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Patellofemoral joint motion: Evaluation by ultrafast computed tomography

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Abstract. Patellofemoral maltracking is a recognized cause of peripatellar pain. Measurements of the patellofemoral relationships during active motion are not available, and clinicians currently rely on observation, palpation, and static radiographic images to evaluate the symptomatic patient. Ultrafast computed tomography (ultrafast CT) offers objective observations of the dynamic influences of muscle contraction on the patellofemoral joint as the knee is actively moved through a range of motion from 90° flexion to full extension. This study reports our initial observations and establishes a range of normal values so that patients with a clinical suspicion of patellar maltracking may be evaluted.

Key words: Patellofemoral maltracking – Ultrafast computed tomography

Patellofemoral maltracking, especially lateral subluxation, is a recognized cause of peripatellar pain [4, 5, 6, 10]. Evaluations have consisted of clinical history, physical examination and static roentgenograms including Merchant, Ficat, and other specialized views of the knee, but no dynamic images of the patellofemoral joint during active motion have been available. The ultrafast computed tomography (CT) scanner now makes these images possible. This study reports our initial observations and establishes a range of normal values so that patients with suspected patellar maltracking can be objectively evaluated.

Materials and methods

Scanner mechanism

The scanner mechanism has been described in detail elsewhere [1]. Briefly, it consists of an electron source, four target rings, and a double bank of detectors. The scanner operates by magnetically deflecting a beam of electrons onto four tungsten target rings located in the gantry beneath the patient. The X-rays generated from these rings are tightly collimated and pass through the patient into a double bank of detectors located in the gantry above the patient. Each sweep of the electron beam requires 0.050 s, and there is a 0.008 s delay in passing to the next target ring.

Eight axial slices, each 8 mm thick, can be imaged in 224 ms. Images are contiguous, but there is a 4 mm interslice separation between images from different target rings. If the scanner is programmed to obtain the above sequence every 0.7 s as the knee is moved from 90° flexion to full extension and back to 90° flexion, ten images at each of eight levels encompassing an 8 cm length of the knee can be acquired in 7 s. The processed images can be played back in a closed loop movie format which allows for visualization of realtime axial images of patellofemoral motion during muscle contraction and leg movement (Fig. 1). Additionally, single frame measurements can be made at any point in the imaging sequence. The imaging field usually begins at the distal aspect of the femoral condyles and extends proximally to encompass the patellofemoral joint at the superior range of patellar excursion.

Study populations

Normal knees from two groups of subjects were studied.

Group I. In Group I the patellofemoral relationships of 18 normal volunteers were studied with ultrafast CT. There were 9 males and 9 females ranging in age from 19 to 25 years (mean 22.5 years). All subjects were asymptomatic, and each denied a history of trauma. The physical examination was normal in all subjects.

Group II. Group II consisted of 20 patients in whom the asymptomatic normal knee was scanned simultaneously with the symptomatic "other" knee. This group was included because each patient had undergone a static 45° Merchant view which was available for comparison with the ultrafast CT 45° dynamic view.

Scanner protocol

The subjects were seated feet first with their knees together and flexed 90°. A small triangular pad was placed beneath the knees to elevate them sufficiently for unobstructed flexion and extension. A localizing scan was performed to ensure that the most caudal image was at the femoral condyle and that the most cephalad image was proximal to the excursion of the pa-

