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Femur Rotation and Patellofemoral Joint Kinematics: A Weight-Bearing Magnetic Resonance Imaging Analysis

Disorders of the patellofemoral joint are among the most perplexing and clinically challenging conditions encountered in orthopaedic practice. Despite the high incidence of patellofemoral pain (PFP) in the general population (10%–20% of all lower-extremity injuries),^{7,12} the cause(s) of this condition are not clearly understood. Although many possible mechanisms have been discussed in the literature, one commonly cited theory is that PFP may be related to excessive patellofemoral joint stress.^{3,34} Accordingly, it is believed that increased shear and compressive loads associated with abnormal patella

tracking or malalignment may lead to the development of PFP.^{9,17,18}

It is commonly assumed that patella maltracking is the result of abnormal patella kinematics on a relatively stable femur. This assumption is based on decades of kinematic studies performed under non-weight-bearing conditions or those under which the femur motion was constrained.^{5,12,16,20,35,36} However, one study suggests that patellofemoral joint kinematics may be different during weight-bearing movements.²⁵ Using dynamic magnetic resonance imaging (MRI) to evaluate patellofemoral joint kinematics during a single-limb squat, Powers and colleagues²⁵ reported that the primary contributor to lateral patella tilt and lateral patella displacement in females with patella instability was medial rotation of the femur, as opposed to lateral patella rotation. Although this finding calls into question the long-held assumption that patella subluxation is the result of the patella moving on the femur, it should be noted that this study was performed using a small sample of subjects ($n = 6$). Furthermore, it could not be determined whether or not the amount of medial femoral rotation observed in these patients was excessive, as no control group was included in the study for comparisons.

• **STUDY DESIGN:** Controlled laboratory study using a cross-sectional design.

• **OBJECTIVES:** To compare patellofemoral joint kinematics, femoral rotation, and patella rotation between females with patellofemoral pain (PFP) and pain-free controls using weight-bearing kinematic magnetic resonance imaging.

• **BACKGROUND:** Recently, it has been recognized that patellofemoral malalignment may be the result of femoral motion as opposed to patella motion.

• **METHODS:** Fifteen females with PFP and 15 pain-free females between the ages of 18 and 45 years participated in this study. Kinematic imaging of the patellofemoral joint was performed using a vertically open magnetic resonance imaging system. Axial-oblique images were obtained using a fast gradient-echo pulse sequence. Images were acquired at a rate of 1 image per second while subjects performed a single-limb squat. Measures of femur and patella rotation (relative to the image field of view), lateral patella tilt, and lateral patella displacement were made from images obtained

at 45°, 30°, 15°, and 0° of knee flexion. Group differences were assessed using a mixed-model analysis of variance with repeated measures.

• **RESULTS:** When compared to the control group, females with PFP demonstrated significantly greater lateral patella displacement at all angles evaluated and significantly greater lateral patella tilt at 30°, 15°, and 0° of knee flexion. Similarly, greater medial femoral rotation was observed in the PFP group at 45°, 15°, and 0° of knee flexion when compared to the control group. No group differences in patella rotation were found.

• **CONCLUSION:** Altered patellofemoral joint kinematics in females with PFP appears to be related to excessive medial femoral rotation, as opposed to lateral patella rotation. Our results suggest that the control of femur rotation may be important in restoring normal patellofemoral joint kinematics. *J Orthop Sports Phys Ther* 2010;40(5):277-285. doi:10.2519/jospt.2010.3215

• **KEY WORDS:** *biomechanics (lower extremity), hip, knee, medical imaging, MRI*

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Using various forms of imaging (ie, computerized tomography and dual fluoroscopy), more recent investigations have provided evidence that patellofemoral joint kinematics may be influenced by femoral rotation.^{14,15} Furthermore, it has been shown that femur and tibia motions can influence patellofemoral joint contact areas and pressures.^{13,26} Although the above-noted studies highlight the interdependence of the femur, tibia, and patella with respect to patellofemoral joint mechanics, additional work is needed to better define these relationships. A clear understanding of the cause of patellofemoral joint maltracking (ie, excessive femoral rotation versus patella motion) is important to better guide surgical and nonsurgical interventions. For example, if femoral rotation is found to contribute to abnormal patella tracking, treatment strategies may need to address stabilization of the femur (as opposed to the patella).

The current investigation expands upon the previous work of Powers et al²⁵ by increasing the sample size and comparing kinematic MRI data from females with PFP to a gender- and age-matched control group. The purpose of the current study was to use weight-bearing kinematic MRI to determine if females with PFP demonstrate greater amounts of medial femoral rotation when compared to a control group, and to determine whether femur motion (as opposed to patella motion) contributes to altered patellofemoral joint kinematics. We hypothesized that females with PFP would demonstrate greater amounts of medial femoral rotation, lateral patella displacement, and lateral patella tilt, and no difference in patella rotation, when compared to a control group.

