Magnetic Resonance Imaging–Based Topographical Differences Between Control and Recurrent Patellofemoral Instability Patients

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Background: Plain films and computed tomography (CT)–based imaging were the first to establish measurements that evaluated patellar instability. Limited research has shown the efficacy of magnetic resonance imaging (MRI) in evaluating these established measurements.

Purpose: To identify morphological differences between normal knees and those with patellofemoral instability on MRI to determine what measurements are significant and how MRI-based means differ from historical means based on radiograph and CT imaging.

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

Methods: Eighty-one controls and 40 patients with recurrent patellar instability between 2006 and 2010 were reviewed. The control patients had a history and an examination negative for patellofemoral symptoms. Patients with patellar instability had a history of at least 2 frank patellofemoral joint dislocations (PFJDs). The MRI images were obtained on the nonweightbearing knee in full extension. Measurements of patellar tilt, trochlear morphologic characteristics, and tibial tuberosity–trochlear groove (TTTG) distance were evaluated on axial slices, and patellar height was measured on sagittal images. Trochlear shape was assessed at the proximal and distal trochlea.

Results: All measurements of patellar tilt (mean ± SD) were found to be significantly different between the 2 groups. For patellar height, the Insall-Salvati ratio (control, 1.08 ± 0.02; PFJD, 1.26 ± 0.03) and Caton-Deschamps ratio (control, 1.13 ± 0.02; PFJD, 1.29 ± 0.03) proved to be significantly different. Trochlear morphologic characteristics had numerous measurements prove to be significantly different proximally and distally. These included classic measurements such as sulcus angle (control, 148.48° ± 0.94°; PFJD, 165.57° ± 2.65°) and lateral trochlear inclination (control, 21.27° ± 0.66°; PFJD, 13.31° ± 1.36°) proximally and less established measurements such as the ratio of external (lateral) trochlea to internal (medial) trochlea (control, 1.51 ± 0.05; PFJD, 2.11 ± 0.17), a measurement of facet asymmetry.

Conclusion: The MRI-based patellar tilt measures proved to be an excellent group of measurements for delineating between controls and those with instability. Patella alta ratios, such as Insall-Salvati and Caton-Deschamps, demonstrated a statistically significant difference between normal and recurrent dislocators. Trochlear measurements proved significantly different at the proximal and distal trochlea. Our findings demonstrate that MRI is appropriate to help discern recognized pathologic abnormalities that characterize patellofemoral instability.

Keywords: patellofemoral; patellofemoral instability; MRI; sports; knee

Although patellofemoral syndrome accounts for 25% of patients seen at sports medicine clinics,[26] a lesser-understood subgroup of these patients includes those with patellofemoral instability. This category includes those patients who experience frank dislocations and those who experience symptoms of subluxation. Incidence rates of pure dislocations have been calculated at 5.8 per 100,000 in younger age groups.[13] Factors that influence patellofemoral instability are numerous[34] but can be divided into 4 categories: (1) ligamentous stabilizers such as the medial retinaculum and patellofemoral ligament, (2) limb geometries in the axial plane (eg, tibial tuberosity–trochlear groove [TTTG] distance), (3) patellar height ratios such as Insall-Salvati, and (4) trochlear morphologic characteristics (eg, trochlear depth and sulcus angle).[2,6,9,10,35,36]

Diagnosis of patellofemoral instability is difficult because patellar instability, patellofemoral pain, and meniscal and cruciate insufficiency can produce similar symptoms of nonspecific pain and knee instability.[7,11,26]

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Thus, careful examination and imaging are helpful in making the correct diagnosis. Accurate diagnosis is crucial, as 15% to 49% of patients with primary dislocations may go on to have subsequent dislocations,[8,13] which has prompted some to recommend surgical interventions at initial presentation.[17] In addition to the history, common physical examination findings include the evaluation of limb alignment, patellar tilt, crepitus, patellar tracking, tenderness, apprehension, and laxity.[6] Imaging is another component to the diagnosis of patellofemoral instability. Fithian et al[13] demonstrated that patients with recurrent dislocations had specific factors such as smaller angles of Laurin (representing an increase in the lateral rotation of the patella along the cephalad-caudal axis) and larger lateral patellar overhang on imaging at the time of their first dislocation. Historically, plain radiographic imaging and subsequently computed tomography (CT) imaging have been more heavily relied on regarding the evaluation of the patellofemoral joint. More recently, magnetic resonance imaging (MRI) has gained a more prominent role in the imaging armamentarium for patellofemoral instability because it gives the clinician the ability to visualize the articular surfaces and soft tissue structures such as the medial patellofemoral ligament (MPFL) in addition to the bony alignment observed on radiographs and CT.

Patellofemoral instability is a problem orthopaedic surgeons have tried to address as early as Albee in 1915.[9] Merchant et al[23] helped visualize the patellofemoral joint in 1974 with the patient's knee flexed 45° and the x-ray beam angled at 30°. Dejour et al[9] used lateral radiographs to analyze osseous femoral characteristics to classify trochlear dysplasia into 4 types (I-IV) based on radiographic findings of the crossing sign, trochlear bump >3 mm, and trochlear depth <4 mm.[8] Radiographic and CT-based standard values for the patellofemoral joint are well established. Measurements of the trochlea such as lateral trochlear inclination <11°, sulcus angle >145°, and trochlear groove depth <4 mm are well-documented cutoffs.[5,6,8,9] Limb geometry evaluation with measurements such as TTTG distance, according to Dejour et al,[9] has proven useful for evaluating patients with instability. A TTTG value greater than 20 mm is considered pathologic.[9,10] Standards for Caton-Deschamps and Insall-Salvati ratios indicative of patella alta are based on either plain films or CT imaging.[9,12,18] Despite its limitations in visualizing chondral architecture and soft tissues, clinicians have erroneously used patellar tilt on CT imaging to draw conclusions about nonosseous or cartilaginous patellofemoral stabilizers.[2,9,14,16,22]

More recently, research has started to implement MRI in the analysis of patellofemoral instability. The ability to clearly show the MPFL and articular cartilage on MRI has improved the clinician's understanding of severe cartilaginous pathologic changes that were not brought to light with previous radiographic studies.[28,32,35] Recent articles have highlighted discrepancies with previously established CT and radiographic cutoffs and tested the reliability of MRI in evaluating the patellofemoral joint.**

Currently, there is a limited amount of research applying MRI to patellofemoral instability. The purpose of this study is to identify key morphological differences between normal knees and those with recurrent patellofemoral instability and to provide a range for normal and abnormal knees. We hypothesized that the MRI-based patellofemoral measures that involve trochlear height, depth, or angle will be altered somewhat (given that the measures will be based on cartilage contour instead of subchondral bone contour), whereas the measures that do not involve the trochlear or patellar chondral surface will not be affected to any significant degree when compared with previously published means of radiograph/CT-based values.