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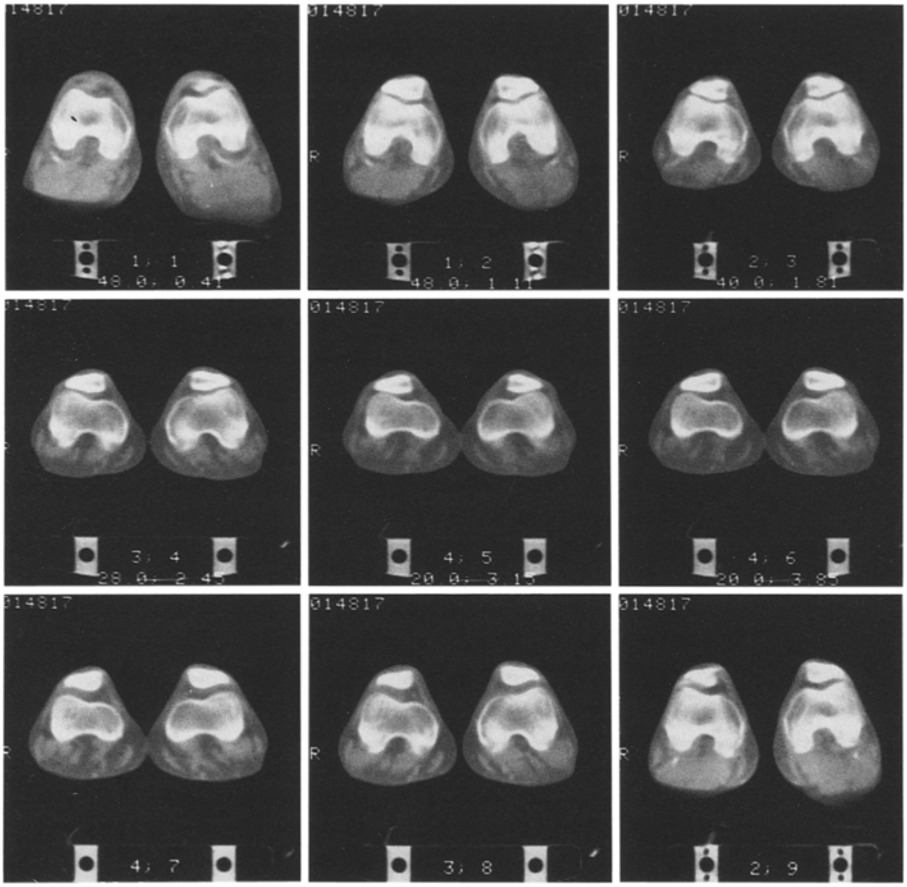

Fig. 1. Composite of selected images showing the patella during movement from 90° flexion to full extension and back to 90° flexion. Image 1,1 is at 90° flexion. Images 1,2 and 2,9 are about 60° flexion. Images 2,3 and 4,7 are about 45° flexion. Images 3,4 and 4,6 about 30° flexion, and image 4,5 is at 0° flexion (full extension)

tella when the leg was fully extended. Upon command, the subjects were instructed to extend their legs smoothly and symmetrically during a counting sequence which was synchronized with the scanner firings. The counting sequence was coordinated so that images one and ten were at 90° flexion. Images three and seven approximated 45° flexion, and image five was at 0° flexion (full extension). Practice runs were carried out prior to initiating the scanning sequence. If jerkiness occurred or if the timing sequence was incorrect, the study was repeated. The protocol was approved by the Human Use Committee, and informed consent was obtained for all volunteer subjects.

Radiation exposure

Radiation exposure was 0.4 rad/slice (multiple slices). Since ten images were obtained at each level, the total dose was four rads. In conventional CT the radiation dose per slice is 4 rad. In order to obtain ten images at each level comparable to those acquired by ultrafast CT, a total of 40 rad would have to be delivered at each slice. Thus the ultrafast CT allows imaging at one-tenth the radiation dose of conventional CT. Irradiation to the gonadal area was minimized by placing a lead apron between the X-ray source and the buttocks.

Data analysis

From the 80 images obtained per study, the views that best showed the patellofemoral relationships at 90°, 45°, and 0° flexion were selected for interpretation. These views were usually the first, third, fifth, seventh, and tenth images obtained during the movement sequence. Images from selected frames were filmed, and manual measurements were made from these images. All measurements were performed by one individual (J.P.). The ultrafast CT view which most closely approximated 45° of flexion was compared with the corresponding 45° Merchant view. Additionally, patellar motion was evaluated dynamically from the closed loop movie sequences.

Measurements

Tangent offset. This measurement was made by drawing a line through the patella to connect its widest points (patellar width line). A second line was then drawn tangent to the anterolateral aspect of the femur through the estimated middle of the lateral femoral cortex (Fig. 2). The extent of patella lateral to the point of line intersection was measured and expressed as a percent of the patellar width. When the tangent line did not intersect the patellar width line, the patellar width line was extended to the point of intersect. The distance from the intersect point to the lateral aspect of the patella was compared to the patellar width and expressed as negative percent offset.