METHODS

Subjects

Two groups of subjects were recruited for this study. Fifteen females with PFP between the ages of 18 and 45 years comprised the experimental group, while 15 pain-free females served as a control group. Subjects were similar in

TABLE	SUBJECT CHARACTERISTICS		
	Patellofemoral Pain (n = 15)	Controls (n = 15)	P Value
Age (y)	30.8 ± 8.9	29.1 ± 4.2	.52
Height (m)	1.67 ± 0.09	1.64 ± 0.09	.38
Body mass (kg)	61.2 ± 7.3	60.7 ± 10.1	.87
Pain score (VAS)*	3.26 ± 1.85	0	N/A
Physical activity (min) [†]	198 ± 188	175 ± 141	.70

Abbreviation: VAS, visual analog scale.
 * The VAS is a 10-cm scale, with 0 indicating no pain and 10 indicating the worst pain imaginable.
 † Physical activity score is recorded from the vigorous activity component of the International Physical Activity Questionnaire (IPAQ) short form and is reported in minutes per week.

terms of age, height, body mass, and activity level (TABLE). Individuals over the age of 45 were excluded from the study to control for the possible effects of degenerative joint disease. Subjects with PFP were recruited from flyers posted in orthopaedic clinics near Stanford University and the surrounding community.

Assignment to the PFP group was established based on patient symptoms and physical examination results. Subjects were screened (through physical examination) to rule out ligamentous or meniscal injury, patella tendinitis, and large knee effusion.^{22,23} Only those subjects meeting the following criteria were admitted to the PFP group: (1) pain originating specifically from the patellofemoral articulation (retropatellar or peripatellar pain, as determined through location of symptoms and palpation), (2) readily reproducible pain (3 out of 10, based on a visual analog scale), with at least 2 of the following functional activities commonly associated with PFP: stair ascent or descent, squatting, kneeling, prolonged sitting, or isometric quadriceps contraction.²⁴

Individuals with PFP were excluded from participation if they reported having any of the following: (1) previous history of knee surgery, (2) history of traumatic patella dislocation, (3) neurological involvement that would influence gait, and (4) implanted biological devices that could interact with the magnetic field (ie, pacemakers, cochlear implants, or ferromagnetic cerebral aneurysm clips).

The control group was selected based on the same criteria as the experimental group, except that subjects had no (1) history or diagnosis of knee pathology or trauma, (2) current knee pain or effusion, (3) knee pain with any of the activities described for the PFP group, (4) limitations that would influence gait, and (5) implanted biological devices, such as pacemakers, cochlear implants, or clips that are contraindicated for MRI.

Procedures

All testing took place at Stanford University Hospital. Prior to participation, procedures were explained to each subject. Subjects then signed a human subject's consent form, as approved by the Institutional Review Boards of the University of Southern California and Stanford University.

Weight-bearing kinematic imaging of the patellofemoral joint was performed using a vertically opened MR system (0.5 T) developed for interventional procedures (General Electric Medical Systems, Milwaukee, WI). The system was equipped with pulse sequence programming and real-time interactive imaging capabilities. The vertically open design of this system allowed subjects to be imaged weight-bearing (ie, standing). Axial-oblique images of the patellofemoral joint were obtained using a flexible transmit-receive surface coil and a fast gradient-echo pulse sequence. Images were acquired at a rate of 1 image per second, using the following parameters:



FIGURE 1. Subjects were positioned in standing within the MRI system.



FIGURE 2. Axial-oblique images were acquired through the patellofemoral joint during a single-limb squat. Lateral side is to the left of the figure.

repetition time (TR), 10.3 milliseconds; echo time (TE), 2.7 milliseconds; flip angle, 30°; field of view, 20 × 20 cm; matrix, 256 × 256; slice thickness, 5 mm; number of excitations, 1.

