Evaluating Patellar Kinematics Through Magnetic Resonance Imaging During Open- and Closed-Kinetic-Chain Exercises
Evaluating Patellar Kinematics Through Magnetic Resonance Imaging During Open- and Closed-Kinetic-Chain Exercises

Lílian Ramiro Felicio, Marcelo Camargo Saad, Rogério Ferreira Liporaci, Augusto do Prado Baffa, Antônio Carlos dos Santos, and Débora Bevilaqua-Grossi

Purpose: To evaluate patellar kinematics of volunteers without knee pain at rest and during isometric contraction in open- and closed-kinetic-chain exercises. Methods: Twenty individuals took part in this study. All were submitted to magnetic resonance imaging (MRI) during rest and voluntary isometric contraction (VIC) in the open and closed kinetic chain at 15°, 30°, and 45° of knee flexion. Through MRI and using medical e-film software, the following measurements were evaluated: sulcus angle, patellar-tilt angle, and bisect offset. The mixed-effects linear model was used for comparison between knee positions, between rest and isometric contractions, and between the exercises. Results: Data analysis revealed that the sulcus angle decreased as knee flexion increased and revealed increases with isometric contractions in both the open and closed kinetic chain for all knee-flexion angles. The patellar-tilt angle decreased with isometric contractions in both the open and closed kinetic chain for every knee position. However, in the closed kinetic chain, patellar tilt increased significantly with the knee flexed at 15°. The bisect offset increased with the knee flexed at 15° during isometric contractions and decreased as knee flexion increased during both exercises. Conclusion: VIC in the last degrees of knee extension may compromise patellar dynamics. On the other hand, it is possible to favor patellar stability by performing muscle contractions with the knee flexed at 30° and 45° in either the open or closed kinetic chain.

Keywords: patellofemoral joint, patellar tracking, isometric contraction

The patellofemoral joint may present several musculoskeletal disorders, including patellofemoral pain (PFP), which has a high incidence in orthopedics, representing about 25% of diagnoses of knee pain. Some authors report that changes in patellar tracking may trigger PFP.
Magnetic resonance imaging (MRI) is broadly used to evaluate patellar kinematics in different exercises because it is a noninvasive procedure capable of quantifying patellar kinematics during isometric contractions or active knee movements.

Guzzanti et al. reported that changes in patellar alignment are better detected during muscle contractions. In this sense, isometric contraction is more indicated, because patellar displacement over the femoral trochea is inevitable and movement artifacts can be observed during active voluntary contraction. According to Muhle et al., motion artifacts are caused by motion of the evaluated object, and this motion as observed during the active contraction could generate an image with ghost images, making it difficult to measure; thus it is more accurate to measure the position of patella during an isometric contraction.

Patellar kinematics during muscle contraction can be evaluated through MRI by measuring the sulcus angle (SA), patellar-tilt angle (PTA), and bisect offset (BO). These measurements permit analysis of patellar position in relation to the femoral trochea during the muscle contraction, as well as the relation between these measurements and patellofemoral disorder.

Few authors have analyzed different parameters such as SA, PTA, and BO in different knee angles at rest and during muscle contraction. Only Tennant et al. evaluated femoral trochea depth, using the SA in clinically healthy individuals during active closed-kinetic-chain (CKC) exercises. According to Tennant et al. and Powers et al., this measurement is related to patellofemoral stability. Other important measures are PTA and BO, which describe lateral patellar inclination and displacement, respectively, during the muscle contraction. According to Powers, alterations in these measurements could be related to patellofemoral disorders. Powers indicates that alterations in the kinematics and position of the patella could be related to patellofemoral disorders because they can increase the lateral tilt and the lateral displacement, increasing the patella pressure contact and the lateral contact. On the other hand, there are no studies in the reviewed literature that compared patellar kinematics during isometric contraction in open-kinetic-chain (OKC) and CKC exercises.

Both OKC and CKC exercises are often performed in PFP rehabilitation programs. Some authors compare electromyographic activity or strength or perform functional evaluations and do not find any difference between these measurements. Nevertheless, we found no patellar-kinematics studies that compared the patellar position during different exercises. That is because most studies analyze these exercises separately. Hence, it is important to clarify patellar kinematics during these exercises.

Patellar kinematics during final knee extension have been established. However, the literature does not present any analyses that associate these parameters with OKC and CKC exercises in movements from 15° to 45° of knee flexion in clinically healthy individuals. This information would enable us to understand normal patellar tracking and would support the elaboration of exercise protocols, especially for patellofemoral disorders.

