The Medial Patellofemoral Complex: Surgical anatomy, dynamic assessment, and considerations for reconstruction in the treatment of patellofemoral instability

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Chapter 10. What are the patterns of patellar maltracking throughout range of motion in patients with and without symptomatic instability?

Characterization of patellar maltracking on dynamic kinematic CT imaging

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Abstract

Purpose: Little has been reported on the relationship between patellar maltracking and instability. Patellar maltracking has been subjectively described with the "J sign" but is difficult to assess objectively using traditional imaging. Dynamic kinematic computed tomography (DKCT) allows dynamic assessment of the patellofemoral joint. DKCT was used to visualize and quantify patellar maltracking patterns, and severity of maltracking was correlated with the presence or absence of patellar instability symptoms.

Methods: Seventy-six knees in 38 patients were analysed using DKCT. Maltracking was defined as deviation of the patella from the trajectory of the trochlear groove and was characterized by patellar bisect offset, which was measured at 10° intervals of knee flexion during active flexion and extension. Bisect offset measurements were grouped by number of quadrants of maximum lateral patellar motion, with one, two, and three quadrants corresponding to 75-99, 100-125, and >125 %, respectively. Patellar instability symptoms were correlated with maltracking severity.

Results: Two knees were excluded because of poor imaging quality. Fifty of 74 knees had patellar instability, and 13 patients had bilateral symptoms. Of these, four (8 %) had normal tracking patterns; 41 (82 %) had increased lateral translation in extension, which we termed the J-sign pattern; 4 (8 %) had persistent lateralization of the patella throughout range of motion; and 1 had increased lateral translation in flexion. In knees with the J-sign pattern, degree of maltracking was graded by severity: J1 (n = 24), J2 (n = 19), and J3 (n = 15). The sensitivities of J-sign grades in predicting patellar instability symptoms were 50 % (J1), 80 % (J2), and 93 % (J3) ($p < 0.01$). There were significant differences in sensitivity between knees with no J sign or J1 versus J2 or J3 ($p = 0.02$).

Conclusion: DKCT showed several patellar maltracking patterns in patients with patellar instability. A J-sign pattern with more than two quadrants of lateral translation correlated with the presence of patellar instability symptoms. Incorporation of this approach of objectively quantifying maltracking patterns is recommended in the evaluation of patellofemoral instability.

Introduction

The assessment of patellar maltracking requires evaluation of kinematic changes that occur within the patellofemoral joint during knee range of motion and dynamic quadriceps contraction. The "J sign" is a clinical evaluation tool used to assess maltracking [9]. The subject sits with knees bent and actively extends the knees while the clinician watches for acute lateral translation of the patella in terminal extension, often described as the pattern of an inverted J [9]. This is thought to be caused by soft tissue insufficiency, which causes lateral translation near the end of maximum extension as the patella disengages from the trochlear groove. Grading of a positive J sign is subjective, with the grades of 1+, 2+, and 3+ used at the clinician's discretion. Currently, no standardization of this grading system exists. Additionally, the association of the J sign with the presence of patellar instability is unclear.

Several measurements have been used to quantify patellar motion in the evaluation of patellar instability. Patellar mobility can be evaluated using examination tools such as the glide test, in which a lateral force is placed on the patella and its motion is quantified in terms of patellar quadrants. Radiographically, measurements such as bisect offset and lateral patellar displacement describe the lateral translation of the patella relative to the trochlear groove and are often performed on axial radiographs (Laurin, Mer- chant, or sunrise views) or axial magnetic resonance imaging (MRI) [2]. Although imaging studies may quantify abnormal patellar position, these images are often taken in a single, static position without active muscle loading. Because patellar maltracking refers to the abnormal position of the patella that occurs throughout range of motion of the knee, it is often difficult to fully characterize on isolated images in a single imaging study.

