Differences in Patellofemoral Kinematics between Weight-Bearing and Non-Weight-Bearing Conditions in Patients with Patellofemoral Pain

Christine E. Draper,[1] Thor F. Besier,[2] Michael Fredericson,[2] Juan M. Santos,[3] Gary S. Beaupre,[4] Scott L. Delp,[2,5] Garry E. Gold[1]

[1]Department of Radiology, Stanford University, Stanford, California, [2]Department of Orthopedics, Stanford University, Stanford, California, [3]Department of Electrical Engineering, Stanford University, Stanford, California, [4]Rehabilitation R&D Center, VA Palo Alto Health Care System, Palo Alto, California, [5]Department of Bioengineering, Stanford University, Stanford, California

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ABSTRACT: Patellar maltracking is thought to be one source of patellofemoral pain. Measurements of patellar tracking are frequently obtained during non-weight-bearing knee extension; however, pain typically arises during highly loaded activities, such as squatting, stair climbing, and running. It is unclear whether patellofemoral joint kinematics during lightly loaded tasks replicate patellofemoral joint motion during weight-bearing activities. The purpose of this study was to: evaluate differences between upright, weight-bearing and supine, non-weight-bearing joint kinematics in patients with patellofemoral pain; and evaluate whether the kinematics in subjects with maltracking respond differently to weight-bearing than those in nonmaltrackers. We used real-time magnetic resonance imaging to visualize the patellofemoral joint during dynamic knee extension from 30° to 0° of knee flexion during two conditions: upright, weight-bearing and supine, non-weight-bearing. We compared patellofemoral kinematics measured from the images. The patella translated more laterally during the supine task compared to the weight-bearing task for knee flexion angles between 0° and 5° ($p = 0.001$). The kinematics of the maltrackers responded differently to joint loading than those of the non-maltrackers. In subjects with excessive lateral patellar translation, the patella translated more laterally during upright, weight-bearing knee extension for knee flexion angles between 25° and 30° ($p = 0.001$). However, in subjects with normal patellar translation, the patella translated more laterally during supine, non-weight-bearing knee extension near full extension ($p = 0.001$). These results suggest that patellofemoral kinematics measured during supine, unloaded tasks do not accurately represent the joint motion during weight-bearing activities. © 2010 Orthopaedic Research Society. Published by Wiley Periodicals, Inc. J Orthop Res 29:312–317, 2011

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Patellofemoral pain, a common knee disorder, accounts for 25% of all knee injuries seen in some sports medicine clinics.[1] Unfortunately, effective treatment is challenging because the underlying causes of pain are often unclear. Furthermore, multiple biomechanical factors likely contribute to the development of pain.[2] Patellofemoral pain typically arises during activities that place high loads across the joint, such as squatting, ascending/descending stairs, and running. Abnormal tracking of the patella relative to the femur is thought to be related to the development of pain in some subjects.[3]

About 50% of patients with patellofemoral pain are diagnosed with maltracking[4] that is typically characterized by excessive lateral translation of the patella relative to the femur and occurs near full knee extension. Accurate diagnosis is important because the underlying cause of pain may differ between a patient with maltracking compared to one with normal patellofemoral kinematics. Treatments that address the specific nature of a patient's pain may be most effective. For example, Draper et al.[5] reported that patellar-stabilizing braces produce larger changes in joint kinematics in patients with maltracking compared to patients with normal kinematics.

Diagnosis of maltracking is typically performed during a physical exam by observing patellar motion during seated knee flexion/extension.[6] This test does not mimic the highly loaded tasks that elicit pain and may not replicate patellofemoral motion during weight-bearing activities. As a result, patients may be misdiagnosed and prescribed inappropriate treatments based upon non-weight-bearing clinical assessments.