METHODS

The study was a retrospective review of patients' charts and magnetic resonance (MR) images from the University of California (UC) San Diego and Kaiser Permanente San Diego between 2006 and 2010. In both instances, the project was approved by each institution's respective institutional review board (IRB) panels before data collection. In total, 126 patients were initially selected for the study by chart review, but 5 patients were later excluded because of the absence of readable MR images on file. Eighty-one patients were collected as controls who presented to the UC San Diego Sports Medicine clinic for knee complaints. Patients categorized as a control had no present symptoms or history of patellofemoral complaints and an examination negative for patellar grind, facet tenderness, and apprehension in their medical records. Patients with symptomatic osteoarthritis were excluded, as they would have been referred to another clinic. Forty patients with recurrent patellar instability based on history and clinical examination were included. The UC San Diego patients were obtained through a chart review of patients seen at the Sports Medicine Clinic between January 2006 and January 2010 with an associated diagnosis of patellofemoral instability, whereas Kaiser patients were obtained through a review of operative records at Kaiser San Diego from March 2008 through March 2010. In both cases, patients with patellar instability must have had a history with at

**References 1, 12, 20, 24, 25, 29, 31, 35.

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TABLE 1
Description of Measurements

Measurement	
Transepicondylar width	Length of a straight line parallel to the horizontal axis from the most medial to most lateral aspect of the femur at the second cut.
Patellar angle	
Angle of Fulkerson	Line 1 is drawn across the posterior margins of the medial and lateral condyles, and line 2 is drawn along the lateral facet of the patella. The angle between the 2 lines is the patellar angle of Fulkerson.
Angle of Grelsamer	Line 1 is drawn to be parallel to the horizontal axis. Line 2 is drawn through the transverse the axis of the patella. The angle between the 2 lines is the patellar angle of Grelsamer. A positive angle is designated as one that opens up medially.
Angle of Laurin	Line 1 is drawn across the anterior margin of the medial and lateral trochlea. Line 2 is drawn tangential to the slope of the lateral facet of the patella. A positive angle is one that opens up laterally.
Patellar inclination angle	Line 1 is drawn across the posterior margins of the medial and lateral condyles, and line 2 is drawn through the transverse axis of the patella. A positive angle is designated as one that opens up medially.
Lateral patellar displacement	The shortest distance between the lateral margin of the trochlea and the lateral margin of the patella facet.
Trochlear morphologic characteristics	
Sulcus angle	The angle between the slopes of the medial and lateral trochlea.
Congruence angle	Line 1 is drawn to bisect the sulcus angle of the trochlear groove. Line 2 is drawn from the center of the trochlear groove to the patella apex. A positive angle is designated as one that is toward the lateral side. Also known as the Merchant angle.
Trochlear groove depth	Line 1 is drawn across the anterior margins of the medial and lateral condyles. Trochlear groove depth is the distance from the center and deepest portion of the trochlear groove to line 1.
Roman arch	Line 1 is drawn across the posterior margins of the medial and lateral condyles. The Roman arch is the perpendicular distance from the center of the posterior femoral condylar groove to line 1.
Trochlear groove thickness	Line 1 is drawn across the posterior margins of the medial and lateral condyles. Two lines parallel to line 1 are drawn crossing the centers of the trochlear groove and the posterior femoral condylar groove, respectively. Trochlear groove thickness (TGT) is the perpendicular distance between these 2 lines.
% of epicondylar width TGT	TGT distance expressed as a percentage of the transepicondylar width.
ETIT	ETIT is the ratio of external (lateral) trochlea to internal (medial) trochlea. Measures the ratio of the lines drawn from the lateral and medial margins of the trochlea along the trochlear surface to the center of the trochlear groove. A ratio >1.0 equates to having a lateral facet larger than the medial facet.
Lateral condylar height	Line 1 is drawn across the posterior margins of the medial and lateral condyles. The lateral condylar height (LCH) is the perpendicular distance from the most anterior margin of the lateral condyle to line 1.
% of epicondylar width LCH	LCH expressed as a percentage of the transepicondylar width.
Central condylar height (from Biedert and Bachmann[4])	Line 1 is drawn across the posterior margins of the medial and lateral condyles. The central condylar height (CCH) is the perpendicular distance from line 1 to the deepest part of the trochlear groove.
% of epicondylar width CCH	CCH expressed as a percentage of the transepicondylar width.
Medial condylar height	Line 1 is drawn across the posterior margins of the medial and lateral condyles. The medial condylar height (MCH) is the perpendicular distance from the most anterior margin of the medial condyle to line 1.
% of epicondylar width MCH	MCH expressed as a percentage of the transepicondylar width.
Lateral trochlear inclination	Line 1 is drawn across the posterior margins of the medial and lateral condyles. Line 2 is drawn along the lateral slope of the trochlear groove. The lateral trochlear inclination is the angle between the 2 lines. A positive angle opens laterally.
Trochlear bossing (AP)	Anteroposterior (AP) dimensions are measured on a sagittal image at the presumed location of the middle/deepest portion of the trochlear groove.
Limb geometry	
TTTG	Two sets of measurements are made. The first measurement is made on the first cut and the second made at the level of where the patellar tendon inserts at the tibial tuberosity. Line 1 is drawn across the posterior margins of the medial and lateral condyles and will be applied to the distal image as well. Line 2 is perpendicular to line 1 and crosses the center of the trochlear groove in the first cut. Line 3 is perpendicular to 1 and runs through the insertion of the patellar tendon on the distal image. The difference in distances of lines 2 and 3 to a fixed point on the image is TTTG.