Dynamic kinematic computed tomography (DKCT) is new technology that allows the dynamic assessment of the patellofemoral joint during knee range of motion. Previous studies have noted the dynamic and kinematic benefits of this imaging modality in the assessment of the patellofemoral anatomy [14, 16]. DKCT was used to assess patellar position during active knee extension and to quantify pat- terns of maltracking, including the J sign, on the basis of measurements of bisect offset. The sensitivity of the J sign was then determined for the presence of patellar instability in this study population, with severity graded on the basis of maximal lateral translation. We hypothesized that the presence of a J sign would be associated with greater likelihood of symptomatic patellar instability, as would a more severe J sign, as noted by greater lateral translation during maltracking.

Materials and methods

Between 2009 and 2013, patients who were evaluated by the senior author for surgical treatment for recurrent patellar instability underwent DKCT as part of their preoperative workup. Forty-six patients were scanned during this time. Inclusion criteria were patients who had failed conservative management of patellar instability, and all ages were included, although this condition occurs in younger patients. Patients with or without previous stabilization surgery were included. Patients with incomplete imaging sequences or those who lacked full knee extension were excluded from the study. Of the 46 patients, 7 were excluded because of lack of available data, and 1 was excluded because of a questionable presence of patellar instability symptoms.

This left a total of 38 patients (76 knees) in this study. Because bilateral scans were obtained in patients with both unilateral and bilateral instability, medical records were reviewed to determine the presence or absence of symptoms for each knee.

DKCT was performed on a Toshiba Aquilion ONE (Toshiba America Medical Systems Corporation), a kinematic CT scanner originally designed for dynamic cardiac imaging. It consists of 320 0.5-mm detectors delivering 16 cm of coverage in a single rotation of the gantry in less than 1 s, while providing high-resolution imaging during knee motion. Settings were defined for extremity imaging, which provides three-dimensional kinematic imaging dur- ing active knee extension and flexion at 0.5-s intervals over a span of 10 s [7]. In comparing one dynamic kinematic CT scan versus obtaining the same amount of information on a 64-row scanner for a 100-mm scan range over 9 positions, the effective dose for a 64-slice scanner would be approximately 1.7 mSv (170 mrem), compared with 0.5 mSv (50 mrem) for a single acquisition on the 320 system. For com- parison, an individual receives approximately 3 mSv (300 mrem) of radiation each year from natural background radiation and 0.05 mSv (5 mrem) for a chest radiograph. Details regarding the radiation exposure, as well as justification for this, were reported in a previous study by the authors [14].

In the gantry, patients were positioned with knees resting on a cushion. The knees were loosely secured with a strap at the thighs to prevent rotation, allowing extension of the knees without constraining the feet. For subjects who experience lateral maltracking, patellar bisect offset index and lateral tilt near full extension have been shown to be similar for upright weight-bearing and unresisted knee extension, although the bisect offset index tends to be larger with weight-bearing beyond 25° of flexion [5]. Patients were asked to rest their knees in flexion and then slowly fully extend and flex both knees over a 10-s interval with no external resistance other than gravity. Patients performed continuous active knee range of motion from flexion to full extension, completing approximately 1.5 cycles of knee motion during each 10-s acquisition. Imaging of the knees took place at 0.5-s intervals throughout the 10-s course, with three-dimensional volumetric image acquisition of the patellofemoral joint (Fig. 1).

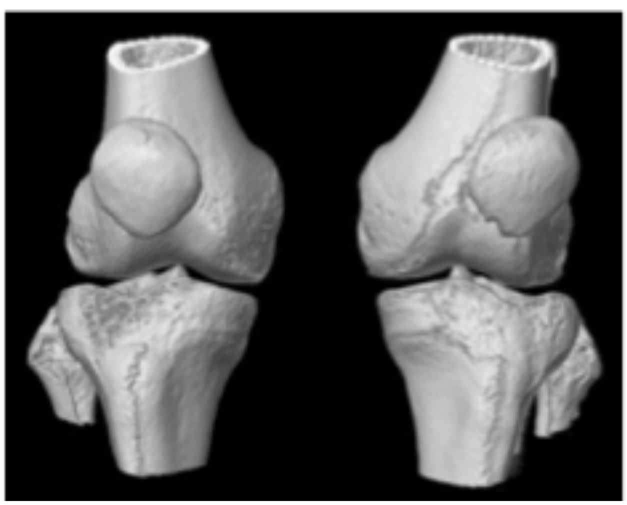

Fig. 1 Imaging of the knees took place at 0.5-s intervals during the course of 10 s to allow for three-dimensional volumetric image acquisition of the patellofemoral joint