Prior to imaging, subjects were

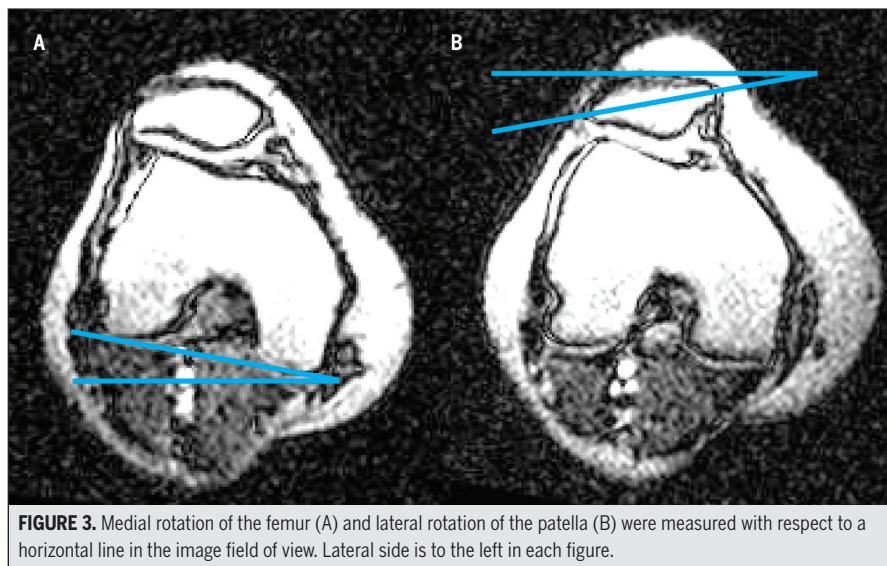


FIGURE 3. Medial rotation of the femur (A) and lateral rotation of the patella (B) were measured with respect to a horizontal line in the image field of view. Lateral side is to the left in each figure.

screened for the MRI environment using a questionnaire and were asked to remove all metallic objects. For subjects with bilateral symptoms, the most painful side at the time of imaging was evaluated. Imaging was performed with subjects barefoot in a single-limb stance (FIGURE 1). The foot position (toe-out) was self-selected by each subject. Once a foot position was chosen, subjects were required to maintain that foot position for the duration of testing. Subjects were asked to squat to approximately 50° of knee flexion and then return slowly to the fully extended position. Subjects were instructed to extend their knee in a slow consistent manner throughout the arc of motion. A plastic goniometer was placed on the lateral aspect of the knee to allow for monitoring of the range of motion. When the knee flexion angle coincided with 1 of the 4 target knee flexion angles (45°, 30°, 15°, and 0°), subjects were asked to pause, at which time the imaging plane was aligned and 2 static images were acquired. Previous MRI studies evaluating patellofemoral joint kinematics in persons with PFP have demonstrated that lateralization of the patella primarily occurs as the knee extends from 45° to 0° of knee flexion.^{20,25} As such, we elected to evaluate this range and direction of motion in the current study.

Several steps were taken to assure that the alignment of the image plane was

consistent among subjects. This was necessary, as subjects demonstrated variable amounts of toe-out and varied lower-limb alignment within the scanner. First, axial image “scouts” were acquired to locate the knee joint center within the MRI system. Once the location of the knee joint was determined, the image plane was positioned such that axial-oblique images aligned through the widest part of the patella, as well as the anterior and posterior femoral condyles, could be obtained (FIGURE 2). This procedure was repeated at each knee flexion angle. Throughout testing, subjects were allowed toe-touch support with the contralateral foot for balance only. They were instructed not to bear weight with their arms (against the side of the scanner) or the opposite foot.

Two sets of images were acquired for each subject. After obtaining the first set of images, subjects were removed from the scanner and permitted to rest. After 5 minutes, subjects were repositioned within the MRI system, and the procedures were repeated. The orientation of the foot remained the same for both scans. This was accomplished by outlining the foot progression angle during the first scan with tape.

Data Analysis

Data from the 2 sets of images were quantified and averaged for statistical

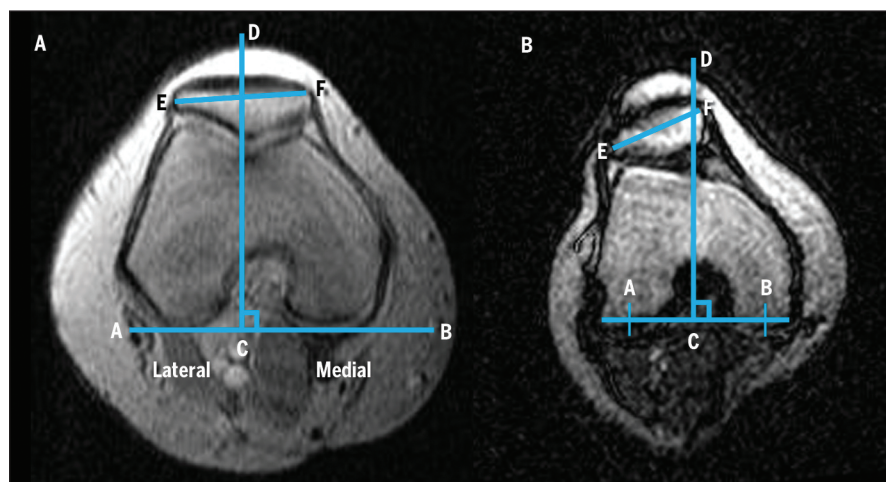


FIGURE 4. (A) Patella displacement using the bisect offset measurement was determined by drawing a line connecting the posterior femoral condyles (line AB), then projecting a perpendicular line anteriorly through the deepest portion of the trochlear groove (line CD) to a point where it bisected the patella-width line (line EF). (B) To obtain data when the trochlear groove was flattened, the perpendicular line was projected anteriorly from the bisection of the posterior condylar line. The bisect offset was reported as the percentage of patella width lateral to the midline. Lateral side of the knee is to the left of each figure.