The overall understanding of weight-bearing patellofemoral kinematics is limited. Some studies measured weight-bearing patellofemoral alignment[7,8] and motion[5,9]; however, most have been performed under supine, non-weight-bearing conditions.[10–16] Patellofemoral joint kinematics can change with quadriceps contraction[10] and joint loading.[17–19] One study found increased lateral patellar translation during a seated task compared to a weight-bearing task in patients with patellar subluxation.[18] While these studies provide valuable insight into joint mechanics, it remains unclear whether patellofemoral joint motion measured during dynamic, supine knee flexion/extension accurately reflects kinematics during dynamic, weight-bearing activities. Previous work investigating abnormalities in patellofemoral joint motion among patients with patellofemoral pain found inconsistent results. This may, in part, be due to differences in the applied loads during measurement. Understanding the effects of weight-bearing on patellofemoral kinematics is needed to evaluate the relevance of joint motion measured under unloaded conditions.

We evaluated whether patellofemoral joint kinematics differ between upright, weight-bearing and supine, non-weight-bearing loading conditions in patients with patellofemoral pain. We hypothesized that the patella will translate and tilt more laterally during the non-weight-bearing task. We also hypothesized that

Correspondence to: Christine E. Draper (T: 650-724-5323; F: 650-724-1922; E-mail: cdraper@stanford.edu)

kinematics in patients with patellar maltracking respond differently to weight-bearing than those in patients with normal tracking.

MATERIALS AND METHODS

We examined the patellofemoral joints of 20 subjects (12 M: 29 ± 5 years, 1.81 ± 0.08 m, 76 ± 11 kg; and 8 F: 31 ± 5 years, 1.65 ± 0.04 m, 58 ± 4 kg) diagnosed with patellofemoral pain by a sports medicine physician. Subjects were included if they experienced reproducible anterior knee pain during at least two of the following activities: stair ascent/descent, kneeling, squatting, prolonged sitting, or isometric quadriceps contraction. Subjects were excluded if they met any of the following criteria: knee ligament instability, patellar tendonitis, joint line tenderness or knee effusion, previous knee trauma or surgery, patellar dislocation, or signs of osteoarthritis. In the case of subjects with bilateral pain, the most painful knee at the time of examination was studied. All subjects were between the ages of 20 and 42. The subjects' general pain level and function was 72 ± 13 (a score of 100 indicates no pain) on the anterior knee pain scale.[20] Prior to participation, all subjects were informed about the nature of the study and provided consent according to the University's Institutional Review Board.

Real-time magnetic resonance (MR) images of all subjects' knees were acquired during dynamic, active knee extension in two different loading conditions: upright, weight-bearing and supine, with no application of external joint loads (Fig. 1). Active quadriceps contraction was required for both conditions, resulting in loading of the patellofemoral joint for both tasks. Real-time MRI accurately measures joint motion to within 1.2 mm in a 1.5T MRI scanner and 1.9 mm on a 0.5T open-bore MRI scanner.[21] The difference in measurement accuracy between scanners is a result of the increased field strength of the 1.5T scanner, which was able to acquire higher resolution images due to increased signal-to-noise ratio. Images were acquired using the RTHawk (Heart Vista, Inc., Los Altos, CA) real-time system.[22] A 0.5T GE Signa SP open-MRI scanner was used for weight-bearing imaging; a 1.5T GE Excite HD MRI scanner was used for supine imaging (GE Healthcare, Milwaukee, WI). In the 0.5T open-MRI scanner, a vertical body coil and 5" receive-only surface coil were used with field-of-view: 16 cm $\times$ 16 cm, number of interleaves: 6, pixel size: 1.88 mm, readout time: 16 ms, and slice thickness: 5 mm (full width at half maximum). Each image was acquired in 171 cm (6 images/s). Continuous image reconstruction was performed using a sliding window algorithm,[23] resulting in a reconstructed frame rate of 35 frames/s. A backrest stabilized subjects in the scanner, yet subjects supported 90% of their body weight.[24] In the 1.5T closed-bore MRI scanner, the body coil and a 5" receive-only surface coil were used with field-of-view: 24 cm $\times$ 24 cm, number of interleaves: 70, pixel size: 1.1 mm, readout time: 2.4 ms, and slice thickness: 5 mm. Each image was acquired in 448 ms, and the reconstructed frame rate was 30 frames/s. In both scanners, real-time MR images were acquired as subjects performed continuous knee flexion/extension from 0° to 30° of knee flexion and back at a rate of 6–10°/s. The subjects maintained this movement speed by completing one movement cycle every 10 s. Only movement cycles performed with speeds between 6 and 10°/s were used in analysis. Oblique-axial images through the widest portion of the patella were acquired (Fig. 2). The image plane was continuously translated and rotated to remain at the widest portion of the patella while keeping the posterior femoral condyles in the image. During weight-bearing scanning, the femur rotates in the sagittal plane by about 20° relative to the scan plane and the knee translates relative to the scanner. During image acquisition, the scan plane was translated to keep the patella and posterior femoral condyles in the image. During supine imaging, the femur is fixed relative to the plane. To maintain a consistent plane relative to the weight-bearing images, the plane was manually rotated by 20° relative to the femur in 5° increments during imaging. To account for variations in scan plane orientation, we acquired two knee extension trials for every subject and averaged the measurements. The weight-bearing and supine images of each subject were taken about 1–2 weeks apart.