Postprocessing measurements of the images were per- formed by a single observer, who was an orthopaedic chief resident trained in performing measurements using this built-in scanner software with a known sensitivity of 0.1 mm and 0.1° as provided by the manufacturer. The observer was blinded to the instability condition of each knee. Both knees were included in the analysis, with the contralateral knees of the patients with unilateral instability acting as controls. The knee flexion angle in each sagittal image was measured by drawing intersecting lines along the centre of the femoral and tibial shafts. Frames were then chosen to represent each 10° interval of flexion from 0° to 90°, and bisect offset measurements were obtained at each flexion angle.

The bisect offset measurement (Fig. 2) quantifies the amount of patellar lateralization relative to the trochlear groove [2]. Using the axial images at the selected flexion angles, we used the image with the largest patellar width to identify the medial–lateral axis of the patella. To maintain a constant femoral reference through flexion angles, we superimposed the patellar frame onto the axial image dis- playing the posterior condyles with the Roman arch [14]. A line was drawn perpendicular to the posterior condylar axis through the deepest portion of the trochlear groove. Using the patellar width line, we measured bisect offset as the percentage of the patella that was lateral to the projected trochlear line and calculated it to 0.990 %. A bisect offset of 50 % indicates the patella is centred within the groove, and a bisect offset of 150 % indicates that none of the patella is in the groove (Fig. 3). Normal ranges of bisect offset have been reported to be between 44 and 66 % on static imaging [15].

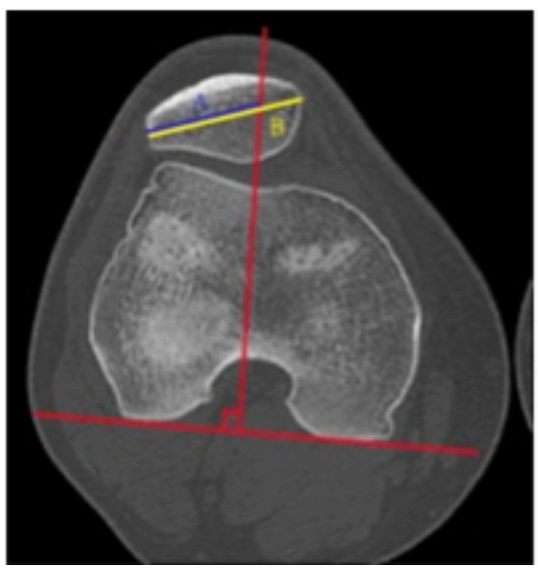

Fig. 2 Bisect offset measurements ($A/A + B \times 100$) were performed by measuring the percentage of the width of the patella that was lateral to a line through the deepest point of the trochlear groove

