In Vivo Noninvasive Evaluation of Abnormal Patellar Tracking During Squatting in Patients with Patellofemoral Pain

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Background: Patellofemoral pain syndrome is one of the most common knee problems and may be related to abnormal patellar tracking. Our purpose was to compare, in vivo and noninvasively, the patellar tracking patterns in symptomatic patients with patellofemoral pain and those in healthy subjects during squatting. We tested the hypothesis that patients with patellofemoral pain exhibit characteristic patterns of patellar tracking that are different from those of healthy subjects.

Methods: Three-dimensional patellar kinematics were recorded in vivo with use of a custom-molded patellar clamp and an optoelectronic motion capture system in ten healthy subjects and nine subjects with patellofemoral pain. The position of osseous knee landmarks was digitized while subjects stood upright, and then patellofemoral kinematics were recorded during squatting. The tracking technique was validated with use of both in vitro and in vivo methodologies, and the average absolute error was $<1.2^\circ$ and <1.1 mm.

Results: At 90° of knee flexion, the patella showed lateral spin (the distal pole of the patella rotated laterally) in subjects with patellofemoral pain (mean and standard deviation, $-10.13^\circ \pm 2.24^\circ$) and medial spin in healthy subjects (mean, $4.71^\circ \pm 1.17^\circ$) ($p < 0.001$). At 90° of knee flexion, the patella demonstrated significantly more lateral translation in subjects with patellofemoral pain (mean, 5.05 ± 3.73 mm) than in healthy subjects (mean, -4.93 ± 3.93 mm) ($p < 0.001$).

Conclusions: Kinematic differences between healthy subjects and subjects with patellofemoral pain were demonstrated through a large, dynamic range of knee flexion angles. Increased lateral patellar translation and lateral patellar spin in subjects with patellofemoral pain suggest that the patella is not adequately balanced during functional activities in this group. Prospective studies are needed to identify when patellofemoral pain-related changes begin to occur and to determine the risk for the development of patellofemoral pain in individuals with abnormal kinematics.

Clinical Relevance: This study presents a simple extension of standard motion analysis tools, which allows for accurate assessment of three-dimensional patellofemoral kinematics in the clinical setting. The identification of kinematic differences associated with patellofemoral pain suggests that the dynamic tracking technique is a potential diagnostic tool for this syndrome.

Patellofemoral pain syndrome is one of the most common knee dysfunctions^{1,2}. Despite the high prevalence (25%) of this condition in the general population^{1,3}, the pathophysiology of patellofemoral pain is not clearly understood^{4,5}. Current literature has suggested that the etiology of patellofemoral pain is multifactorial^{3,6,7} and may be associ-

ated with static patellar malalignment and abnormal patellar tracking⁵⁻¹⁰.

Numerous studies have investigated patellofemoral kinematics^{2,7,11-26}; however, few have investigated the specific role that static malalignment and patellar maltracking play in patellofemoral pain²⁷⁻³³. In vitro experiments^{7,11-15} are unlikely to

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represent dynamic patellar kinematics accurately because of the lack of in vivo forces or the pathological changes associated with patellofemoral pain syndrome. A number of in vivo studies have been conducted with use of imaging techniques such as biplane fluoroscopy²⁶ and both dynamic^{17-19,27-29} and static magnetic resonance imaging^{20,21,30}. Because the use of biplane fluoroscopy involves exposure to ionizing radiation, it is not ideal for clinical assessment. In addition, accuracies for this technique, specifically with respect to the patellofemoral joint, have not been reported, to our knowledge. Magnetic resonance imaging-based techniques typically have long imaging times (2.5 to five minutes), which require the patient to contract the quadriceps muscle for long periods, and they cannot evaluate functional tasks during full weight-bearing. Intracortical pins have also been used to obtain reliable patellar tracking data^{22,23,31}. However, because of their invasive nature, these pins are not well suited for clinical assessment³⁰. Previous studies with use of clamping techniques to evaluate patellar tracking could only assess limited ranges of motion under non-weight-bearing conditions^{2,24} or were validated only for the translational degrees of freedom (medial-lateral, inferior-superior, and anterior-posterior displacement)²⁵. The rotational degrees of freedom are likely to play a critical role in differentiating important tracking patterns between symptomatic and asymptomatic subjects^{15,30,34}, and techniques that do not incorporate active extension with quadriceps contraction are less likely to demonstrate abnormal motion than are techniques that assess functional activities^{7,32,34}. Finally, few techniques have been used to study patellofemoral pain syndrome clinically^{30,33}.