(continued)

TABLE 1
(Continued)

Measurement	
Coronal measurements	
Varus-valgus angle	Line 1 is drawn through the axis of the femur, and line 2 is drawn through the axis of the tibia. Varus-valgus angle is the angle between these 2 lines.
Lateral condylar height	LCH is the distance from the physeal scar to the lateral margin of the lateral femoral condyle articular surface.
Medial condylar height	MCH is the distance from the physeal scar to the medial margin of the medial femoral condyle articular surface.
Patellar height	Using the sagittal image through the mid-patella facet as determined on the axial image, the following measurements are made: • Patellar height A: Measured from the most proximal articular margin of the patella to the most distal (nonarticular) aspect of the patella • Patellar height B: Measured from most proximal to most distal articular margin of the patella • Patellar height C: Measured from the most distal aspect of the patella to the distal insertion of the patellar tendon at the tibial tuberosity (patella tendon length) • Patellar height D: Measured from the most distal articular surface of the patella to the anterior margin of the articulating surface of the tibia plateau • Patellar height E: Measured from the most distal aspect of the articular surface of the patella to the distal insertion of the patellar tendon at the tibial tuberosity • Patellar height F: Measured from the most distal aspect of the patella to the anterior margin of the articulating surface of the tibia plateau
Patellar trochlear overlap	Measures the length of the overlap between patellar and trochlear articulating cartilage.
Insall-Salvati ratio	Patellar height C divided by height A.
Modified Insall-Salvati ratio	Patellar height E divided by height B.
Caton-Deschamps ratio	Patellar height D divided by height B.
Morphology ratio	Patellar height A divided by height B.
Femoral contacting surface ratio	Patellar height B divided by the trochlear overlap.

least 2 frank patellofemoral joint dislocations (PFJDs) to be included.

The MR images were obtained with a nonweightbearing knee in full extension. Patellar tilt was evaluated on axial slices, and patellar height was measured on sagittal images. Trochlear morphologic characteristics were assessed on axial images at the proximal and distal trochlea. The proximal trochlea (first cut) was established at the slice in which trochlear articular cartilage spanned the entire trochlear surface and maintained contact with the patella. The distal trochlea (second cut) was established at the point with the greatest epicondylar width based on measurements on axial slices. In total, 44 measurements were collected for each patient: these measures included variations on patellar height, patellar alignment, trochlear characteristics, limb geometry, and others. The measurements were made to include articular cartilage: description of these measures can be found in Table 1 and Figures 1 to 4. A musculoskeletal radiologist collected the measurements for the initial 10 controls and 5 PFJD patients; the remaining measurements were collected by 2 medical students. The data then underwent statistical analysis with Student t tests to establish means, standard deviation (SD), significance, and confidence interval calculations. Interobserver variation was also calculated by having the 3 researchers repeat all measurements on 11 patients.

Statistical Analysis

Data were analyzed using SPSS (version 19.0; SPSS Inc, Chicago, Illinois) using independent Student t tests for each group's means, SD, standard error, and confidence intervals (CIs). Significance was set a P value of $<.05$. Interobserver correlations were also calculated.

RESULTS

Measurements are expressed as mean ± SD. Of the 81 controls and 40 PFJD patients, some measurements were unobtainable because the limitation in MRI imaging quality and/or the anatomy was so skewed that a particular measurement made no sense. This was most prevalent in the patellar height measurements, which only allowed us

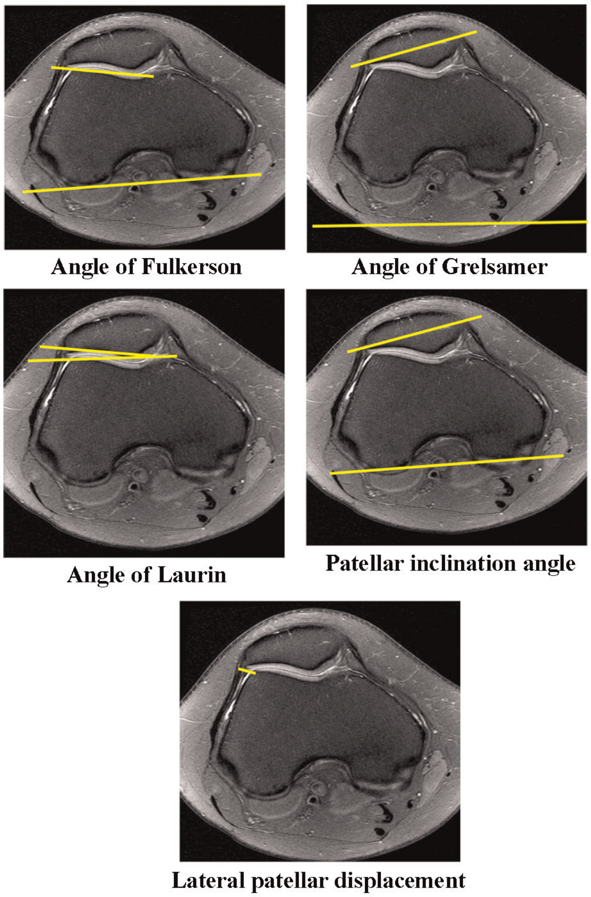

Figure 1. Patellar alignment.