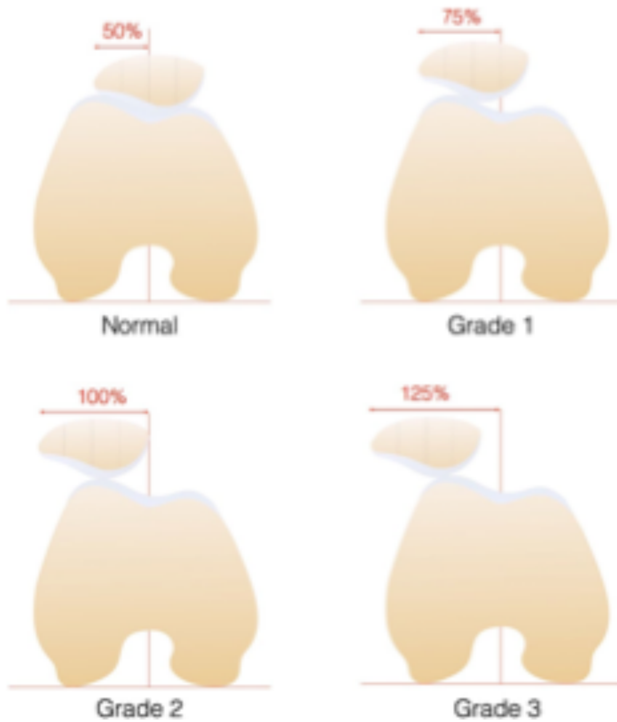

Fig. 3 Using the patellar glide test as a reference, bisect offset was quantified in terms of patellar quadrants of lateralization relative to the deepest portion of the trochlea, with 50 % representing a patella that is centered within the groove