We believe there is a need to evaluate patellar tracking in vivo and noninvasively, especially during functional activities under full weight-bearing conditions. Thus, the purpose of this study was to quantify, in vivo and noninvasively, the patellar tracking patterns in symptomatic patients with patellofemoral pain and compare them with those in healthy subjects during squatting. We tested the hypothesis that patients with patellofemoral pain exhibit characteristic patterns of patellar tracking that are significantly different from those seen in subjects with no history of patellofemoral joint pain.

Materials and Methods

Three-dimensional patellar kinematics were assessed in healthy volunteers and in subjects with patellofemoral pain syndrome. All subjects with patellofemoral pain had a clinical diagnosis that was defined by a positive result, on the basis of clinical examination, for at least one of the following tests: the J sign⁶, squat test³⁵, or glide test⁶. In order to eliminate other potential sources of pain, patients were excluded if they had positive signs of a meniscal, ligamentous, or iliotibial band lesion, traumatic onset of patellofemoral pain, signs of patellar instability (for example, a positive apprehension test³⁵), or a history of any other injury or pathological condition involving the lower extremity. The diagnosis of patellofemoral pain was provided by a clinician on the basis of the history and a physical examination^{36,37}. All patients had to have active patellofemoral pain at the time of testing, evidenced by repro-

TABLE I Demographic Characteristics of the Subjects

	Subjects with Patellofemoral Pain	Healthy Subjects	P Value
Sex (M/F)	2/7	5/5	0.350
Age* (yr)	30.22 ± 12.5	26.70 ± 7.7	0.465
Height* (cm)	169.05 ± 9.6	171.44 ± 9.3	0.589
Weight* (kg)	69.70 ± 18.3	66.39 ± 15.1	0.672
*The values are given as the mean and the standard deviation.			

ducible patellofemoral pain in at least two of the following activities: squatting, climbing up or down stairs, or seated knee extension. These activities were selected because of their specificity to patellofemoral pain³⁸. All healthy participants had no current or past symptoms of patellofemoral pain.

Previous studies have shown that patellar spin (rotation about the anterior-posterior axis) is the component of patellar motion with the smallest range during knee flexion. A minimum range of spin of 10° during the first 60° of knee flexion has been documented previously³⁰. Pilot data from the current study suggested that a minimum detectable difference of 2° for patellofemoral rotations (20% of the smallest component of patellar motion) would be diagnostically significant, and suggested a standard deviation of approximately 1.5° for patellar rotation. A power analysis showed that two groups of at least eight subjects each were needed to yield a power of 80%. Therefore, these pilot data suggested that an effect size of 1.25 could be detected with an experimental group of sixteen subjects. Ten healthy subjects and nine subjects with patellofemoral pain volunteered to participate in this institutional review board-approved study and provided informed consent prior to participation. There were no significant differences between the two groups with respect to sex, age, height, or weight (Table I).

A patellar clamp was custom-molded with use of thermoplastic material (Aquaplast; WFR/Aquaplast, Wyckoff, New Jersey) for the patella in each subject with the leg in full extension (Fig. 1). The thermoplastic material was heated and pressed around the edges of the patella to conform closely to its borders. Three active infrared markers were affixed to each custom clamp. The clamp was then stabilized on the patella with use of an elastic wrap (SuperWrap; FabriFoam, Exton, Pennsylvania) with a foam inner layer (Fig. 1, C). The foam layer increased friction of the wrap with the skin and patellar clamp without excess compression and prevented the wrap from migrating during flexion-extension movements of the knee. A custom-developed spatial linkage (the goniometer) was instrumented with infrared markers (Fig. 1, D) and was used as a rigid frame to track the relative motion of the tibial and femoral segments. An optoelectronic motion capture system (Optotrak 3020; Northern Digital, Waterloo, Ontario, Canada) was used for all digitization and tracking measurements.

Fig. 1

Photographs of the patellar tracking setup. *A*: Custom clamp after molding. *B*: Custom clamp with an outline of the underlying patella digitally overlaid. *C*: Custom clamp affixed to the leg with use of elastic wrap with foam inner layer. *D*: Custom patellar clamp and the goniometer. Active infrared markers are indicated on both the clamp and the goniometer.