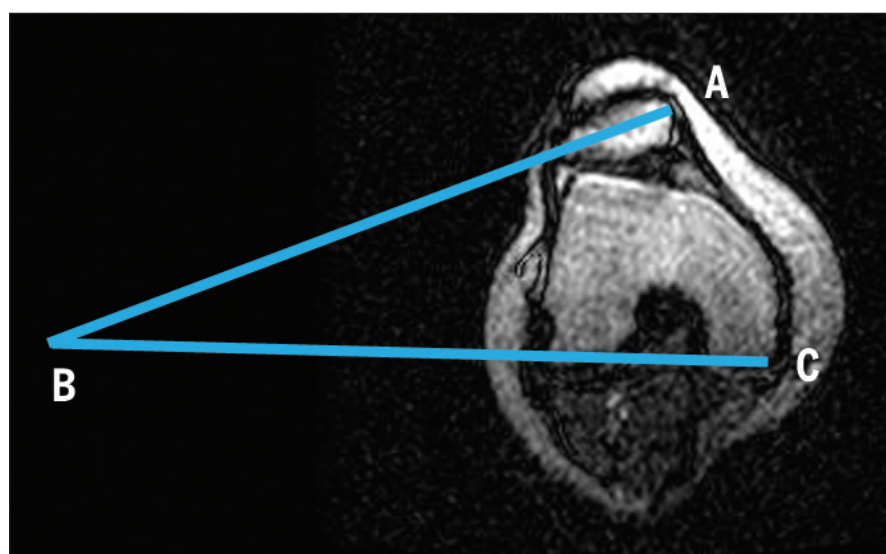


FIGURE 5. Patella tilt was defined as the angle formed by lines joining the maximum width of the patella (line AB) and the posterior femoral condyles (line BC). Lateral side of the knee is to the left of the figure.

analysis. Primary variables of interest included femoral rotation, patella rotation, lateral patella displacement, and lateral patella tilt. Medial/lateral femoral rotation (transverse plane) relative to the external field of view was quantified as the angle formed by the line joining the posterior femoral condyles and a line parallel to the horizontal orientation of the field of view (**FIGURE 3A**). Medial rotation was defined as positive, and lateral rotation

was defined as negative. Femoral rotation measurements were reported in degrees.

Medial/lateral patella rotation (transverse plane) relative to the external field of view was assessed by measuring the angle between a line defining the maximum patella width and a line parallel to the horizontal orientation of the field of view (**FIGURE 3B**). As with femoral rotation, medial patella rotation was defined as positive and lateral patella rotation as

negative. Patella rotation measurements were reported in degrees.

Medial/lateral patella displacement was assessed using the bisect offset index, as initially described by Stanford et al.³¹ and modified by Brossman et al.⁶ The bisect offset was measured by drawing a line connecting the posterior femoral condyles and then projecting a perpendicular line anteriorly through the deepest point (apex) of the trochlear groove. This line intersected the patella width line, which connects the 2 widest points of the patella (**FIGURE 4**). To obtain data when the trochlear groove is flattened, the perpendicular line was projected anteriorly from the bisection of the posterior condylar line (**FIGURE 4**). The bisect offset is representative of the extent of the patella lateral to the midline and was expressed as a percentage of the total patella width.⁶

Medial/lateral patella tilt was measured as the angle formed by the line joining the maximum width of the patella and the line joining the posterior femoral condyles, as previously described (**FIGURE 5**).^{19,27} Tilt measurements were reported in degrees.

All measurements were made using a custom-written macro for Scion image software (Scion Corp, Frederick, MD). Values for patella displacement, patella tilt, femoral rotation, and patella rotation consisted of the average of 4 measurements (2 images were analyzed from each of the 2 trials). All measurements were made by a single unblinded investigator. Intraobserver repeatability was found to be excellent for all variables with intraclass correlation coefficients ($ICC_{2,4}$) of 0.91, 0.95, 0.96, and 0.99 for patella displacement, patella tilt, femoral rotation, and patella rotation, respectively. The standard error of the measurement for patella displacement, patella tilt, femoral rotation, and patella rotation were 3.6%, 1.3°, 1.0°, and 0.7°, respectively.

Statistical Analysis

To determine whether patella displacement, patella tilt, femoral rotation, and

patella rotation differed between groups across knee flexion angles, a 2-by-4 (group by knee flexion angle) mixed-model analysis of variance (ANOVA) with a repeated factor of knee flexion angle was performed. This analysis was repeated for each dependent variable of interest (ie, patella displacement, patella tilt angle, femoral rotation, and patella rotation). Significant statistical interactions were explored using independent samples *t* tests. SPSS statistical software (SPSS, Inc, Chicago, IL) was used for all analyses. Significance levels were set at $P < .05$.