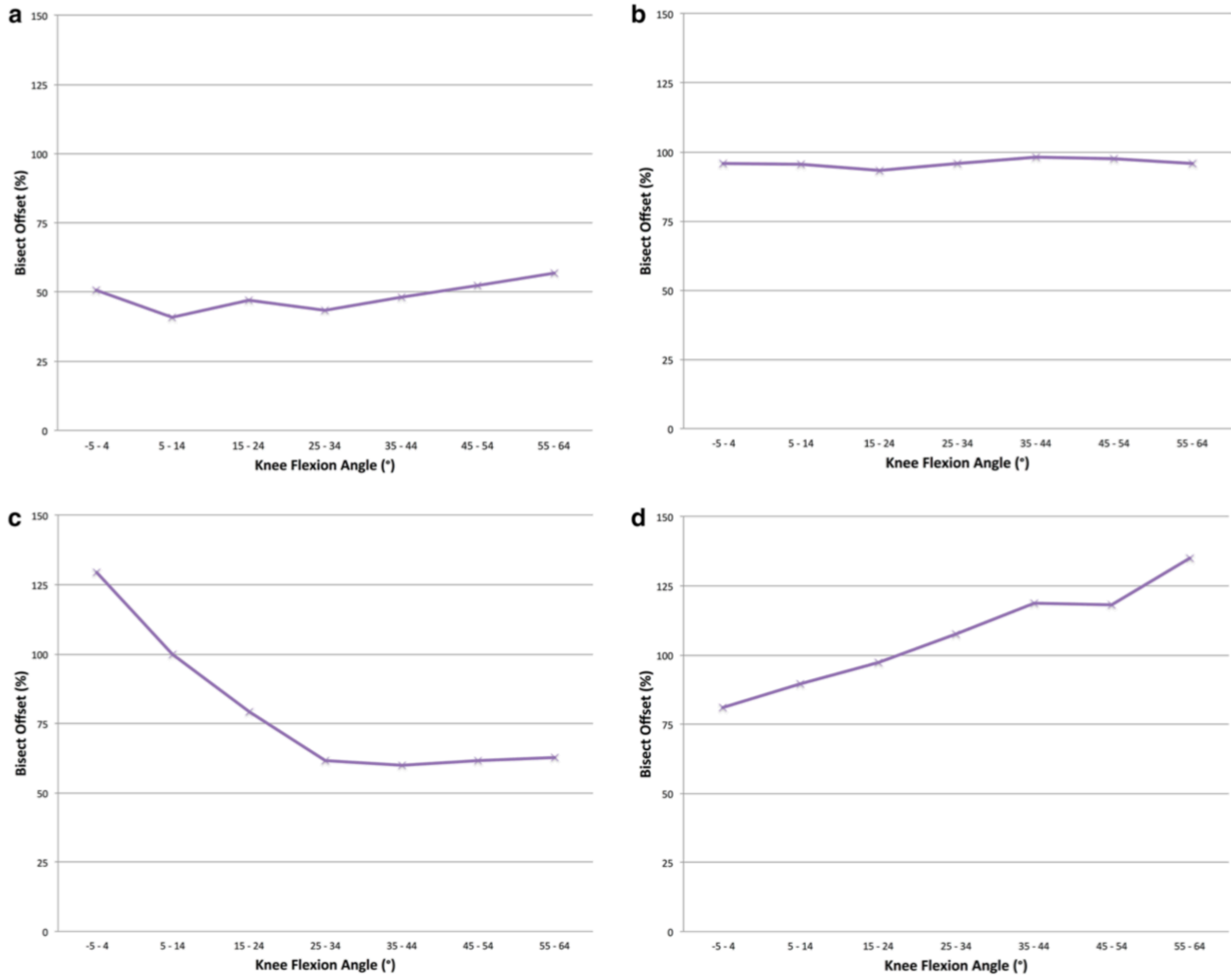

Fig. 4 Examples of the various tracking patterns noted are shown below. **a** Normal tracking. **b** Lateral tracking. **c** J-sign pattern. **d** Reverse J-sign pattern

Intraobserver and interobserver variability of the measurements was assessed in previous studies at our institution [14, 16]. Intraclass correlation coefficients had been calculated from three repeated measurements performed by three observers. Agreement among observers was strong, with intraclass correlation coefficients of 0.990 for intraobserver variability and 0.867 for interobserver variability.

Bisect offset measurements were assessed at 10° intervals of knee flexion angles to determine qualitative pat- terns in patellar translation during active knee extension. Maltracking was defined as a deviation of the patella from the trajectory of the trochlear groove on the basis of previously reported normal values on static imaging of 44–66 % [14]. The bisect offset measurements were categorized, using the patellar glide test as a reference, according to quadrants of patellar motion represented by 25 % increments of increasing bisect offset from a normal value of 50 % (Fig. 3). Based on this, normal tracking was defined as having less than one quadrant of lateral translation throughout range of motion, equivalent to 75 % bisect offset (Fig. 4a). Lateral tracking was defined as having one or more quadrant (≥75 % bisect offset) throughout range of motion (Fig. 4b). A radiographic J sign was defined as having greatest patellar lateralization in extension, with a one-quadrant or greater (≥25 %) increase in lateral translation in extension vs flexion (Fig. 4c). Increased lateral translation in flexion only was termed the "reverse J sign" (Fig. 4d).

Each case of maltracking was graded in terms of severity according to maximum lateral translation, as follows: grade 1, bisect offset of 75–99 % (one quadrant of patellar motion); grade 2, bisect offset of 100–124 % (two quadrants of lateral patellar motion); and grade 3, bisect offset of ≥125 % (three or more quadrants of lateral patellar motion) (Fig. 3).

The presence or absence of symptomatic patellar instability was reviewed for each knee.

This study was approved by The Johns Hopkins University School of Medicine Institutional Review Board (ID 00082500).

Statistical analysis

The initial hypothesis relating presence of a J sign to increased risk of instability was addressed with a 2 × 2 Chi-square analysis, including Yates correction for continuity that did not distinguish between J-sign subgroups.

The secondary hypothesis based on level of lateral tracking and categorization of J-sign subgroups allowed for additional Chi-square analyses, including the three sub- groups and those without a J sign (4 × 2 analysis). If a significant difference was identified for the 4 × 2 analysis, a post hoc comparison was planned for combinations of sub- groups with similar rates of instability, using a Bonferroni correction for multiple comparisons. Significance was set at $p < 0.05$.

On the basis of the available sample size for the current study and an assumption of 67 % of the knees with a J sign, the initial hypothesis was powered to 0.8 for a rate of instability of 80 % for knees with a J sign and 48 % in the absence of a J sign.

Results

The study group included 13 men and 25 women with a mean age of 23 ± 7.3 years. Of the 76 knees, two were excluded from analysis because of incomplete imaging sequences. Of the 74 knees included in the analysis, 50 had symptomatic patellar instability. Thirteen patients had bilateral symptoms. The study group included 19 knees with previously failed patellar stabilization surgery (Table 1). Additionally, one knee in the asymptomatic group had previous surgery (tibial tuberosity osteotomy).