Bisect offset

Bisect offset was measured by drawing a line tangent to the dorsal convexities of the medial and lateral femoral condyles (posterior condylar line). The midpoint between the condyles was selected, and a perpendicular line was projected anteriorly to intersect the patella and the previously drawn patellar width

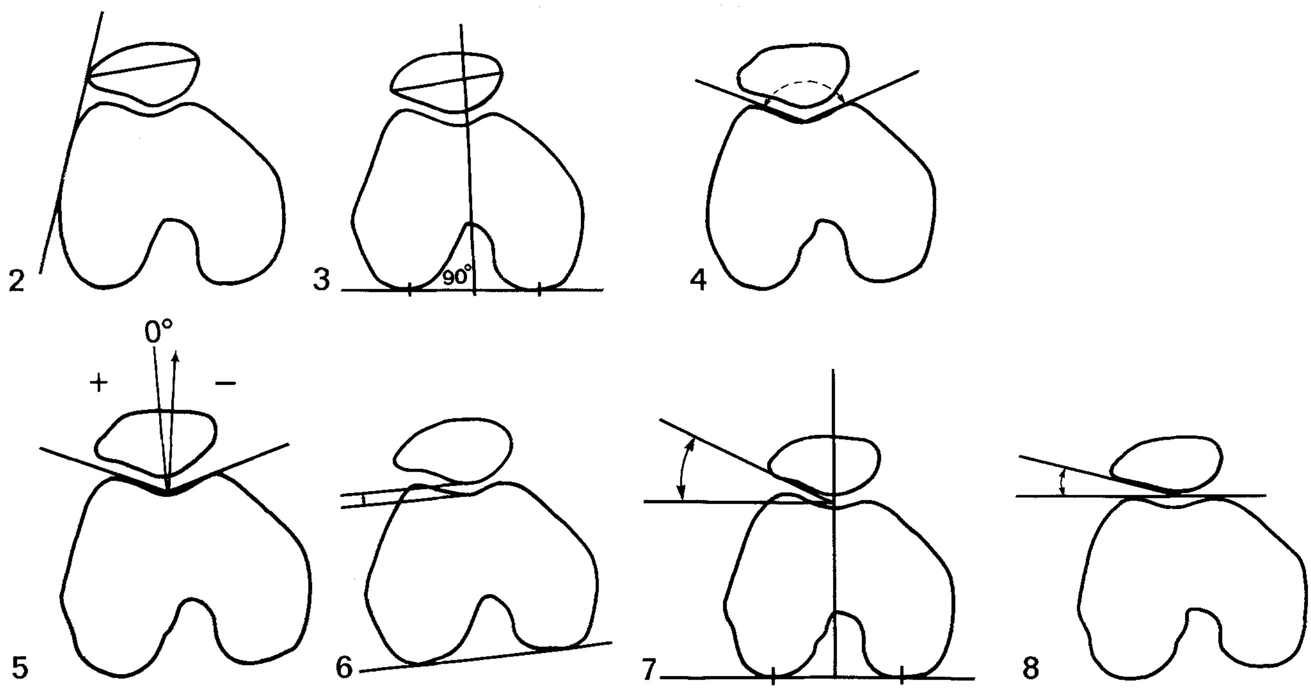

Fig. 2. Tangent offset. For description see text

Fig. 3. Bisect offset. For description see text

Fig. 4. Sulcus angle. For description see text

Fig. 5. Congruence angle. For description see text

Fig. 6. Sulcus depth. For description see text

Fig. 7. Patellar tilt angle. For description see text

Fig. 8. Lateral patellofemoral angle. For description see text

line. The extent of patella lateral to the perpendicular line was calculated and expressed as percent of the total patellar width (Fig. 3).

Sulcus angle

The anterior intercondylar angle (sulcus angle) was measured by drawing a line from the highest points on the medial and lateral anterior femoral condyles to the lowest point in the intercondylar sulcus, as described by Brattstrom [2] (Fig. 4).