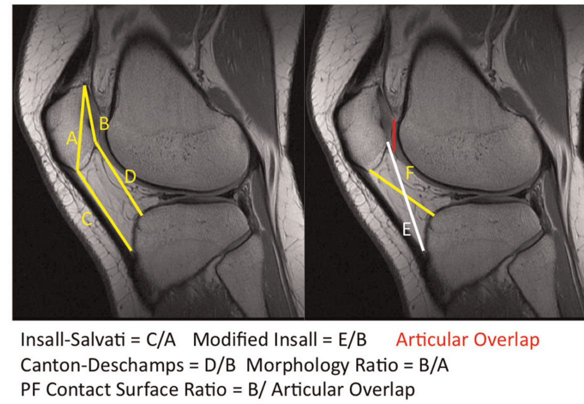

Figure 2. Patellar height.

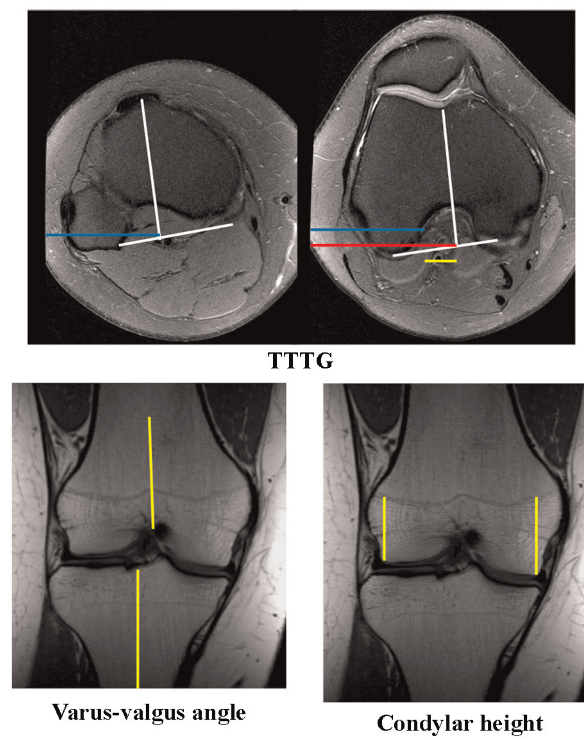

Figure 3. Limb geometry and other measurements TTTG, tibial tuberosity–trochlear groove.

to collect 34 PFJD patients for those measurements. This was due in some cases to a lateralized patella that did not allow proper correlation to tibial landmarks, and others lacked sagittal images. There was also difficulty obtaining the transepicondylar width for the initial patients collected by the musculoskeletal radiologist. This resulted in all of our measurements requiring transepicondylar width to have only 71 control and 35 PFJD patients. Two of the PFJD patients lacked adequate coronal images for condylar height; as a result, only 38 patients had those measurements. All measurements are listed in Table 2.

Patellar Tilt. All patellar tilt measurements were found to be significantly different between the 2 groups. The angle of Laurin (control, 10.10° ± 0.48°; PFJD, –5.23° ± 2.96°; $P < .001$) and angle of Fulkerson (control, 18.18° ± 0.56°; PFJD, –3.5° ± 2.62°; $P < .001$) are examples of well-described measures that were found to be significant. As with all of our measurements of patellar tilt, these angles reflect that patients with patellofemoral instability had an increase in the lateral rotation of the patella around its cephalad-to-caudal axis. The lateral displacement of the patella (control, 3.28 ± 0.24 mm; PFJD, 6.59 ± 0.69 mm; $P < .001$) was also significant between the 2 groups.

Patellar Height. Patellar height has been researched extensively and repeated in reviews with a variety of measurements,[††] yet our research found significance between the 2 groups with the Insall-Salvati ratio (control, 1.08 ± 0.02; PFJD, 1.26 ± 0.03; $P < .001$), the Caton-Deschamps ratio (control, 1.13 ± 0.02; PFJD, 1.29 ± 0.03; $P < .001$), and morphology ratio (control, 0.76 ± 0.01; PFJD, 0.79 ± 0.01; $P = .029$).

Trochlear Characteristics. Numerous measurements of trochlear morphologic characteristics proved significant between the control and PFJD groups at the proximal

[††]References 3, 6, 9, 10, 12, 15, 25, 28, 37.