Previous surgery	Total knees (no.)
Lateral release or medial reefing	12
Medial patellofemoral ligament reconstruction or repair	3
Tibial tuberosity osteotomy	2
Unknown soft tissue stabilization surgery	2

Table 1 Description of previously failed patellar stabilization surgery for 19 knees in the study group

Eight of 74 knees (11 %), four of which were symptomatic, had normal tracking patterns (Table 2). Fifty-eight of 74 knees (78 %) had the J-sign maltracking pattern on DKCT. Seven of 74 knees (9.5 %) had persistent lateralization of the patella throughout range of motion. One knee (1.4 %) had increased lateral translation in flexion only, consistent with the reverse J sign.

Tracking pattern	Total knees (no.)	Symptomatic knees [no. (%)]
J sign		
Grade 1	24	12 (50)
Grade 2	19	15 (79)
Grade 3	15	14 (93)
Lateral tracking		
Grade 1	6	3 (50)
Grade 2	1	1 (100)
Grade 3	0	0 (0)
Reverse J sign		
Grade 1	0	0 (0)
Grade 2	0	0 (0)
Grade 3	1	1 (100)
Normal	8	4 (50)
Total	74	50 (68)

Table 2 Distribution of patellar tracking patterns and the presence of patellar maltracking in 38 patients with bilateral or unilateral symptomatic patellar instability

In the 50 symptomatic knees, four (8 %) had normal tracking patterns, and four (8 %) had lateral tracking. Forty-one of 50 (82 %) had a J-sign pattern with increased lateral translation in extension, and one (2 %) had a reverse J sign. A comparison of tracking patterns between symptomatic and asymptomatic knees in patients with unilateral symptoms is shown in Table 3. Table 4 shows the comparison of presence of instability symptoms for all knees with or without a J sign. The rates of instability were not significantly different for subjects with and those without a J sign (n.s.).

Tracking pattern	Symptomatic knees (no.)	Asymptomatic knees (no.)
J sign		
Grade 1	7	11
Grade 2	7	4
Grade 3	4	1
Lateral tracking		
Grade 1	2	3
Grade 2	1	0
Grade 3	0	0
Reverse J sign		
Grade 1	0	0
Grade 2	0	0
Grade 3	1	0
Normal	1	4

Table 3 Distribution of tracking patterns in 23 patients with unilateral symptoms of patellar maltracking

J sign present	Symptomatic knees [no. (%)]	Asymptomatic knees [no. (%)]	Total knees	*p* value
Yes	41 (71)	17 (29)	58	0.43
No	9 (56)	7 (44)	16	

Table 4 Rate of patellar instability for all knees with or without the J sign

When only the presence or absence of a J sign was considered, there was no statistically significant relationship between maltracking pattern and symptoms of patellar insta- bility. However, when the grade of maltracking pattern was considered, increased severity in those who had the radio- graphic J sign was related to a greater risk of symptomatic patellar instability. The 58 knees that had the J-sign pattern werecategorizedasJ1(n=24),J2(n=19),orJ3(n=15) (Table 5). The rate of instability varied significantly among the four groups, and the J1 and no-J-sign groups were combined for comparison versus the combined J2 and J3 groups on the basis of similar rates of instability. The rates of instability were significantly different for the combined J1 and no-J-sign groups versus the combined J2 and J3 group ($p = 0.02$). This analysis was not performed on the lateral and reverse J-sign maltracking patterns because of a limited number of knees in these categories.