RESULTS

A SIGNIFICANT GROUP-BY-ANGLE INTERACTION was found for lateral patella displacement ($P = .011$). Post hoc pairwise comparisons revealed that the individuals in the PFP group demonstrated greater lateral patella displacement compared to the control group at each of the knee flexion angles evaluated (FIGURE 6). The largest difference between groups was observed at 0° of knee flexion (mean $\pm$ SD, $75\% \pm 8\%$ versus $58\% \pm 7\%$ of patella lateral to midline).

A significant group-by-angle interaction was found for lateral patella tilt ($P = .03$). Post hoc pairwise comparisons revealed that the individuals in the PFP group had greater lateral patella tilt compared to the control group at 30° , 15° , and 0° of knee flexion (FIGURE 7). As with lateral patella displacement, the largest difference between groups was observed at 0° of knee flexion (mean $\pm$ SD, $13.1^\circ \pm 5.8^\circ$ versus $8.1^\circ \pm 4.1^\circ$).

A significant group-by-angle interaction also was found for femoral rotation ($P = .037$). Post hoc pairwise comparisons revealed that the individuals in the PFP group demonstrated greater medial femoral rotation compared to the control group at 45° , 15° , and 0° of knee flexion (FIGURE 8). The largest group difference was observed at 0° of knee flexion, where the subjects with PFP had nearly twice the amount of medial femoral rotation

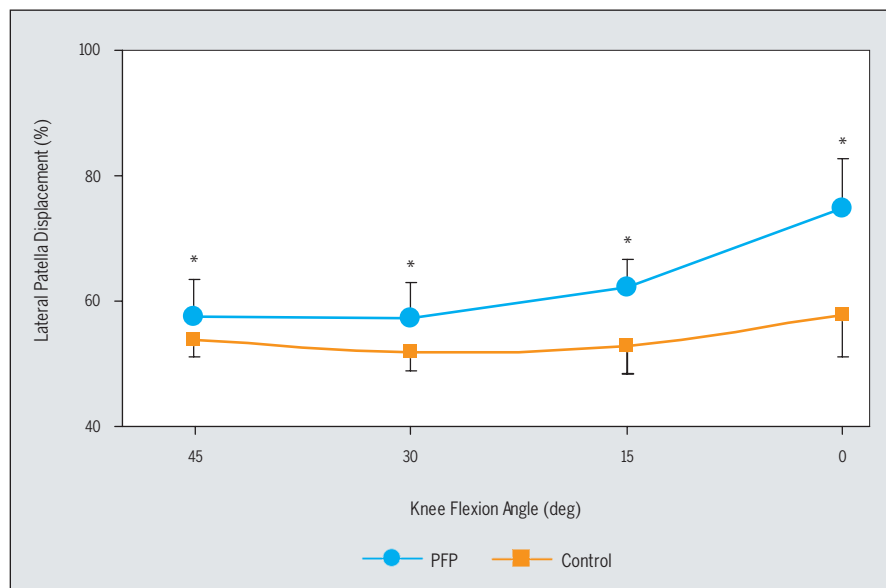


FIGURE 6. A significant group-by-angle interaction was found for lateral patella displacement measured as a percent of patella lateral to midline ($P = .011$). *Indicates significant group differences based on post hoc pairwise comparisons ($P < .05$). Data presented are mean $\pm$ SD.

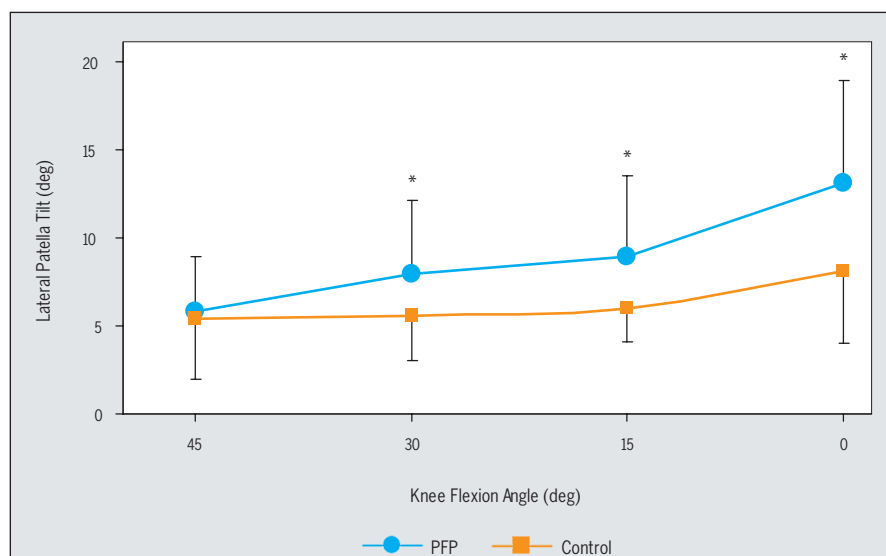


FIGURE 7. A significant group-by-angle interaction was found for lateral patella tilt ($P = .03$). *Indicates significant group differences based on post hoc pairwise comparisons ($P < .05$). Data presented are mean $\pm$ SD.