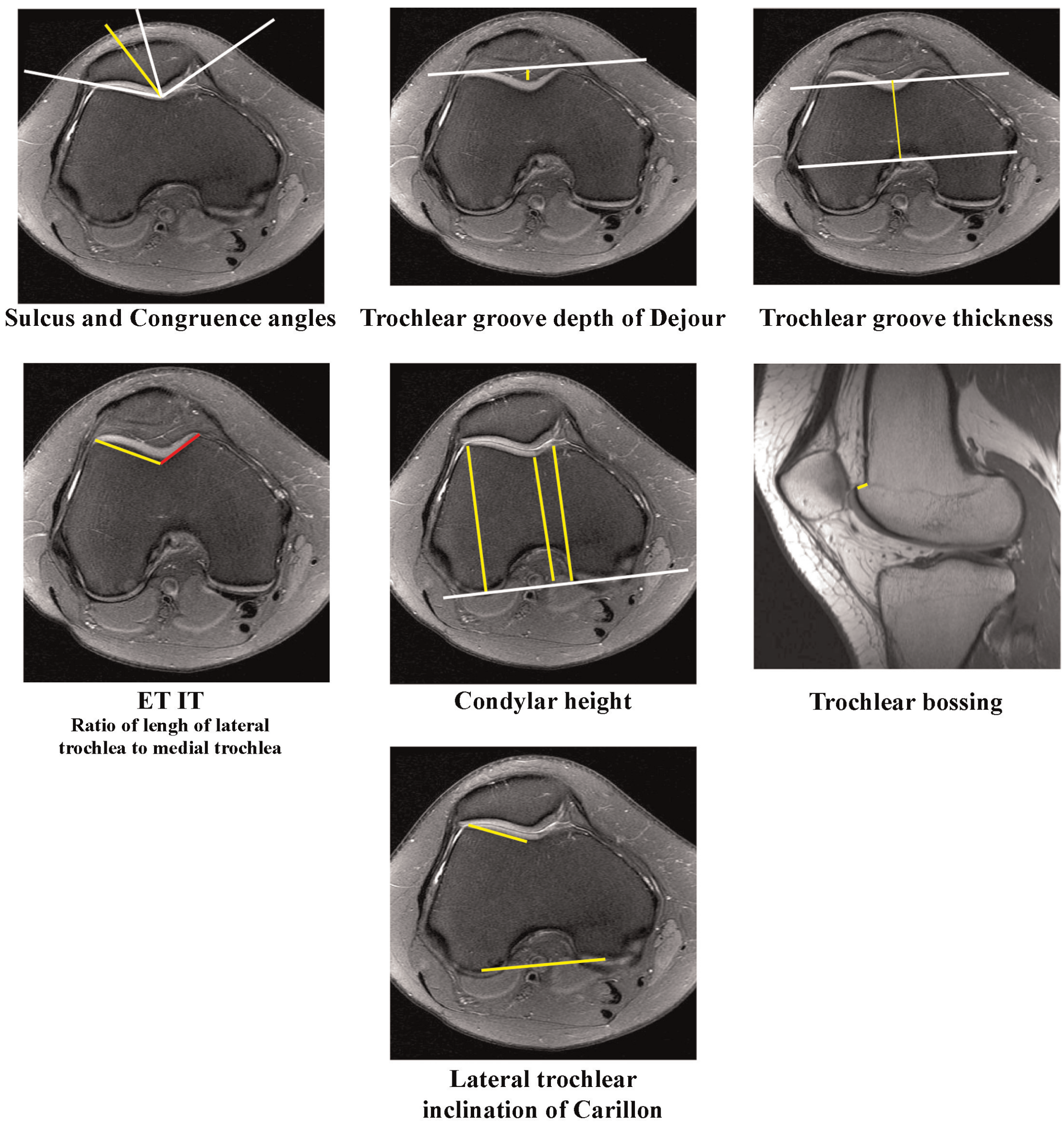

Figure 4. Trochlear morphologic characteristics

and distal trochlea. At the proximal trochlea (first cut), significant measurement included well-described measurements such as sulcus angle (control, 148.48° ± 0.94°; PFJD, 165.57° ± 2.65°; $P < .001$) and lateral trochlear inclination (control, 21.27° ± 0.66°; PFJD, 13.31° ± 1.36°; $P < .001$). But lesser-known measurements such as ETIT (control, 1.51 ± 0.05; PFJD, 2.11 ± 0.17; $P < .001$), which is a measurement of facet asymmetry, were also found to be significant between the 2 groups. Lateral condylar height (LCH) and medial condylar height (MCH) were both found to be significantly different between the 2 groups at the proximal trochlea. The central condylar height (CCH) measurement was not significantly different at either aspect of the trochlea.

A greater proportion of measures at the distal trochlea demonstrated significance between the control and PFJD groups, although the difference between the means was often larger at the proximal trochlea. Interestingly, lateral condylar height lost significance at the distal trochlea ($P = .643$). Also worth noting is that MCH ($P = .048$) was the only standard condylar height measurement that was significantly different at the distal trochlea. Transepicondylar width demonstrated a significant difference between groups (control, 71.00 ± 0.76 mm; PFJD, 75.23 ± 0.95 mm; $P < .001$). The trochlear groove thickness was not significantly different at either point along the trochlea, whereas lateral trochlear inclination was significantly different ($P < .001$) at both points of the trochlea.

Limb Geometry and Other Measures. Among the coronal and limb geometry measurements, only the varus-valgus and TTTG measurements proved to be significantly different between the 2 groups. The varus-valgus angle, which is

TABLE 2
Results of Measurements[a]

Measurement	Control, Mean ± SE	PFJD, Mean ± SE	95% CI: Normal PFJD	P Value
Transepicondylar width, mm	71.00 ± 0.76	75.23 ± 0.95	80.14 to 83.16 73.30 to 77.16	<.001
Patellar angle				
Angle of Fulkerson, deg	18.18 ± 0.56	–3.5 ± 2.62	17.08 to 19.29 –8.79 to 1.79	<.001
Angle of Grelsamer, deg	14.00 ± 0.73	24.82 ± 2.03	12.55 to 15.45 20.72 to 28.92	<.001
Angle of Laurin, deg	10.10 ± 0.48	–5.23 ± 2.96	9.14 to 11.05 –11.23 to 0.76	<.001
Patellar inclination angle, deg	8.10 ± 0.55	24.03 ± 2.42	7.02 to 9.19 19.14 to 28.92	<.001
Lateral patellar displacement, mm	3.28 ± 0.24	6.59 ± 0.69	2.79 to 3.77 5.19 to 7.97	<.001
Trochlear characteristics at first cut				
Sulcus angle, deg	148.48 ± 0.94	165.57 ± 2.65	146.61 to 150.34 160.76 to 171.44	<.001
Congruence angle, deg	13.95 ± 2.00	40.14 ± 4.57	9.97 to 17.92 30.89 to 49.38	<.001
Trochlear groove depth, mm	6.47 ± 0.24	4.00 ± 0.43	5.99 to 6.94 3.11 to 4.87	<.001
Roman arch, mm	17.13 ± 0.45	15.39 ± 0.73	16.23 to 18.02 13.91 to 16.87	.036
Trochlear groove thickness, mm	42.90 ± 0.48	42.73 ± 0.95	41.95 to 43.86 40.81 to 44.64	.853
% of epicondylar width TGT	53.00 ± 0.00	56.00 ± 1.00	52.00 to 54.00 55.00 to 58.00	<.001
ETIT	1.51 ± 0.05	2.11 ± 0.17	1.42 to 1.61 1.77 to 2.46	<.001
Lateral condylar height, mm	63.94 ± 0.61	59.69 ± 0.89	62.73 to 65.16 57.89 to 61.01	<.001
% of epicondylar width LCH	78.00 ± 1.00	80.00 ± 1.00	77.00 to 79.00 78.00 to 82.00	.061
Central condylar height (from Biedert and Bachmann[4]), mm	60.03 ± 0.63	58.12 ± 1.43	58.78 to 61.29 55.22 to 61.01	.157
% of epicondylar width CCH	73.00 ± 1.00	76.00 ± 1.00	72.00 to 75.00 74.00 to 79.00	.018
Medial condylar height, mm	58.77 ± 0.63	55.53 ± 0.99	57.52 to 60.03 53.52 to 57.53	.005
% of epicondylar width MCH	72.00 ± 1.00	74.00 ± 1.00	70.00 to 73.00 72.00 to 77.00	.036
Lateral trochlear inclination, deg	21.27 ± 0.66	13.31 ± 1.36	19.95 to 22.58 10.56 to 16.07	<.001
TTTG, mm	10.96 ± 0.39	18.69 ± 0.81	10.19 to 11.73 17.06 to 20.32	<.001
Trochlear bossing (AP), mm	3.64 ± 0.13	3.97 ± 0.31	3.38 to 3.91 3.35 to 4.60	.245
Trochlear characteristics at second cut				
Trochlear groove depth, mm	5.87 ± 0.15	4.06 ± 0.37	5.57 to 6.18 3.31 to 4.81	<.001
Roman arch, mm	24.25 ± 0.42	21.28 ± 0.48	23.42 to 25.08 20.30 to 22.25	<.001
Trochlear groove thickness, mm	37.75 ± 0.65	41.35 ± 0.93	36.46 to 39.04 39.46 to 43.24	.002
% of epicondylar width	47.00 ± 1.00	57.00 ± 1.00	46.00 to 49.00 56.00 to 58.00	<.001
ETIT	1.40 ± 0.02	1.97 ± 0.07	1.36 to 1.44 1.83 to 2.12	<.001