J-sign grade	Total knees (no.)	Symptomatic knees (no.)	Sensitivity (%)	p value[a]
1	24	12	50	0.02
2	19	15	79	
3	15	14	93	
No J sign	16	9	56	

[a] p value for difference between J2 and J3 versus J1 and no J sign

Table 5 Sensitivities of the J sign, versus no J sign, in predicting patellar instability in 58 knees

Discussion

The most important findings of this study were that mal- tracking patterns could be characterized by pattern and severity; furthermore, the severity correlated with the presence of symptoms in this study population. Three distinct patterns of patellar maltracking were visualized using bisect offset measurements. These included the J-sign pattern (in which the patella lateralizes in extension), lateral maltracking (in which the patella remains laterally trans- lated throughout range of motion), and the reverse J sign (in which the patella lateralizes in flexion). Although the type of maltracking patterns alone did not correlate with symptoms of patellar instability, we were able to describe a grading system of these maltracking patterns in which sub- groups of the J-sign pattern were associated with the presence of symptoms. Using this system, 79 % of those with a grade-2 J sign and 93 % of those with a grade-3 J sign had symptoms of patellar instability, indicating that more than two quadrants of lateral patellar translation during active extension may be a positive indicator for symptomatic patellar instability.

A recent study by Yao et al. [17] attempted to quantify patellar tracking by correlating patellar position with knee flexion angles. The authors studied MRI at 0°, 45°, 60°, 90°, and 120° of knee flexion on a single control patient. The authors assessed patellar tracking and described an "L-shaped curve" pattern of motion in the sagittal plane on the basis of the finite helical axis. This was a small study of one subject performed with static imaging sequences that lacked quadriceps activation, which is a critical factor in assessing patellar mobility. However, it highlights the clinical benefit of categorizing patellar tracking according to motion patterns.

Clinical evaluation of the J sign is performed in a similar manner to our imaging protocol, in which the patients are asked to actively extend their knees from a resting, flexed position. A previous study on the inter- and intraobserver reliability of the J sign have shown that among 10 patellofemoral surgeons, there was moderate agreement among testers when assessing patients for the J sign, with moderate interobserver reliability of 0.53 and fair intraobserver reliability of 0.28 [12]. However, the criteria for grading the J sign have been largely qualitative, and the sensitivity and specificity of this test have not been determined [13]. In this study population, we report increased sensitivity for symptomatic patellar instability with increased severity of the J sign based on patellar quadrants of motion, for each increase in 25 % bisect offset. We propose that the clinical J sign be quantified in a similar manner, with grade 1 showing greater than one quadrant of motion, grade 2 showing greater than two quadrants of motion, and grade 3 showing greater than three quadrants of patellar motion, to allow future comparisons in the clinical evaluation of mal- tracking. Further studies comparing normal controls would be the next step in determining the true sensitivity of this finding.

The use of DKCT allows for knee range of motion, as well as the activation of the quadriceps muscle for more accurate assessment of patellar tracking. McDermott et al. [8] described a simulated J-sign examination using MRI at 30° of flexion and complete hyperextension during voluntary contraction of the quadriceps and considered this a positive finding when the patella translated more than 5 mm in full extension. They found that the presence of a false- negative J sign, in which the patella was subluxated at 30° of knee flexion and did not increase in lateralization with extension, was associated with requiring greater medialization of the tibial tuberosity to attain patellofemoral congruency, while using intraoperative femoral nerve stimulation [8]. In our study, the severity of the J sign in extension was based not on its position at 30° of knee flexion, but relative to the deepest portion of the trochlear groove, while also providing information about patellar position at other flexion angles through knee range of motion.

Sheehan et al. [11] performed dynamic MRI to assess three-dimensional patellar motion in patients with and without patellofemoral pain from 40° of knee flexion to full extension. They created a new measure called the quantitative J sign, assuming that varus rotation influences the J sign. They described a positive sign if the patellofemoral varus angle was outside the 95 % confidence interval of the asymptomatic population (<0.25° varus per degree of knee extension), which would be considered clinically difficult to detect and was not based on discrete patellar motion. They also reported that the presence of a clinical J sign did not correlate with lateral patellar position on dynamic imaging, although there was a correlation with patellofemoral tilt. They found no correlation between the clinical J sign and the quantitative J sign, which they based on motion analysis of the MRI findings. However, the clinical J sign in their study was not quantified or graded. Further- more, this study involved patients with patellofemoral pain, rather than patients with patellofemoral instability. Further studies are needed to correlate findings of the J sign and grading with respect to this specific population.