A joint coordinate system^{34,39} was used to describe patellofemoral kinematics after the method described by Lin et al.²⁴ (Fig. 2). The proximal-distal and medial-lateral poles of the patella were manually located and digitized. The origin of the patellar coordinate system was located at the centroid of the patella (the intersection of the lines connecting the poles). The origin (zero-position) for patellar rotations was defined as the position of the patella when the proximal-distal axes of the femur and the patella were parallel²⁴. This allowed for assessment of static alignment, as there may be initial patellar rotation at standing with the knee in full extension. The patellofemoral position at standing in full extension was the origin for linear translations. The subjects stood upright with their feet shoulder-width apart while osseous landmarks were located with use of palpation (Fig. 2, *D*), and the initial positions of the markers were digitized. Transformations of the positions of the markers to the local coordinate systems were calculated from the initial marker coordinates and the osseous landmarks by finding the rotation matrix on the basis of the eigenvalue decomposition and then a straightforward calculation of the translation vector⁴⁰. The subjects performed three squats to a self-selected depth while patellofemoral kinematics

were recorded at 100 Hz. The subjects were asked to squat as deeply as possible while maintaining a smooth squatting motion and maintaining their balance unaided. All subjects squatted to at least 90° of knee flexion. The kinematics from three squats for each subject were averaged for further analysis.

For validation of the patellar tracking measurements, two fresh-frozen cadaver specimens were fitted with a custom clamp and the goniometer. In addition, cortical screws were inserted into the patella, femur, and tibia of each specimen. Modifications were made to the custom clamps to ensure that movement of the clamp was independent of and did not interfere with movement of the cortical screw. A small Y-shaped frame with an infrared marker on each of the three arms was attached to each cortical screw. Patellofemoral and tibiofemoral movement were induced with use of a servomotor to move the knee passively through 0° to 120° of flexion. Muscle force was simulated by applying a 179.6-N extensor force, which was distributed among the individual muscles according to their proportional physiologic cross-sectional area⁴¹. After minimal skin resection, the individual muscles crossing the knee joint were separated from each other with use of the fascial planes between the muscles as a guide. Fiberglass mesh

Fig. 2

The positive directions of motion for each degree of freedom. A: Patellar flexion-extension occurred about the transepicondylar line of the femur⁴⁹ (X_f -axis). B: Patellar medial-lateral tilt occurred about the longitudinal axis of the patella (Y_p -axis). C: Patellar spin occurred about the anterior-posterior floating axis (Z_p -axis; perpendicular to both the X_f and the Y_p axes). Patellar translation relative to the femur was described along the three axes of the femoral coordinate system. D: Medial-lateral translation along X_f . The asterisks indicate the osseous landmarks that were digitized for reference position definitions. E: Proximal-distal translation along Y_f . F: Anterior-posterior translation along Z_f . The positive directions of motion for the patellofemoral joint are extension (A), lateral tilt (B), medial spin (the distal patellar pole rotates medially about the anterior-posterior axis) (C), lateral shift (D), distal shift (E), and anterior shift (F).

was sutured to the dissected end of each muscle to prevent the muscle tissue from pulling apart during loading. Compliant steel cables (1.12-mm diameter; Carl Stahl Sava Industries, Riverdale, New Jersey) were sutured to the mesh ends of the muscles and were passed through adjustable pulleys to main-

tain the physiologic line of action of each muscle⁴². Loading was combined for the rectus femoris and vastus intermedius muscles. Patellofemoral movements measured from the markers attached to the cortical screws and the markers on the patellar clamp were compared in six degrees of freedom.

TABLE II Average Absolute Error for in Vitro and in Vivo Validation Experiments

In Vitro Experiments	Mean Difference (Range)
Flexion-extension	1.12° (0°-3.01°)
Medial-lateral tilt	0.97° (0°-3.19°)
Medial-lateral spin	1.11° (0°-2.90°)
Medial-lateral translation (mm)	0.77 (0-1.88)
Proximal-distal translation (mm)	1.01 (0-3.21)
Anterior-posterior translation (mm)	1.04 (0-3.28)
In vivo displacements (mm)	0.97 (0-2.43)

The patellar tracking method was also validated with use of a single subject in vivo. A radiopaque marker was attached to the custom clamp, and sagittal-view fluoroscopy was used to examine the movement of the clamp and the movement of the underlying patella during knee flexion up to approximately 105°. The position of the marker and the most inferior point on the patella were digitized for each frame of the fluoroscopy. For in vivo measurements with use of fluoroscopy, the individual degrees of freedom could not be separated because of the two-dimensional nature of the images. Therefore, general displacements were calculated from the sagittal-plane image.