(continued)

TABLE 2
(Continued)

Measurement	Control, Mean ± SE	PFJD, Mean ± SE	95% CI: Normal PFJD	*P* Value
Sulcus angle, deg	137.57 ± 0.93	155.33 ± 1.98	135.72 to 139.41 151.32 to 159.34	<.001
Lateral condylar height, mm	65.63 ± 0.52	65.21 ± 0.72	64.59 to 66.67 63.76 to 66.66	.643
% of epicondylar width LCH	81.00 ± 1.00	88.00 ± 1.00	80.00 to 82.00 86.00 to 89.00	<.001
Central condylar height (from Biedert and Bachmann[4]), mm	62.00 ± 0.55	62.63 ± 0.74	60.90 to 63.10 61.13 to 64.12	.508
% of epicondylar width CCH	77.00 ± 0.00	84.00 ± 1.00	76.00 to 78.00 83.00 to 86.00	<.001
Medial condylar height, mm	63.83 ± 0.52	62.02 ± 0.73	62.79 to 64.87 60.54 to 63.50	.048
% of epicondylar width MCH	78.00 ± 0.00	83.00 ± 1.00	77.00 to 79.00 82.00 to 84.00	<.001
Lateral trochlear inclination, deg	21.74 ± 0.52	15.95 ± 0.85	20.71 to 22.77 14.24 to 17.66	<.001
Coronal measurements				
Varus-valgus angle, deg	5.45 ± 0.29	10.02 ± 0.53	4.87 to 6.03 8.94 to 11.10	<.001
Lateral condylar height, mm	27.94 ± 0.36	26.48 ± 0.50	27.22 to 28.67 25.47 to 27.49	.022
Medial condylar height, mm	34.23 ± 0.44	33.08 ± 0.55	33.36 to 35.10 31.97 to 34.19	.122
Patellar height				
Patellar trochlear overlap, mm	14.49 ± 1.52	11.91 ± 1.00	11.89 to 14.29 9.88 to 13.94	.297
Insall-Salvati ratio	1.08 ± 0.02	1.26 ± 0.03	1.04 to 1.12 1.20 to 1.33	<.001
Modified Insall-Salvati ratio	1.64 ± 0.03	1.72 ± 0.04	1.58 to 1.69 1.64 to 1.80	.085
Caton-Deschamps ratio	1.13 ± 0.02	1.29 ± 0.03	1.09 to 1.17 1.22 to 1.35	<.001
Morphology ratio	0.76 ± 0.01	0.79 ± 0.01	0.74 to 0.78 0.76 to 0.83	.029
Patellofemoral contacting surface ratio	0.45 ± 0.05	0.37 ± 0.03	0.36 to 0.54 0.30 to 0.43	.240

[a]AP, anteroposterior; CCH, central condylar height; CI, confidence interval; MCH, medial condylar height; PFJD, patellofemoral joint dislocation; TGT, trochlear groove thickness; TTTG, tibial tuberosity–trochlear groove.

anatomic alignment, had means of 5.45° ± 0.29° for controls and 10.02° ± 0.53° for PFJD patients ($P < .001$) in which a positive number reflects a valgus alignment. The TTTG (control, 10.96 ± 0.39 mm; PFJD, 18.69 ± 0.81 mm; $P < .001$) was significantly different between the 2 groups and corresponds to CT-based values from other studies in which controls had means of 10 mm, those with increased likelihood were 15 to 20 mm, and absolute instability was >20 mm.[9,10]

Interobserver Analysis. For more details, see the Appendix (available in the online version of this article at http://ajs.sagepub.com/supplemental/). Twenty-nine of our measurements had at least moderate correlation between the 3 researchers. Patellar tilt measurement often had an intraclass correlation coefficient (ICC) >0.9. Surprisingly, TTTG had a poor to fair correlation (ICC = 0.233).

DISCUSSION

Axial radiographs and CT imaging of the patellofemoral joint are well documented and are the basis for many of our current diagnostic measurements. Magnetic resonance imaging has the distinct advantage of revealing chondral morphologic characteristics, which more accurately depicts the patellar-trochlear relationship in comparison with subchondral bone morphologic characteristics.[28,32,35] It also spares the patient the radiation exposure of CT imaging. Recent MR-based studies have begun to show that previously established pathological cutoffs for those with patellofemoral instability (eg, sulcus angle) are not exactly the same when applied to MRI,[1,35] whereas other measurements such as trochlear groove depth have remained similar.[1,12,25] Given these mixed results, one could question the reliability of applying current normal versus abnormal values to MRI measurements. Authors such as Miller et al[24] and Smith et al,[33] however, have shown the reliability of MRI in performing many of the established measurements. Our research shows how these classic measurements can vary from their radiograph and CT imaging means when applied to MRI, whereas some measurements remain the same.