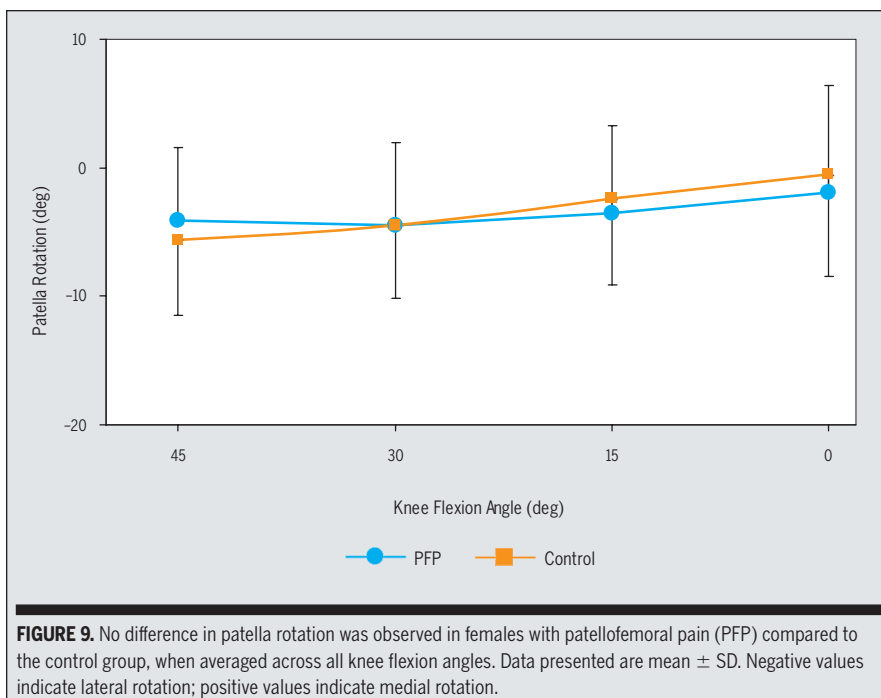
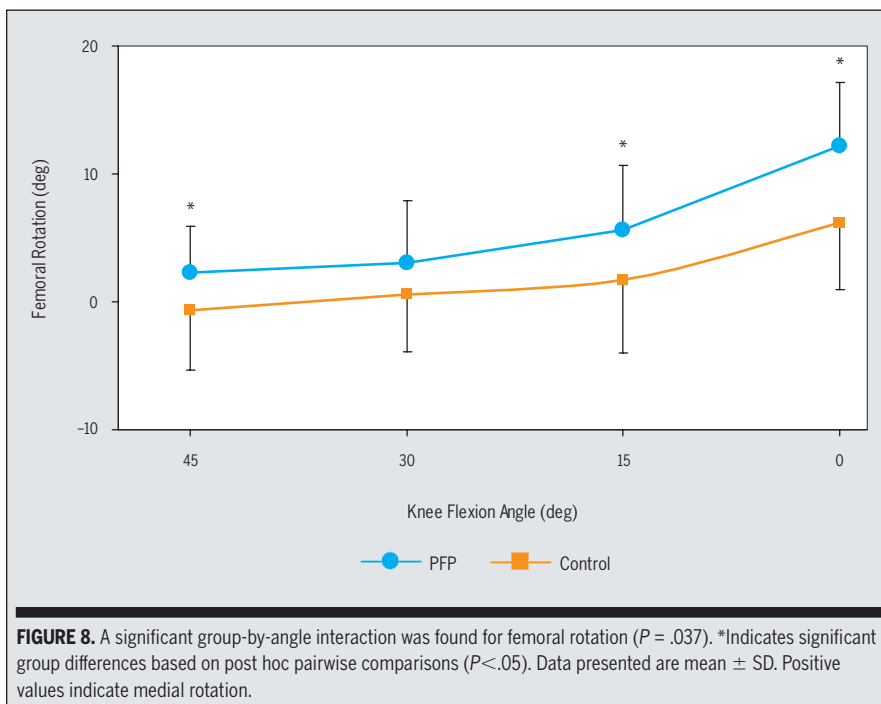
when compared to the control group (mean $\pm$ SD, $12.2^\circ \pm 5.0^\circ$ versus $6.2^\circ \pm 5.2^\circ$).