2D patellofemoral joint kinematics were measured by a single observer identifying bony-landmarks in all images using a semi-automatic tracking algorithm.[5] The landmarks were the most medial and lateral points of the patella, the medial and lateral posterior femoral condyles, and the deepest point in the trochlea. Oblique-axial plane patellar translations and rotations were computed from the landmarks (Fig. 3). Medial/lateral translation was described using the bisect offset index, defined as the percentage of the patella lateral to the midline of the femur.[10,25] Larger values of bisect offset indicate that the patella is more lateral to the femur. The average intra-observer variance of this measurement was 1.7% and 3% based on images from the 1.5T and 0.5T scanners, respectively.[5,21] Medial/lateral rotation was measured using the patellar tilt angle, the angle between the patella and the posterior femoral condyles.[26] Larger values of tilt indicate that the lateral side of the patella is tilted more posteriorly relative to the distal femur. The average intra-observer variance of patellar tilt was found to be 0.4° and 2° based on images from the 1.5T and 0.5T MRI scanners, respectively.[5,21] Accuracy may also be affected by variations in scan plane orientation. Scan plane rotations of 10° will result in differences in bisect offset of 3% and in tilt of 2° in the 0.5T scanner. The kinematics were smoothed with a low-pass filter with a cut-off frequency of 1 Hz.

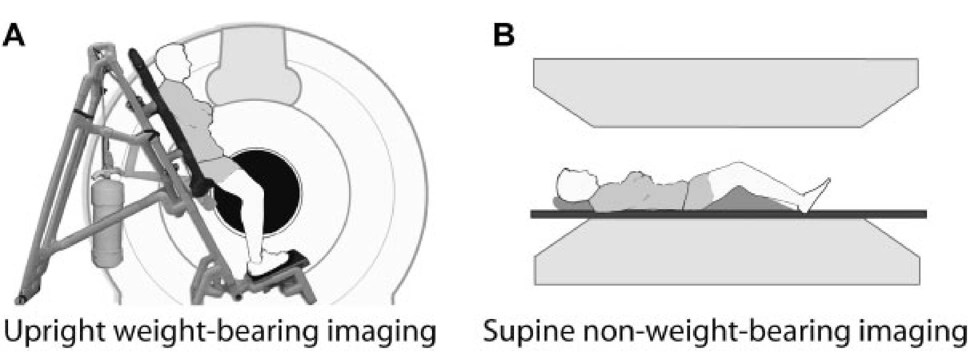

Figure 1. (A) The open-MRI scanner used for upright, weight-bearing imaging. Patients are stabilized by the backrest and support 90% of their bodyweight. (B) Closed-bore scanner used for supine, non-weight-bearing imaging. Patients voluntarily extend their knee against no external resistance.