Reasons for positive J-sign findings have not been fully defined in the literature. Some contributing factors have been reported to include lateral patellar instability and vastus medialis obliquus deficiency [9, 13]. Other possible contributing factors that were not assessed in this study include the contribution of morphological abnormalities of the patellofemoral joint, including malalignment. The increase in tibial tuberosity–trochlear groove (TTTG) distance as the knee nears extension has been shown by several authors [4, 6, 10, 14]. Dietrich et al. [4] studied 30 asymptomatic volunteers via static MRI performed with the quadriceps relaxed, at full extension, and at 15° and 30° of flexion, finding that the mean TTTG distance val- ues were significantly different (15.1, 10.0, and 9.1 mm, respectively). Tanaka et al. [14] reported similar findings in a previous study, of a 5.7-mm difference in TTTG distance between 5° and 30° of knee flexion in a similar cohort of patients with symptomatic patellar instability using DKCT. Biyani et al. [1] performed a study using MRI during iso- metric knee extension at multiple flexion angles and quantified patellar position at each flexion angle. They noted that patellar position correlated with TTTG distance and lateral trochlear inclination. In an MRI study comparing controls with patients with patellofemoral instability, Charles et al. [3] found that the measurements of patella alta and trochlear dysplasia were significantly higher in the symptomatic group.

The radiographic factors that have been associated with patellar position may make different contributions at different knee flexion angles, leading to the different pat- terns and severity of patellar maltracking. In addition to the radiographic J sign, we describe a less common lateral mal- tracking pattern and reverse J sign in this study population. These patterns were infrequent and did not allow for specific analysis. In general, the final 30° of extension are considered to be at the highest risk of dislocation because of the reliance on soft tissue restraints at this point. It is possible that there was a bony deficiency that allowed for lateralization in flexion in these pattern types, although this was beyond the scope of this study. Further studies are needed to identify the structural abnormalities that correlate with various maltracking patterns and their severity.

This study had some limitations. Because the images were acquired at standard time intervals determined by rotation of the gantry, we were unable to capture data at standardized flexion angles for all knees. However, doing so allowed for the dynamic assessment of the patellofemoral joint during active quadriceps extension. Although the risks of radiation exposure are modest when considered against the amount of information obtained from imaging, the radiation from the DKCT could be considered a limitation of this study. Additionally, the contralateral, asymptomatic knee was used as the control knee in patients with unilateral instability. Strictly speaking, these knees may not have been true controls, considering the history of instabil- ity in the other knee, and the patients were not followed for future development of symptoms. Furthermore, there were no controls for the patients with bilateral symptoms. Although we assessed the values of bisect offset with relation to knee flexion angle, we did not assess patellar tilt, which may also play a role in patellar maltracking. Finally, morphological factors that may influence maltracking patterns such as TTTG distance, patella alta, genu valgum, and trochlear dysplasia were not accounted for in this study.

Technological advancements in imaging, such as DKCT, allow visualization of the patellofemoral joint during active knee extension. This study highlights the need and ability for further understanding of the J sign and other maltracking patterns that can be noted at the time of physical examination in their relationship to patellofemoral symptoms.

Conclusion

DKCT showed patterns of patellar maltracking in addition to the J-sign pattern in knees with and without patellar instability. Although the type of maltracking pattern did not correlate with the presence of symptoms, the severity of the J-sign maltracking pattern, as quantified by using bisect offset measurements, correlated with the presence of symptomatic patellar instability in this patient population. Objectively quantifying maltracking patterns and J sign can be useful in the clinical assessment of patients with patel- lar instability as a tool for diagnosis, as well as a potential research tool for future comparisons in the evaluation of patellofemoral abnormality.

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Part III: Understanding the factors that influence medial patellofemoral complex reconstruction