Therefore, this study was designed to verify the patellar position and to compare it between the OKC and CKC in different knee-flexion angles during isometric muscle contraction, as well as the effect of knee position on patellar kinematics, through SA, PTA, and BO using MRI.
Materials and Methods

Subjects

Twenty women (mean age 21.5 ± 2.16 y; mean body weight 54.44 ± 5.23 kg; mean height 160.75 ± 5.23 cm) without knee pain or any previous history of lower limb musculoskeletal damage participated in this study. According to Cowan et al.\textsuperscript{18} the main symptom of patellofemoral disorder is pain in the anterior knee, so individuals with anterior knee pain were excluded from the study. These volunteers did not practice any kind of sport activities more than once a week. All volunteers were submitted to a function test following the inclusion and exclusion criteria described in Table 1. According to Powers et al.\textsuperscript{3} and Dye,\textsuperscript{19} individuals without PFP signs can still present signs of lower limb misalignment; hence, individuals with up to 2 signs of nonsignificant misalignment were included in the study.

Before participation, all study procedures were explained and each volunteer provided written informed consent according to the norms set by the research ethics committee of the University of São Paulo, Brazil. The study was approved by this ethics committee (process number: HCRP 4250/2005).

Instrumentation

Images were obtained using 1.5T Siemens Magnetom Vision equipment (Erlangen, Germany) and a coil measuring 52 × 21 cm. The center of the coil was aligned with the center of the patella. Images were obtained at a rate of 1 image per 3 seconds, using the following parameters: repetition time 15 milliseconds, echo time 6 milliseconds, matrix size 512 × 128, and slice thickness 7 mm. Acquisition time for the 6 frames of each evaluated situation, rest and voluntary isometric contraction, was 18 seconds, and the average time for each examination was 50 minutes.

Table 1 Inclusion and Exclusion Criteria

<table>
<thead>
<tr>
<th>Inclusion criteria</th>
<th>Exclusion criteria</th>
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<tbody>
<tr>
<td>No lower limb surgeries, traumas, or musculoskeletal damage</td>
<td>Use of medication and previous physical therapy treatment within 6 mo before the study</td>
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<tr>
<td>No pain or discomfort in the knee area</td>
<td>Neuralgic and systemic diseases</td>
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<td>No knee pain during squatting (0–90°) and step function tests, both performed for 60 s</td>
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<tr>
<td>No pain during activities such as squatting, stair ascent or descent, kneeling, running, prolonged sitting, or isometric quadriceps contraction (Cowan et al\textsuperscript{18})</td>
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<tr>
<td>Presence of a maximum of 2 clinical signs observed in the function test, including increased Q angle, external tibial torsion, excessive subtalar pronation, medialized patella, pain during the palpation of patellar grooves\textsuperscript{22}</td>
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Procedures

Examinations were performed with volunteers in the dorsal decubitus position. Patellofemoral-joint images were obtained with the knee randomly positioned at 15°, 30°, and 45° of flexion, appropriately stabilized on the distal extremity and on the hip, on a custom-made nonferromagnetic support (Figure 1) to adjust the angles that were determined with a goniometer (São Paulo, Brazil). The volunteers became familiarized with the type of exercise and the magnetic resonance equipment before the images were obtained.

Images were obtained in the axial plane during rest and voluntary isometric contraction in the OKC and CKC for each knee angle. Volunteers were verbally encouraged to extend the knee (OKC) or push the support (CKC) as hard as possible with a continuous verbal command (“attention,” “prepare,” “push,” “push and relax,” or “raise your leg and relax”) (Figure 2). However, external loads were

Figure 1 — Custom-made nonferromagnetic support used during voluntary isometric contraction in the (a) open kinetic chain and (b) closed kinetic chain at angles of 15°, 30°, and 45°.

Figure 2 — The arrow represents the direction of force made by the volunteer.
not controlled, because the exercises were performed with magnetic resonance equipment in a closed electromagnetic field; it is difficult while using accurate equipment to control those measurements. A 2-minute rest was given between imaging sequences.

**Data Analysis**

The acquired images were analyzed using Medical e-film software, version 1.8.3 (Wisconsin, USA). Axial section measurements were analyzed using the frame that had the maximum patellar width (the distance between medial and lateral borders) of the 6 frames at each knee-flexion angle and, after that, the measurement was taken.2

The following parameters were evaluated: SA, formed by the intersection of lines drawn parallel to the medial and lateral trochlear facets1,8; PTA, defined as the angle formed by drawing a line connecting the medial and lateral borders of the patella and the posterior femoral condyles1,3,21; and BO, measured by drawing a line connecting the posterior femoral condyles and then projecting a perpendicular anterior line through the deepest point of the femoral sulcus and another line connecting the medial and lateral borders of the patella, then measuring the distance between the lateral border of the patella and the vertical line3,10 (Figure 3). These anatomic points were visually determined by the software on the selected slide.