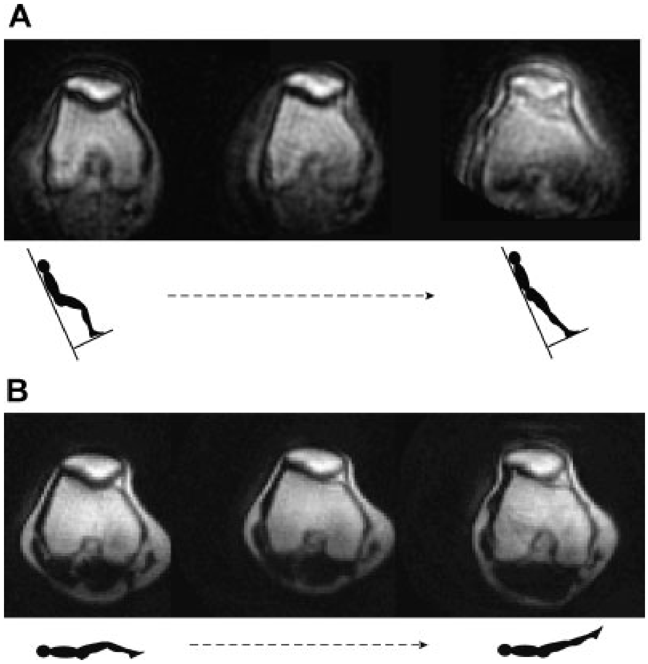

Figure 2. Oblique-axial real-time MR images through the patellofemoral joint during upright, weight-bearing knee extension (A) and supine, non-weight-bearing knee extension (B) in a maltracker from 30° of knee flexion to full extension.

Previous studies revealed that sub-groups of patients with different patellofemoral kinematics exist.[5,16] One study developed a system to classify patients as maltracking based on thresholds derived from weight-bearing kinematics of pain-free controls.[5] We used these thresholds (65% for bisect offset and 9° for tilt)[5] to classify our subjects. Subjects were defined to have excessive bisect offset if their bisect offset at full extension during the weight-bearing task was >65%. Subjects were defined as having excessive patellar tilt if their patellar tilt at extension during the weight-bearing task was >9°. We evaluated the effects of weight-bearing in each group separately.

Differences between the upright, weight-bearing and the supine, non-weight-bearing knee extension conditions were assessed by fitting a linear mixed-effects regression model to the data. This takes into account the fact that the data are paired (each subject performed both activities) and that multiple comparisons were performed (flexion angles from 0° to 30°). To identify the knee flexion angles over which differences in kinematics between movement conditions occur, we separated the data into ranges spanning 10° of knee flexion and fit separate regression models to the curves in each angle range. Differences within each range were reported only if they were significant ($p < 0.05$) and larger than the measurement accuracy of the open-bore scanner images (1.9 mm).

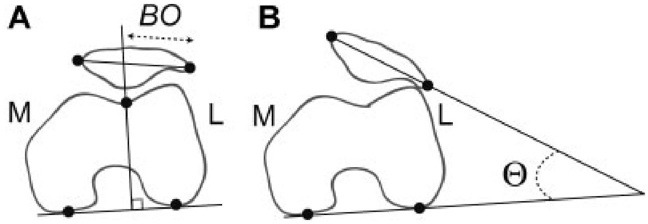

Figure 3. Descriptions of axial-plane patellofemoral kinematic parameters. (A) Bisect offset index (BO), a measure of the percentage of the patellar width lateral (L) to the midline of the femur. (B) Patellar tilt angle (Θ), the angle formed by lines joining the posterior femoral condyles and the maximum width of the patella. The black circles indicate the bony landmarks tracked in the real-time images and used to compute each measurement.

RESULTS

We detected differences in the lateral translation of the patella relative to the femur between upright, weight-bearing and supine, non-weight-bearing knee extension. The bisect offset during the supine task was 5% larger than that during the weight-bearing task for knee flexion angles between 0° and 5° ($p = 0.001$). We did not detect differences in patellar tilt between the weight-bearing and non-weight-bearing conditions.

The effect of weight-bearing on patellofemoral kinematics differed between those with excessive bisect offset and those with normal bisect offset (Fig. 4). Twelve subjects (7 male) had excessive lateral patellar translation, and 8 subjects had normal bisect offset. In subjects with excessive weight-bearing bisect offset, the bisect offset during the upright, weight-bearing task was, on average, 5% greater than that during the supine task for knee flexion angles between 25° and 30° ($p = 0.001$). In subjects with normal weight-bearing translation, the bisect offset during the supine knee extension task was, on average, 7% greater than that during weight-bearing knee extension for knee flexion angles between 0° and 8° ($p = 0.001$).