Previous authors have used MRI to perform measurements of patellar tilt.[12,31] Patellar tilt proved to be an excellent group of measurements for delineating between controls and those with instability. The confidence intervals between the 2 groups were separated by at least 5° for each measurement. For the angle of Fulkerson, the means of 18.18° ± 0.56° and –3.5° ± 2.62° for controls and PFJD patients, respectively, support the established cutoff of <8° for pathologic disorder established by Schutzer et al.[30] Patellar inclination angle, however, differed from previously published values. Our results of 8.10° ± 0.55° for controls and 24.03° ± 2.42° for PFJD patients differed from the findings of Dejour et al[9] (10° ± 4.3° vs 16° ± 3.3°) in their CT-based study. Our results were very similar, however, to those by Escala et al,[12] whose MRI-based study found means of 9.2° and 21.7° for controls and PFJD patients, respectively. This is an interesting result as patellar inclination angle would not be predicted to change between CT and MR imaging as articular cartilage is not involved in its measurement. For the angle of Laurin, our results (control, 10.10° ± 0.48°; PFJD, –5.23° ± 2.96°) differed from Biedert and Gruhl's[5] CT-based study with means of –0.1° and –3.1°, which would be expected since it relies on the articular cartilage both on the trochlea and the patella. As mentioned earlier, all of our measurements reflected an increase in the lateral tilt of the patella between the PFJD and control groups. Current literature has argued that the increase in lateral tilt could be due to a laxity or weakness of medial soft tissue structures, such as the MPFL and vastus medialis.[5,10]

The significance of patella alta is that an elevated patella will not engage enough of the bony architecture of the proximal trochlea that is necessary to prevent lateralization of the patella.[36] In this study, patellar height demonstrated limited success in terms of finding significant differences. One could assume that MRI inclusion of articular cartilage would make some of these measurements unreliable, but Miller et al[24] demonstrated that patellar height measurements could be reliably recorded on MRI. Our results of 1.08 ± 0.02 for the control and 1.26 ± 0.03 for PFJD patients for the Insall-Salvati ratio parallels the well-documented pathological value of >1.2 for patella alta for radiographic measures[19] and what Escala et al[12] found in their MRI-based study (1.11 and 1.35). The Caton-Deschamps ratio was the only other patellar height ratio found to be significant. Our values of 1.13 ± 0.02 for controls and 1.29 ± 0.03 for PFJD patients again reflect the standard cutoff of >1.2 significant for patella alta.[9,18]

Trochlear morphologic characteristics were a major aspect of our research and yielded some very interesting results. Our sulcus angle values of 148.48° ± 0.94° (controls) and 165.67° ± 2.65° (PFJD patients) reflect a difference from the classic cutoff of 145°.[5,6,8,9] Although they do reflect an increase in the angle, likely due to inclusion of articular cartilage, our patellofemoral instability patients did not have quite as large a sulcus angle as found by van Huyssteen et al[35] (186.5°) and Ali et al[1] (173°). These differences could be attributed to a difference in the location where the measurement was made: van Huyssteen et al[35] made their measurements within 3 mm of the start of articular cartilage, and Ali et al[1] based their location on the portion with the greatest ventral prominence. The sulcus angle means at our distal trochlea were closer to the classic cutoff. But since the initial cutoff was established on a Merchant view of the knee, one can see how the values may vary. Trochlear groove depth is another classic measurement, with a cutoff of <4 mm being pathological for patellofemoral instability.[9] The MRI-based trochlear depth measures have not varied much from the initial CT or radiographic values.[1,12,25] Our values of 6.47 ± 0.24 mm for control and 4.00 ± 0.43 mm for PFJD patients at the proximal trochlea differ from the classic cutoff but prove similar to the results of Escala et al.[12] This could be a result of better visualization of the articular cartilage, but other MRI studies have actually reported means less than 3 mm for patients with patellofemoral instability.[1,25] The mean values of trochlear groove depth at the distal trochlea of our patients were nearly equal to those at the proximal trochlea.

Lateral trochlear inclination is another measurement of trochlear morphologic characteristics prevalent in patellofemoral literature.[1,7,21,28,37] These studies are primarily MRI-based studies, with Carrillon et al[7] establishing the cutoff between controls and those with patellar instability at 11°. This value is lower than our results of 21.27° ± 0.66° and 13.31° ± 1.36° at the proximal trochlea and 21.74° ± 0.52° and 15.95° ± 0.85° at the distal trochlea. Salzmann et al[28] had values closer to ours, but their research was based on patients selected on radiographic criteria of trochlear dysplasia. Carrillon et al[7] had similar methodology to our study with regard to clinical criteria for patient selection and similar location of measurements. Our data still reflect the trend that a decrease in lateral trochlear inclination results in less resistance to the lateralization of the patella, which increases chances of patellar instability.

Facet asymmetry is an aspect of trochlear dysplasia that has had very limited research until recently and has mostly been studied in MRI-based studies.[25,28] Pfirrmann et al[25] first showed that a facet ratio less than 2:5 (medial to lateral) could identify those with trochlear dysplasia with a sensitivity and specificity of 100% and 96%, respectively. We inverted this ratio (5:2 lateral to medial) to correspond to our lateral to medial ratio of ETIT. Our mean values of 1.51 and 2.11 at the first cut and 1.40 and 1.97 at the second cut for control and PFJD patients, respectively, are lower than the 2.5 cutoff Pfirrmann et al[25] documented. This difference may be due to a difference in patient selection in that ours were selected on a criterion of patellar dislocation, whereas Pfirrmann et al[25] divided patients based on radiographic evidence of trochlear dysplasia. Salzmann et al[28] also researched facet asymmetry in comparing axial radiographs to MRI. Their means for MRI, although not found to be significant, saw the lateral to medial facet ratio increase from 1.6 to 1.9 as the degree of dysplasia increased. This makes our research unique in that it was the first application of facet asymmetry in the clinical context of patellar instability.