No significant group effect or interaction was observed for patella rotation. On average, the patella was laterally rotated in both groups, with values being nearly identical (mean $\pm$ SD, $-3.8^\circ \pm 6.8^\circ$ versus $-3.3^\circ \pm 6.5^\circ$) (FIGURE 9).

DISCUSSION

CONSISTENT WITH THE HYPOTHESES proposed, females with PFP demonstrated greater amounts of lateral patella displacement and lateral patella tilt when compared to the control group. In addition, the PFP group also demonstrated greater medial femoral

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rotation compared to the control group. However, no group differences in patella rotation were observed. In all instances, the observed group differences exceeded the measurement error of variables examined. These findings support previous assertions that femoral rotation, as opposed

to patella rotation, is more pronounced in females with PFP during weight-bearing movements.²⁵

Our results are in agreement with those of previous investigators who have reported that subjects with PFP demonstrate greater lateral patella displacement

when compared to pain-free controls during weight-bearing knee extension.^{35,36} In the current study, both groups exhibited a similar pattern of lateral patella motion that consisted of increasing lateral patella displacement as the knee extended. Although the females in the PFP group demonstrated greater lateral patella displacement across all knee flexion angles, group differences were most pronounced at 0° of knee extension. The maximum lateral patella displacement observed in our PFP group (75% of patella lateral to midline) is similar to that reported by previous investigators who have quantified patellofemoral joint kinematics under weight-bearing conditions.^{5,25,28}

With respect to patella tilt, group averages were similar at 45° of knee flexion but steadily diverged as the knee extended. As with lateral patella displacement, the PFP group exhibited increasing amounts of lateral tilt compared to the control group, with maximum differences occurring at 0°. On average, patella tilt in the PFP group increased from 5.8° at 45° of knee flexion to 13.1° at 0° of knee flexion. In contrast, patella tilt in the control group increased from 5.4° at 45° of knee flexion to 8.1° at 0° of knee flexion. The maximum lateral patella tilt angle observed in our PFP group is within the range of previously reported values obtained under weight-bearing conditions (6°–16°).^{5,16,25,28}

As hypothesized, the PFP group exhibited significantly greater amounts of medial femoral rotation compared to the control group. This finding was consistent across all knee flexion angles. Although the overall pattern of femur rotation was similar for both groups (ie, increasing medial rotation with knee extension), the individuals in the PFP group exhibited twice the amount of rotation at 0° of knee flexion. The maximum medial rotation exhibited in our PFP group (12.2°) is similar to that previously reported by Powers et al²⁵ (13°), who used a similar weight-bearing protocol to that employed by the current study.

In contrast to femur rotation, patella

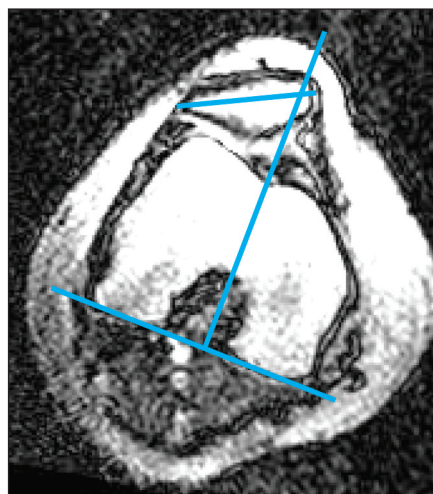


FIGURE 10. Excessive medial femoral rotation results in relative lateral patella displacement and lateral patella tilt. Lateral side of the knee is to the left of the figure.

rotation did not differ between groups. When averaged across all knee flexion angles, the amount of patella rotation in the PFP group was within 1.5° of that of the control group. Although the patella in both groups was in a position of slight lateral rotation across all knee flexion angles, there was a tendency for the patella to rotate medially (ie, less lateral rotation) as the knee extended. This pattern of motion is in contrast to what has been reported during non-weight-bearing conditions (ie, the progressive lateral rotation of the patella with knee extension).^{16,20,25}

When evaluating the potential contributions of femur and patella rotation to lateral tilt and displacement, it appears that femur rotation contributed to the altered patellofemoral joint kinematics in the PFP group to a greater extent than patella rotation. This was illustrated by the fact that the pattern of medial femur rotation closely paralleled the pattern of lateral patella displacement and tilt (FIGURES 6-8). As shown in FIGURE 10, medial femoral rotation would contribute to relative lateral tilt by moving the lateral anterior femoral condyle towards the lateral facet of the patella. Similarly, medial femur rotation would move the femoral sulcus away from the central ridge of the

patella, resulting in relative lateral patella displacement. Our finding of medial femoral rotation being more aligned with the pattern of lateral patella tilt and displacement is consistent with the work of Li and colleagues,¹⁴ who reported that rotation of the femur was strongly correlated with patella tilt ($R^2 = 0.73$), as quantified in weight bearing using dual-orthogonal fluoroscopy.