The angles (PTA and SA) and patellar lateral displacement (BO) measurements were analyzed blind to knee position and OKC and CKC and repeated 3 times by the same rater with 7-day intervals between measures (Table 2). This was done to analyze intrarater reliability (repeatability) for the comparison between kinetic chains and knee positions. Average measurement was calculated for the referred analysis.

**Statistical Analysis**

Intraclass correlation coefficient model 2,1 (ICC 2,1)22 was used to verify intrarater agreement between the analyzed measurements during each knee position. The ICC values were classified as follows: <.4 poor reliability, .4 to .75 moderate reliability, and >.75 excellent reliability.23

To perform the statistical analysis of the comparison between the parameters evaluated in the exercises and the knee position, the following were considered: SA,
PTA, and BO as dependent variables and the types of exercises (OKC and CKC) and knee-flexion angles as independent variables. To analyze the effect of exercises (OKC and CKC) and knee-flexion angles (15°, 30°, and 45°) over the dependent variables, we used a mixed-effects linear model (PROC MIXED). The fixed effects were exercises, knee angles, and the interaction between them, and the random effect was the individuals, with multiple comparisons between the dependent-variable and independent-variable levels. These interactions were calculated based on orthogonal contrasts with a significance level of \( P < .05 \). All statistical procedures were carried out using SAS software version 8 (Cary, NC, USA).

**Results**

Measurements of SA, PTA, and BO showed excellent intraobserver reliability rates (ICC > .85) during rest and voluntary isometric contraction in the OKC and CKC, as well as for all knee positions: 15°, 30°, and 45° of flexion (Table 2).

Data regarding the SA revealed that both knee position and voluntary isometric contraction in the OKC and CKC affected this measurement. SA values were significantly greater for contractions in the OKC and CKC than in the rest position for all evaluated angles, but we did not observe a difference between the OKC and CKC contractions. At rest and during exercises in the OKC and CKC, SA values were significantly smaller as knee flexion increased (Table 3).

Comparing PTA between rest and voluntary isometric contraction in the OKC, there was a reduction in patellar tilt during muscle contraction for every knee position. There were no significant differences in PTA values at rest for the different knee positions and between the contractions. On the other hand, a reduction in

<table>
<thead>
<tr>
<th>Angle</th>
<th>Exercises</th>
<th>Sulcus angle</th>
<th>Patellar-tilt angle</th>
<th>Bisect offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>15°</td>
<td>Rest</td>
<td>.94</td>
<td>.94</td>
<td>.94</td>
</tr>
<tr>
<td></td>
<td>Open kinetic chain</td>
<td>.94</td>
<td>.94</td>
<td>.95</td>
</tr>
<tr>
<td></td>
<td>Closed kinetic chain</td>
<td>.96</td>
<td>.97</td>
<td>.94</td>
</tr>
<tr>
<td>30°</td>
<td>Rest</td>
<td>.92</td>
<td>.98</td>
<td>.93</td>
</tr>
<tr>
<td></td>
<td>Open kinetic chain</td>
<td>.92</td>
<td>.98</td>
<td>.93</td>
</tr>
<tr>
<td></td>
<td>Closed kinetic chain</td>
<td>.94</td>
<td>.97</td>
<td>.87</td>
</tr>
<tr>
<td>45°</td>
<td>Rest</td>
<td>.96</td>
<td>.96</td>
<td>.91</td>
</tr>
<tr>
<td></td>
<td>Open kinetic chain</td>
<td>.90</td>
<td>.94</td>
<td>.93</td>
</tr>
<tr>
<td></td>
<td>Closed kinetic chain</td>
<td>.91</td>
<td>.98</td>
<td>.93</td>
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</tbody>
</table>

**Table 2 Intrarater Reliability (ICC) for Each of the Measures**
this measurement was observed during muscle contraction in the OKC with 30° of knee flexion, compared with 45°. Regarding voluntary isometric contraction in the CKC, we observed reduced PTA values at 30° compared with 15° of knee flexion (Table 4).

When we analyzed patellar displacement through BO values, comparing rest with voluntary isometric contraction in the OKC and CKC, data revealed that there was an increase in patellar lateralingation with the knee flexed at 15°. However, no differences were observed in BO between the positions of 30° and 45° or between the contractions (Table 5).