Congruence angle

This angle was measured using the method described by Merchant et al. [9]. The sulcus angle was drawn and bisected to establish a zero reference line. A second line was then extended from the apex of the sulcus angle through the most dorsal aspect of the articular surface of the patella. The angle created by these two lines constituted the congruence angle (Fig. 5). If the second line passed medial to the reference line, the angle was expressed as a negative value.

Sulcus depth

Sulcus depth was determined using the method described by Martinez et al. [8] by constructing two lines parallel to the posterior condylar line. The first line passed through the deepest point of the anterior condylar sulcus, and the second line lay parallel to the first line, just touching the most anterior projection of the lateral condyle. The distance between these lines constituted the sulcus depth (Fig. 6).

Patellar tilt angle

The patellar tilt angle was measured by the method described by Martinez et al. [8] and Schutzer et al. [11]. It was the angle subtended by a line tangent to the lateral patellar facet with a line through the deepest part of the sulcus parallel to the posterior condylar line (Fig. 7).

Lateral patellofemoral angle

The angle was determined by the method of Laurin et al. [7]. A line was drawn tangent to the highest points of the lateral and medial anterior femoral condyles. A second line was drawn tangent to the lateral patellar facet. This angle formed the lateral patellofemoral (P-F) angle (Fig. 8).

Merchant views

Static images were taken as described by Merchant et al. [9]. The subject was supine with the knees flexed 45° and supported in a wooden frame. The film cassette was placed perpendicular to the midtibia, and the X-ray tube was angled 30° thereby allowing the X-ray beam to pass through the patellofemoral joint perpendicular to the cassette.

Table 1. Group I volunteer "normals"

Measurement	Knee flexion	Men ($n=18$)	Women ($n=18$)	P-value[a]	Total group mean & ranges ($n=36$)
Tangent offset	45°	11.0± 5.8%	10.5± 7.6%	0.8257	10.8±6.7% (0–29)
Tangent offset	0°	22.8±13.4%	22.6±12.8%	0.9637	22.7±12.9% (0–46)
Bisect offset	45°	68.1± 6.7%	75.7± 5.4%	0.2449	66.9±6.1% (55–83)
Bisect offset	0°	58.8±11.5%	69.9±11.9%	0.0074	64.4±12.9% (43–85)
Congruence angle	45°	−3.0± 8.8°	−5.4± 4.2°	0.3037	−4.2± 6.9° (−14 to 27)
Patellar tilt angle	45°	11.9± 5.8°	12.5± 4.9°	0.7395	12.2±5.3° (0–25)
Lateral P-F angle	45°	8.9± 5.4°	12.4± 4.1°	0.0355	10.7±5.1° (0–19)
Sulcus angle	45°	124.3± 9.7°	118.4± 7.9°	0.0534	121.4±9.3° (103–150)
Sulcus depth	45°	6.6± 1.4 mm	6.4± 1.5 mm	0.6818	6.5±1.4 mm (3.5–10.0)

[a] P-values less than 0.05 indicate significant differences between males and females

Results

The mean, standard deviation, and complete ranges for tangent offset, bisect offset, congruence angle, patellar tilt angle, lateral patellofemoral angle, sulcus angle, and sulcus depth in the Group I volunteers with their knees at 45° flexion are listed in Table 1. Additionally, values at 0° flexion (full extension) are listed for selected parameters. (Not all parameters could be measured at 0° flexion because the patella would ride proximally out of the sulcus, and certain measurements are dependent upon the patella remaining within the sulcus.) Gender differences are also shown in Table 1. Correlations between selected parameters and between selected parameters and Merchant views are seen in Tables 2 and 3.

As measured by the tangent offset method in normal knees at 45° flexion, subluxations of 7.25±6.71% (ultrafast CT) and 9.25±7.6% (Merchant views) appeared normal (Table 3). These figures increased to 22.7±12.9% at full extension (ultrafast CT). Analyses also disclosed significant gender differences in bisect offset at 0° and lateral patellofemoral angle at 45°, but not in tangent offset, bisect offset, congruence angle, patellar tilt angle, sulcus angle, and sulcus depth at 45° nor with tangent offset at 0°.