Condylar height has thus far had limited research, and it has lacked any clear answers. Escala et al[12] evaluated LCH, MCH, and CCH measurements, but none were found to be significant between controls and those with patellar instability. Our data demonstrated that LCH (control, 63.94 ± 0.61 mm; PFJD, 59.69 ± 0.89 mm) and MCH (control, 58.77 ± 0.63 mm; PFJD, 55.53 ± 0.99 mm) proved significantly different at the proximal trochlea, and only MCH at the distal trochlea proved significantly different. Interestingly, we also evaluated condylar heights as a proportion of epicondylar width, as Biedert and Bachmann[4] published in 2009. At the distal trochlea, despite having only MCH prove to be significantly different from our standard condylar heights, all 3 condylar heights expressed as a percentage of epicondylar width proved significantly different. For example, standard LCH had a P value of .643, but as a percentage of epicondylar width, the results for LCH were 81% ± 1% for controls and 88% ± 1% for PFJD patients ($P < .001$). Biedert and Bachmann's published mean values[4] for LCH (control, 81%; PFJD, 82%), CCH (control, 73%; PFJD, 77%), and MCH (control, 76%; PFJD, 79%) proved similar to our own at the lateral condyle of the distal trochlea, but our groups differed at the central and medial condyle. Biedert and Bachmann[4] and our group did, however, find a larger difference between the control versus PFJD groups with the medial and central condylar heights than at the lateral condyle. The discussion of which condylar measurement is ideal for evaluating patellar instability is still muddled. Our standard measurement of the lateral condyle supports its biomechanical role in resisting lateral displacement of the patella, and the significance of the central and medial condyles may reflect a lack of condylar development or failure to form a trochlear groove. We find the use of the ratio of condylar height to transepicondylar width difficult to justify. Given that the transepicondylar width means were significantly different (control, 71.00 ± 0.76 mm; PFJD, 75.23 ± 0.95 mm), the fact that condylar measurements at the distal trochlea only became significant when expressed as a percentage of transepicondylar width could be a result of standardization of the measurements or a statistical anomaly. Interestingly, despite the increase in width and the decrease in condylar height when comparing controls to PFJD patients, the measurements for percentage of transepicondylar width were higher among patients with patellar instability.

The greater separation of means at the proximal trochlea does support the importance of the proximal trochlea in stabilization of the patella. Given that our standard error and confidence intervals were also larger, however, these results could also be due to a greater variation of the proximal trochlea.

The TTTG has been well researched in patients with patellar instability.[6,9,10,20,29] Researchers have had mixed results regarding the validity or reliability of MRI-based TTTG measurements compared with CT.[20,29] Our means (control, 10.96 ± 0.39 mm; PFJD, 18.69 ± 0.81 mm) fall short of the cutoff of 20 mm for certain pathology but correspond with the increased likelihood of instability in those with 15 to 20 mm.[10] Our results indicate that instability can exist at TTTG distances <20 mm; whether this is due solely to TTTG distance or multiple influences is unclear.

Our study had both strengths and weaknesses. A major strength of our study is the population size. Only 5 other studies on patellofemoral instability have had as many or more patients than our study,[4,9,12,13,31] and 1 study was CT based. Another strength was that our location of measurements was based on morphological features. Unlike Pfirrmann et al,[25] who performed their measurements at set distances from the joint line, our measurements will not vary from patient to patient by being at a fixed distance. This is particularly important at the proximal trochlea, because our location pinpoints the starting point between trochlear and patellar articular surfaces.

In terms of weaknesses, some arose from one of our project's greatest strength: its size. In collection of the patients, our MRI protocol was not as precise, resulting in some patients lacking the adequate slices to make proper measurements. This problem, however, could also be attributed to the patient population as patients with patellofemoral instability often have patellar malalignment. An increase in the lateral displacement of the patella could explain why patellar height measurements were most affected. Future projects should include a stricter protocol to ensure the sagittal images are true sagittal images, increasing our chances of obtaining proper measurements. It would also have been ideal to blind the researchers, making the measurements to prevent bias. Finally, by having controls selected from patients at the sports medicine clinic, our controls often had other knee injuries, including meniscal and cruciate ligament tears. Although these patients lacked any history or clinical signs of patellofemoral instability, this does not exclude them possibly having abnormal patellofemoral joints.

An arguable weakness of the study is that our patients had their imaging performed with a straight leg without engagement of the quadriceps. Although Ward et al[36] and Biedert and Gruhl[5] demonstrated that active quadriceps contraction can be applied to these studies, our goal was to create values that the everyday physician could use without concern for strict parameters. Many of these measurements of patellar angle, tilt, and trochlear characteristics were originally obtained with the knee in various degrees of partial flexion. Our results demonstrate that with MRI, an observer could reliably discern key morphological differences between a patient who has patellar instability and one with normal knees without active contraction of the quadriceps.

The next logical step is to pursue statistical analysis of our data to create established cutoffs for MRI as previous groups have with CT and radiography and apply them to prospective trials to establish which measurements remain a reliable delineator between normal knees and those with patellofemoral instability.

CONCLUSION

By detecting significant morphological differences between the 2 groups, these results show that MRI could be used to obtain many of the measures of patellofemoral instability historically obtained with CT and plain radiographs. The multifactorial nature of patellofemoral instability was supported by our results with significant measures in each of the 4 recognized factors of patellar instability. Patellar tilt measures proved to be an excellent group of measurements for delineating between controls and those with instability. Patella alta ratios, however, had only the Insall-Salvati and Caton-Deschamps ratios demonstrate significant difference between the 2 groups. Trochlear morphologic characteristics had numerous significant measures at the proximal and distal trochlea, of which only sulcus angle and lateral trochlear inclination differed from established values. As such, MRI is an appropriate tool to aid the clinician in obtaining the radiographic information needed in patients with recurrent patellofemoral instability.

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