.08*PCL insertion width	0.12
	ACL midsubstance width = 1.72 + 0.50*patellar midsubstance thickness + 0.18*PCL midsubstance thickness	0.09
12- to 18-year-old female patients	ACL length = −0.99 + 0.08*patellar length + 0.14*patellar midsubstance width + 0.69*PCL length − 0.11*PCL insertion thickness	0.44
	ACL midsubstance thickness = 2.10 + 0.23*patellar midsubstance thickness + 0.10*PCL origin width + 0.16*PCL insertion thickness	0.08
	ACL midsubstance width = 0.57 + 0.23*PCL midsubstance thickness + 0.07*PCL midsubstance width + 0.16*PCL insertion width	0.24

width of 9.5 ± 1.7 mm in female patients and 10.9 ± 2.0 in male patients.

In our opinion, there are 3 important findings that can be concluded from this current study. First, reliable measurements of the ACL, PCL, and patellar tendon can be made in various dimensions. This is important because the use of the aforementioned equations is based on this idea that the measurements are reliable and reproducible between different readers, thus increasing the generalizability of our findings. Second, correlations exist between the ACL, PCL, and patellar tendon, with some moderated by age and/or sex. This correlation allows the creation of a way to predict one variable based on others. Third, equations can be created that predict ACL size based on the intact PCL and patellar tendon. Equations have been created for different age and sex groups that may help predict size for many ACL dimensions, including those that predict ACL length, midsubstance thickness, and midsubstance width. It is these equations that may most aid in estimating the ideal or target graft size for each individual patient. In the setting of an ACL rupture, the treating surgeon can make measurements of the intact PCL and patellar tendon on the preoperative MRI; select the equations for ACL length, midsubstance thickness, and midsubstance width based on the sex and age of the patient; and get the estimated measurements of patients' ACLs before rupture. This could then be useful in harvesting a graft that is most similar in size to individual patients' pre-injury anatomy.

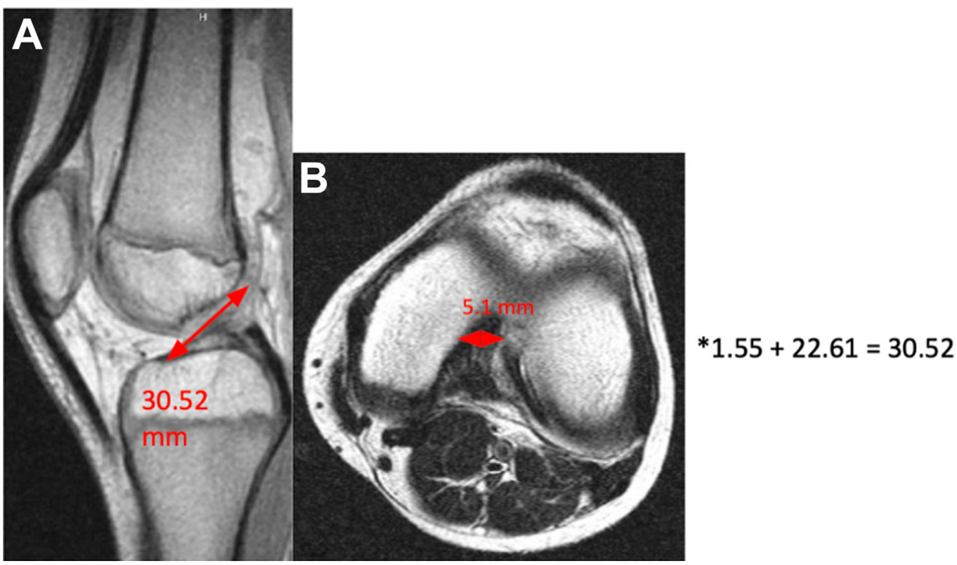

Fig 3. Example of using an equation to predict ACL length in a 10-year-old male patient. The formula is as follows: ACL length = 22.61 + 1.55*PCL origin width. Here, the PCL origin width would be measured (5.1 mm), and plugged into the equation. Next, ACL length would be solved for (30.52 mm). (A) ACL length. (B) PCL width at femur origin. (ACL, anterior cruciate ligament; PCL, posterior cruciate ligament.)

Limitations

There are several limitations of this study. First, this was a single-center study, with a population that may or may not be representative of the general population. Second, there may be debate as to which ACL variables or measurement may be the most clinically useful to be predicted. In addition, the equations themselves are complex, but this can be mitigated by the creation of a calculator or app available via a link that would allow providers to simply plug in the measurements requested to be presented with the predicted ACL variable that is desired. Finally, a possible appropriate next step might be to test these equations on a different set of patients to confirm their efficacy, potentially making measurements on one set of normal knees, and then using the equations to predict the size of the structures on the patients' contralateral knees. However, this would require bilateral knee MRIs in normal healthy subjects. Another relevant consideration is that time that elapses from MRI to reconstruction might play a role, as measurements and predictions made at the time of the MRI may be less accurate if the patient has grown considerably by the time of reconstruction.

Conclusions

We found correlations between ACL, PCL, and patellar tendon measurements that can be used to create equations that predict ACL size in various dimensions based on PCL and patellar tendon measurements

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