When comparing the amount of femur rotation to patella rotation, it is evident that the femur exhibited greater amounts of motion as the knee extended. The fact that the patella is attached to the tibia via the patella tendon, combined with the fact that the tibia rotates very little during weight-bearing activities,²¹ may explain why patella rotation was minimal. The combination of quadriceps contraction and a fixed tibia during weight bearing would result in a relatively stable patella. On the other hand, the ball-and-socket configuration of the hip joint would afford the femur a high degree of mobility.

In addition to influencing patellofemoral joint kinematics, excessive medial rotation of the femur also may affect patellofemoral joint stress (ie, force per unit area). For example, medial rotation of the femur relative to the tibia (ie, knee external rotation) has been shown to be associated with decreased patellofemoral joint contact area in persons with PFP.²⁶ In turn, it has been shown that reduced contact area is the primary factor underlying elevated patellofemoral joint stress during walking in females with PFP.⁴ More specifically, Heino-Brechter and Powers⁴ reported that peak patellofemoral joint stress in their PFP group occurred during early stance, a time at which the knee was flexing from 0° to 15° . Interestingly, this corresponds to the same range of knee flexion where the largest group differences in medial femoral rotation were observed in the current study (0° to 15°). Thus, it is possible that medial femoral rotation with the knee in a relatively extended position could contribute to elevated patellofemoral joint stress. Although the group differences in medial

femoral rotation were less pronounced with the knee flexed to 30° and 45° , only a slight decrease in contact area would be needed to increase patellofemoral stress, as the joint reaction forces are known to be greater with increasing knee flexion during weight bearing.³³

The cause of the excessive medial rotation of the femur in the PFP group was not assessed in the current study, so it is unclear if the observed kinematics were the cause of PFP, the result of PFP, or merely an association. However, proposed mechanisms include skeletal abnormalities (femoral anteversion, trochlear dysplasia, and patella dysplasia),^{1,2,25} and diminished hip muscle performance.^{7,8,29,30} In addition, it has been proposed that excessive femoral rotation may be the result of an exaggeration of the “screw-home mechanism” at the knee.³² Given that the tibia is relatively fixed during weight bearing, the femur would have to medially rotate relative to the tibia to achieve full knee extension.

Regardless of the cause of the higher amounts of medial femoral rotation observed in our PFP group, our findings contribute to the growing body of literature suggesting that the cause of altered patellofemoral joint kinematics during weight-bearing may differ from non-weight-bearing movements. However, care must be taken in generalizing our results to all patients with patellofemoral symptoms, as our sample size was relatively small. Furthermore, no attempt was made to ascertain the cause of PFP in our cohort. It is possible that our patient group could have been biased by the fact that a majority of our subjects had poor hip and trunk stability (not quantified). Future studies should attempt to evaluate a more homogenous patient sample with more stringent inclusion/exclusion criteria.

There are several limitations of our study that need to be acknowledged. First, the investigator who took the measurements from the MR images was not blinded to group assignment. Although the measurements obtained were based

on the identification of specific bony landmarks, the potential for measurement bias needs to be considered when interpreting the data presented. Second, pain was not assessed during testing, so it is unclear if the group differences in patellofemoral joint kinematics are related to symptoms. Finally, no attempt was made to control for the squat mechanics utilized by each subject within the MR scanner. Although our methodology provided a realistic evaluation of how subjects would normally perform a squat, future studies should consider the mechanics of the task and how that may be related to altered patellofemoral joint kinematics.

CONCLUSION

FEMALES WITH PFP DEMONSTRATED greater amounts of lateral patella displacement and lateral patella tilt during a weight-bearing task. Furthermore, females with PFP also demonstrated a greater amount of medial femoral rotation and no differences in patella rotation when compared to the control group. Our findings contribute to the growing body of literature suggesting that the cause of altered patellofemoral joint kinematics during weight bearing may be more related to abnormal femur motion than patella motion. Our data suggest that the control of femur rotation during weight-bearing tasks, particularly at small degrees of knee flexion, may be important in restoring normal patellofemoral joint kinematics. ●

KEY POINTS

FINDINGS: Females with PFP demonstrated greater amounts of lateral patella displacement, lateral patella tilt, and medial femoral rotation when compared to the control group.

IMPLICATION: Our results suggest that the control of femur rotation may be important for more optimal patellofemoral joint kinematics.

CAUTION: The cause of medial rotation of the femur in the PFP group was not

assessed in the current study, so it is unclear if the observed kinematics were the cause of PFP, the result of PFP, or merely an association.

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