Differences in patellofemoral kinematics were analyzed with use of two-way analysis of variance (condition $\times$ knee flexion angle) with multiple comparisons. Condition had two levels: patellofemoral pain and control. Knee flexion angle had seven levels: 0°, 15°, 30°, 45°, 60°, 75°, and 90°. Alpha and beta

were preset to 0.05 and 0.20, respectively. If significance was detected, the Tukey honestly significant difference was used to test for differences at specific knee flexion angles. Least-squares linear regression was used to assess the linearity of patellar flexion with respect to knee flexion angle, and analysis of covariance was used to test for differences between regression lines. The groups were compared, with use of the Student *t* test, with respect to subject age, height, and weight.

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Results

During in vitro experiments, the mean absolute error was $<1.2^\circ$ for patellofemoral rotations between cortical screws and the patellar clamp method (Table II) and <1.1 mm for the translational degrees of freedom (Table II) for the first 100° of knee flexion. For in vivo measurements with use of fluoroscopy, the mean absolute difference in displacements between the radiopaque marker and the most inferior point on the patella was <1.0 mm for knee flexion angles from 0° to 90° (Table II). The mean squat depth (and standard deviation) was $104.5^\circ \pm 15.5^\circ$ of knee flexion for healthy subjects and $102.8^\circ \pm 16.5^\circ$ of knee flexion for subjects with patellofemoral pain ($p = 0.465$).

The patellar flexion angle lagged behind the knee flexion angle for both healthy subjects and subjects with patellofemoral pain (Fig. 3). A linear relationship was found between the knee flexion angle and the patellar flexion angle for both subjects with patellofemoral pain ($r^2 = 0.996$) and healthy subjects ($r^2 = 0.999$), and it was possible to calculate a pooled regression equa-

Fig. 3

Patellofemoral extension angle for patients with patellofemoral pain (PFP) and healthy subjects for the first 90° of knee flexion. The error bars indicate the standard deviation.

Fig. 4

Medial spin angle for patients with patellofemoral pain (PFP) and healthy subjects for the first 90° of knee flexion. The error bars indicate the standard deviation. * $p < 0.05$ and ** $p < 0.01$.

tion to describe patellar extension with respect to knee flexion angle for both groups of subjects ($y = -0.159x - 0.124$).

For healthy subjects, the patella showed gradual medial spin to $4.71^\circ \pm 1.17^\circ$ as the knee flexed to 90° . For subjects with patellofemoral pain, the patella showed continuous lateral spin from $0.18^\circ \pm 0.17^\circ$ to $-10.13^\circ \pm 2.24^\circ$ at 90° of knee flexion. This difference was significant ($p < 0.001$) (Fig. 4).

There were no significant differences between healthy subjects and subjects with patellofemoral pain with respect to patellar tilt ($p = 0.092$). For healthy subjects, the patella progressively tilted medially to $-1.78^\circ \pm 0.65^\circ$ as the knee was flexed to 45° , and then it tilted laterally to $2.47^\circ \pm 0.75^\circ$ as knee flexion continued to 90° (Fig. 5). For subjects with patellofemoral pain, the patella gradually tilted medially to $-1.05^\circ \pm 3.53^\circ$ as

Fig. 5

Lateral tilt angle for patients with patellofemoral pain (PFP) and healthy subjects for the first 90° of knee flexion. The error bars indicate the standard deviation.

Fig. 6

Lateral patellar translation for patients with patellofemoral pain (PFP) and healthy subjects for the first 90° of knee flexion. The error bars indicate the standard deviation. * $p < 0.05$.

the knee was flexed to 90°. For subjects with patellofemoral pain, the patella shifted significantly more in the lateral direction than it did in healthy subjects ($p < 0.001$). For healthy subjects, the patella gradually shifted medially starting at 2.80 ± 1.38 mm and shifted to -4.93 ± 3.93 mm as the knee was flexed from 15° to 90° (Fig. 6). For subjects with patellofemoral pain, the patella shifted laterally starting at 1.12 ± 0.50 mm and shifted to 5.05 ± 3.73 mm as the knee was flexed from 0° to 90°.