The comparison of knee positions during rest showed that BO is higher at 30° and 45° of knee flexion than at 15° of knee flexion. In addition, with the knee flexed at 45°, the BO is higher than with 30° of knee flexion. However, during voluntary isometric contractions in the OKC and CKC, we observed that BO decreases with the knee flexed at 30° and 45°, compared with 15° of knee flexion (Table 5).

### Table 3  Sulcus Angle (Degrees) During Rest and Voluntary Isometric Contraction in the Open Kinetic Chain (OKC) and Closed Kinetic Chain, Mean ± SD

<table>
<thead>
<tr>
<th>Knee-flexion angle</th>
<th>Rest</th>
<th>OKC</th>
<th>CKC</th>
</tr>
</thead>
<tbody>
<tr>
<td>15°</td>
<td>139.60 ± 10.07&lt;sup&gt;a,b&lt;/sup&gt;</td>
<td>144.92 ± 9.09&lt;sup&gt;b&lt;/sup&gt;</td>
<td>147.08 ± 10.12&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>30°</td>
<td>128.68 ± 7.34&lt;sup&gt;a,b&lt;/sup&gt;</td>
<td>134.08 ± 8.75&lt;sup&gt;b&lt;/sup&gt;</td>
<td>136.17 ± 7.41&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>45°</td>
<td>125.08 ± 6.81&lt;sup&gt;a,b&lt;/sup&gt;</td>
<td>128.82 ± 6.54&lt;sup&gt;b&lt;/sup&gt;</td>
<td>129.22 ± 8.62&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>P < .05.</sup>

<sup>a</sup> Significant difference between rest and voluntary isometric contraction in the OKC and CKC.

<sup>b</sup> Significant difference between knee positions of 15°, 30°, and 45°.

### Table 4  Patellar-Tilt Angle (Degrees) During Rest and Voluntary Isometric Contraction in the Open Kinetic Chain (OKC) and Closed Kinetic Chain (CKC), Mean ± SD

<table>
<thead>
<tr>
<th>Knee-flexion angle</th>
<th>Rest</th>
<th>OKC</th>
<th>CKC</th>
</tr>
</thead>
<tbody>
<tr>
<td>15°</td>
<td>8.93 ± 6.42&lt;sup&gt;a&lt;/sup&gt;</td>
<td>7.02 ± 5.55</td>
<td>7.80 ± 6.28&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>30°</td>
<td>8.22 ± 4.60&lt;sup&gt;a,b&lt;/sup&gt;</td>
<td>6.03 ± 4.81&lt;sup&gt;c&lt;/sup&gt;</td>
<td>5.97 ± 4.33</td>
</tr>
<tr>
<td>45°</td>
<td>9.33 ± 3.51&lt;sup&gt;a,b&lt;/sup&gt;</td>
<td>7.40 ± 4.70</td>
<td>6.83 ± 4.56</td>
</tr>
</tbody>
</table>

<sup>P < .05.</sup>

<sup>a</sup> Significant difference between rest and voluntary isometric contraction in the OKC.

<sup>b</sup> Significant difference between rest and voluntary isometric contraction in the CKC.

<sup>c</sup> Significant difference between knee positions of 30° and 45°.

<sup>d</sup> Significant difference between knee positions of 15° and 30°.
Data revealed that SA values were significantly different between the evaluated knee positions. This provides evidence of an increase in this angle as knee flexion decreases, a consequent reduction in femoral trochlea depth as knee extension increases, and, therefore, an increase in patellar instability. This increase in trochlea depth may be caused by the tendency of the patella to elevate over the femoral trochlea during knee extension. Data also revealed that voluntary isometric contractions in the OKC and CKC significantly increased SA values in all knee positions compared with rest. However, no differences were observed between isometric contractions in the OKC and CKC.

These findings disagree with those of Witonski and Góraj,\textsuperscript{10} who did not verify any differences in SA values between rest and contraction. However, those authors evaluated both men and women in the same group. Thus, the disagreement between their findings and those of the current study may be explained by differences in method. In the current study, we decided to evaluate only women to ensure sample homogeneity; according to Kujala et al.,\textsuperscript{4} women presented greater SA than men, and those authors indicate that this difference could alter women’s patellar stability, so evaluating a group with both genders would not have allowed us to observe the patellar-position difference between the exercises.

On the other hand, our data agree with those of Powers\textsuperscript{1} and Powers et al.,\textsuperscript{14} who, despite evaluating extension from 30° of knee flexion, verified an increase in femoral trochlea depth with knee extension in the OKC.