Significant correlations were found between tangent offset and bisect offset at 45° and at 0°, and between sulcus angle and sulcus depth at 45°. There were no correlations between tangent offset and congruence angle at 45°, between bisect offset and congruence angle at 45°, between tangent offset and sulcus angle at 45°, and between lateral patellofemoral angle and patellar tilt angle at 45°.

Merchant views and ultrafast CT views showed significant correlations in tangent offset, patellar tilt angle, congruence angle and lateral patellofemoral angles. There was no correlation in the sulcus angle parameter.

Analysis of the movie sequences demonstrated two predominant patterns of motion: in some patients the patella was centered over the femur and remained so throughout its excursion; in others the patella was centered until the last 10–20 degrees of extension, at which point it would displace laterally ("J" pattern).

Discussion

It is recognized that knee roentgenograms can appear normal in patients with clinical subluxation of the patella [7, 12]. This occurs because patellar subluxation is most apparent at 0–20° flexion. With flexion greater than 30°, the patella is drawn caudally into the femoral intercondylar groove and tends to center directly in the groove [11]. Because of difficulties in positioning of X-ray tube and cassette, most routine radiographs of the patellofemoral joint are made with the knees in excess of 30° of flexion, and subluxation may be missed. Re-

Table 2. Correlations: Group I volunteer "normals" ($n=36$), Parameter comparisons (averages)

Parameter				r	P-value[a]
Tangent offset	(45°)	versus Bisect offset	(45°)	0.5758	0.0002
Tangent offset	(0°)	versus Bisect offset	(0°)	0.5440	0.0006
Tangent offset	(45°)	versus Congruence angle	(45°)	−0.0821	0.6340
Tangent offset	(45°)	versus Sulcus angle	(45°)	−0.1626	0.3435
Bisect offset	(45°)	versus Congruence angle	(45°)	−0.0504	0.7703
Lateral patellofemoral angle	(45°)	versus Patellar tilt angle	(45°)	−0.2008	0.2403
Sulcus angle	(45°)	versus Sulcus depth	(45°)	−0.3908	0.0184

[a] P-values less than 0.05 indicate a significant relationship between the variables, r = the simple correlation coefficient

Table 3. Group II clinical case "normals"

Measurement	Knee flexion	Ultrafast CT ($n=20$)	Merchant views ($n=20$)	r	P-value[a]
Tangent offset	45°	7.25±6.71% (0–18)	9.25± 7.6% (0–29)	0.7598	0.0001
Congruence angle	45°	−3.4 ±8.1° (−20 to +14)	+5.45±20.1° (−38 to +47)	0.4953	0.0264
Patellar tilt angle	45°	16.0 ±6.9° (4–30)	15.5 ± 6.9° (2–25)	0.6673	0.0013
Lateral P-F angle	45°	9.9 ±5.8° (−4 to +19.0	6.1 ± 6.8° (−8 to +18.0)	0.4976	0.0256
Sulcus angle	45°	126.6 ±9.4° (109–143)	137.9° ± 7.5° (127–154)	0.3746	0.1037

[a] P-values less than 0.05 indicate significant relationships between the variables, r = is the simple correlation coefficient

cognizing these difficulties several authors have imaged the patellofemoral joint at 0°, 30°, 60°, and 90° flexion using computerized tomography [3, 8, 12]. Even with these techniques, interpretive discrepancies exist. Delgado-Martins [3] states that "the position of the patella when the knee is in extension is eccentric in 87% of knees when the quadriceps is relaxed and in 96% of knees when the quadriceps is contracted", whereas Martinez et al. [8] state "that in full extension, with the quadriceps muscle relaxed, 19 of 20 knees showed the patella well centered in the femoral trochlear groove." In both these studies only static images were available, and the dynamic changes that influence patellofemoral relationships at specific degrees of flexion were not assessed.

With ultrafast CT the influences of muscle contraction on the patellofemoral joint can be observed during the time the leg is moving in a 90° arc from flexion to full extension. Additionally, individual images can be filmed and specific parameters of subluxation measured.