Discussion

To our knowledge, this study is the first to assess patellofemoral kinematics, in vivo and noninvasively, during full weight-bearing activity in subjects with patellofemoral pain. In the present study, subjects with patellofemoral pain showed significantly more lateral patellar spin and lateral translation than did healthy subjects during squatting. However, the results must be interpreted in light of the limitations. The clinical diagnosis of patellofemoral pain was based on the medical history, physical examination, and the exclusion of other causes of anterior knee pain^{36,43}. Selection bias was limited through the exclusion of other related causes of anterior knee pain and by ensuring that subjects with patellofemoral pain had active pain during testing. However, the current clinical definition of patellofemoral pain syndrome likely encompasses superficially similar symptoms arising from a number of discrete causes⁴⁴. Thus, it is probable that the subjects with patellofemoral pain in the current study had pain arising from various causes.

Tracking the patella in vivo is difficult because the quadriceps tendon and the patella slide beneath the skin during knee movement. Acceptable amounts of error have been reported to range from 0.9° to 2.4° for rotations and from 0.5 to 3.3 mm for translations^{11,19,34,45}. The results from this study showed that, for 90° of knee flexion, the mean absolute error

between the patella and the custom clamp was $<1.2^\circ$ (rotations) and approximately 1.0 mm (translations). Therefore, while error because of skin movement cannot be eliminated, it is possible to perform noninvasive measurements of patellar tracking with a reliability that is sufficient to detect potentially clinically important differences in patellar tracking.

Numerous reports have been published on patellar tracking patterns in vitro^{7,11-15}, in healthy subjects^{2,16-26}, and in subjects with patellofemoral pain²⁷⁻³³. In agreement with previous studies^{15,30}, our investigation found that healthy subjects exhibited minimal medial patellar spin as the knee flexed from full extension to 90°. However, the patellae of subjects with patellofemoral pain showed progressive lateral spin during knee flexion. In healthy subjects, the pattern of a slight lateral shift during initial knee flexion (prior to engagement with the trochlear groove) followed by a continuous medial shift as the knee continued to flex is consistent with previously reported in vivo patterns^{19,20,23,28}. In contrast, in subjects with patellofemoral pain, the patella shifted progressively laterally throughout knee flexion. Increased lateral patellar translation and spin in subjects with patellofemoral pain syndrome, as seen in the present study, suggest the patella is not adequately stabilized during active knee flexion-extension in these individuals. Weakness of the vastus medialis oblique muscle may cause the patella to shift and rotate laterally during knee flexion^{30,43,46}. Although the vastus medialis oblique muscle is commonly implicated, it is only one of the soft-tissue structures potentially involved, and the important factor is the relative contribution of each structure to the balance of forces in the patellofemoral joint. It is equally possible that imbalances in the material properties of the medial compared with the lateral tendons or retinacular structures surrounding the joint contribute to patellar maltracking³³.

Previous work has shown substantial differences in patellofemoral kinematics near full extension²⁸, which have been attributed to the action of the quadriceps muscles prior to engagement of the patella in the trochlear groove^{28,30}. Differences near full extension were not found in the current study probably because of decreased quadriceps contraction during standing with the knee in full extension. However, divergent kinematic trends were seen at higher knee flexion angles, consistent with the widening geometry of the trochlear groove as the knee flexes^{47,48}. Although the current study only assessed patellofemoral kinematics to 90° of knee flexion, the geometry of the trochlear groove suggests that divergent kinematic patterns may continue to diverge as knee flexion deepens further and patellar motion is less constrained.

The abnormal tracking patterns identified in this study may result from medial quadriceps muscle weakness, an imbalance in knee extensor tendon stiffness, or a combination of these factors. However, what initiates the shift from healthy to pathological patellofemoral biomechanics remains unclear. Because patellofemoral pain remains a diagnosis of exclusion, several subgroups (with respect to etiology) may exist within the definition of patellofemoral pain. In vivo and noninvasive evaluation of patellar tracking during functional activities may

provide key information regarding the underlying differences between healthy knees and knees in patients with patellofemoral pain syndrome. The development of a system of quantitative, reliable diagnostic tools for patellofemoral pain could lead to better characterization of patellofemoral pain syndrome and to the identification and definition of subgroups within the definition of patellofemoral pain syndrome. The methods used in the current research form a strong basis for clinical tool development. An ideal patellar tracking system would be easily implemented in a clinical setting and could be used for prospective risk assessment and diagnosis. ■

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