Only Tennant et al.\textsuperscript{13} evaluated the SA in healthy men and women during active exercise in the CKC in movement ranging from 0° to 55° of knee flexion. They verified that SA decreases as knee flexion increases, which agrees with the current study’s results. Despite those authors’ having evaluated both men and women, the

<table>
<thead>
<tr>
<th>Knee-flexion angle</th>
<th>Rest</th>
<th>OKC</th>
<th>CKC</th>
</tr>
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<tbody>
<tr>
<td>15°</td>
<td>50.61 ± 8.40\textsuperscript{a,b}</td>
<td>56.25 ± 8.47\textsuperscript{b,d}</td>
<td>56.66 ± 9.70\textsuperscript{b,d}</td>
</tr>
<tr>
<td>30°</td>
<td>52.08 ± 5.74\textsuperscript{c}</td>
<td>52.22 ± 4.98</td>
<td>52.83 ± 4.53</td>
</tr>
<tr>
<td>45°</td>
<td>54.72 ± 4.95</td>
<td>53.13 ± 5.47</td>
<td>53.01 ± 5.65</td>
</tr>
</tbody>
</table>

\textit{P} < .05.

\textsuperscript{a} Significant difference between rest and voluntary isometric contraction in the OKC.

\textsuperscript{b} Significant difference between knee positions of 15° and 45°.

\textsuperscript{c} Significant difference between knee positions of 30° and 45°.

\textsuperscript{d} Significant difference between knee positions of 15° and 30°.

**Table 5** Bisect Offset (Percentage) During Rest and Voluntary Isometric Contraction in the Open Kinetic Chain (OKC) and Closed Kinetic Chain (CKC), Mean ± SD
experimental groups consisted mostly of women, which possibly permitted the
difference in femoral trochlea depth observed with knee extension in as much as
women present greater SA values than men do. No studies comparing SA values
in CKC and OKC exercises were found in the reviewed literature.

As for PTA, these findings suggest that OKC and CKC exercises with the knee
flexed to 30° reduce it. However, patellofemoral stress is increased during OKC
exercises in this angle. In the CKC, patellofemoral stress is less when the knee
is flexed at 45° than in 30° of flexion.

Only Powers evaluated PTA during active exercises with a movement range of
45° to 0° of knee extension in the OKC. Confirming our findings, they also verified
a reduction in PTA as knee-flexion angles increased. Other authors have verified
PTA during OKC exercises in a movement range of 0° to 30° of knee flexion and
also verified a reduction in lateral tilt as knee flexion increased.

The reduction in PTA during OKC exercises with the knee flexed to 45° is
caused by centralization of the patella in the trochlear groove. Thus, there is a
better distribution of forces affecting the patella because of muscle contraction.
No studies evaluating this measurement in clinically healthy individuals during
isometric contraction in the CKC were found in the reviewed literature.

Patellar displacement was measured through BO, during voluntary isometric
contraction in the OKC and CKC, and patellar lateralization reduced as knee
flexion increased. With the knee flexed to 15°, significant patellar lateralization
was observed in both the OKC and CKC. At this knee angle, the patella is more
unstable and has a greater tendency to lateralize. It has also been observed that, at
this angle, the trochlear surface is shallower during muscle contraction, reinforcing
the greater tendency of the patella to lateralize. Thus, despite the patellar stress being
smaller during CKC exercises with 15° of knee flexion, the patellar positioning
is lateral in both, and it may be because of the lateral resultant of forces acting on
the patella. Therefore, performing exercises with 15° flexion in the CKC and OKC
could cause patellar subluxation in individuals with instability.

Powers suggested that one of the causes for patellar lateralization during
muscle contraction may be the increase in SA. However, our findings revealed an
increase in patellar lateralization during muscle contraction only when the knee
was flexed to 15°. Hence, considering the BO analysis, exercises with the knee
flexed at 30° and 45° do not increase patellar lateralization.

The current study’s results revealed that, generally, voluntary isometric con-
traction at the last degree of knee extension may compromise patellar dynamics.
Yet, on the other hand, it is possible to increase patellar stability during voluntary
isometric contraction with the knee flexed to 30° and 45°, in both the CKC and
OKC. Besides, Steinkamp et al demonstrated that CKC exercises with the knee
flexed to 30° and 45° reduce patellofemoral stress. Thus, considering the analysis
of patellofemoral kinematics and patellofemoral stress, exercises in the CKC and
OKC with knee flexion at 30° and 45° should be encouraged because they promote
better patellofemoral stability and reduction of pain; according to Witvrouw
et al both exercises during a protocol for patellofemoral disorders reduced pain
in daily activities.
Acknowledgments

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References