In analyzing our data we found no significant parameter differences between men and women at 45° flexion in tangent offset, bisect offset, congruence angle, patellar tilt angle, and sulcus depth nor with tangent offset at 0°; however, significant gender differences were apparent in bisect offset at 0° and lateral patellofemoral angle at 45°. Gender differences approached significance in the sulcus angle at 45° (Table 1).

We also demonstrated that lateral subluxations of up to 22.7±12.9% as measured by the tangent offset method were normal and, in this regard, our data support Delgado-Martins's [3] contention that the patella often lies laterally and incongruently in contact with the lateral femoral condyle in full extension. We found that lateral subluxation becomes most apparent in the final 20° of extension when the patella rides proximally out of the anterior intercondylar groove. However, in measuring the lateral offset by the tangent offset method, it should be pointed out that although location of the tangent line was easily definable at 90° flexion, at 0° flexion the femur becomes more rounded proximally and location of this line becomes increasingly subjective. Because of these problems we elected to measure patella offset via the bisect offset method, but found that this measurement also suffered from similar problems of "rounding" of the femoral shaft. When these two measurements were compared, there were significant statistical correlations at both 0° and 45° flexion ($p=0.0002$ and $p=0.0006$).

Another accepted method for measuring lateral offset is the congruence angle as described by Merchant et al. [9] and Schutzer et al. [12]. The latter authors found that congruence angles measured with the leg at 0° to 20° flexion varied from +2 degrees to −2 degrees and ranged from −7 degrees to +13 degrees. They concluded that any congruence angle greater than zero at 10° flexion confirmed subluxation. In attempting to duplicate their experiment during active motion, we found that at full extension the patella would often ride cephalad above the level at which the condyles could be defined; hence sulcus and congruence angle parameters were not measurable. One possible explanation might be that, during active motion, the patient may extend his leg beyond zero degrees to a −10° position which would allow the patella to ride even higher above the intercondylar sulcus. Schutzer et al. strictly limited knee extension to zero degrees. At 45° flexion the congruence angle was measurable; however, there were no statistically significant correlations between congruence angles at 45° flexion and tangent offset at 45° flexion, nor between congruence angles and bisect offset at 45° flexion. These differences are due to the difficulty in defining an exact point on the posterior projection of the patella. Small differences in defining this point can result in wide variations in the congruence angle measurement. Because of these findings, we would urge caution in depending upon measurements of the congruence angle at full extension.

Similar problems were encountered with measurements of the lateral patellofemoral angle and patellar tilt angle. We found that these could not be measured at full extension; however, comparisons of the lateral patellofemoral angle at 45° flexion with the patellar tilt angle at 45° flexion were possible, and these showed no significant correlation. Because of these inconsistencies, we would also urge caution in interpreting the lateral patellofemoral angle and patellar tilt angle measurements when the knee is in full extension.

With increasing flexion the patella is pulled inferiorly into the patellofemoral groove, and subluxation is less likely to occur. Merchant et al. have studied knees at 45° flexion and have described lateral offset on films taken with this degree of flexion. We compared our ultrafast CT images at 45° flexion with the standard Merchant views. There were high correlations ($p=0.0001$ to $p=0.0264$) for tangent offset, patellar tilt angle, congruence angle, and lateral patellofemoral angle. The only parameter not found to have a significant correlation was the sulcus angle ($p=0.1037$). These differences may result from the narrow field imaged by ultrafast CT (8 mm) as compared to the larger field of the standard radiograph.

From our cine strips, two patterns of patellar movement were observed. In the first pattern, the patella would initially center over the patellofemoral groove when the knee was flexed at 90° and then would remain centered over the femur as the leg was brought to full extension. In the second pattern, the patella would remain centered over the patellofemoral groove until the last 20° of extension, at which point it would sublux into a lateral position ("J" subluxation pattern).

These observations lead us to conclude that patellar movement as viewed from the cine strip gives the best qualitative assessment of the patellofemoral relationships. Although parameters have some importance in attempting to quantitate patellofemoral relationships, none is without problems, and no single parameter appears consistently reliable. Further studies with three-dimensional reconstructions are now possible, and these images may be of further help in understanding patellar subluxation.

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