Thirteen subjects had excessive lateral patellar tilt during weight-bearing (8 male), and seven patients had normal patellar tilt during weight-bearing. Patellar tilt was not affected by loading condition in either population (Fig. 5).

We did not detect differences in supine bisect offset between the males with weight-bearing maltracking and those without weight-bearing maltracking ($p = 0.4$); however, differences existed in supine bisect offset between females with and without weight-bearing maltracking for flexion angles between 0° and 10° ($p = 0.01$).

DISCUSSION

This study examined the joint effects of upright, weight-bearing on patellofemoral kinematics in patients with patellofemoral pain. Patellar translation during supine, non-weight-bearing knee extension differed from translation during upright, weight-bearing knee extension. Furthermore, the effects of weight-bearing on the lateral translation of the patella relative to the femur differed between maltrackers and non-maltrackers. These results provide insight into patellofemoral kinematics and are relevant for the treatment of patellofemoral pain.

To provide patient-specific treatments, accurate detection of maltracking is critical. Weight-bearing kinematics are likely relevant for this patient population because it is during these activities that most patients experience pain. We first tested the hypothesis that patellofemoral motion differs between weight-bearing

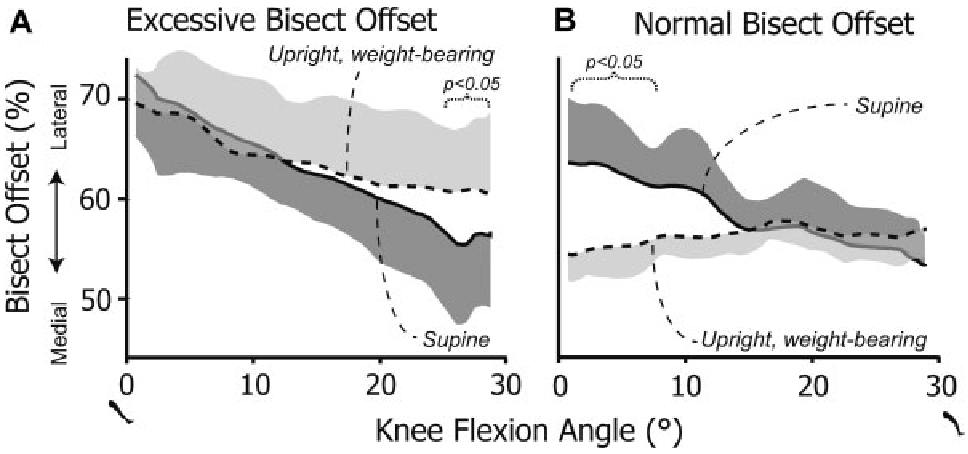

Figure 4. Comparison of bisect offset between upright, weight-bearing (dashed line), and supine, non-weight-bearing (solid line) knee extension. The shaded region = ±1 SD. (A) In subjects with excessive weight-bearing bisect offset, the bisect offset was larger during the weight-bearing task for knee flexion angles between 25° and 30°. (B) In subjects with normal weight-bearing bisect offset, the bisect offset was significantly greater during the supine task near full extension.

and non-weight-bearing conditions in patients with patellofemoral pain. While we did not detect changes in patellar tilt with weight-bearing, our results indicate that lateral patellar translation is decreased during an upright, weight-bearing task compared to a supine, non-weight-bearing movement. As a result, patient evaluation based on supine examination alone may result in a misdiagnosis in some patients.

Patellar motion is largely governed by quadriceps activity near full extension. Hip alignment, quadriceps activation, and quadriceps force all differ between movement conditions and could explain the observed differences in bisect offset. The onset of EMG activity in the four components of the quadriceps is more simultaneous in closed-chain, isometric contraction compared to open-chain isometric contraction.[27] In open-chain contraction, the onset of vastus medialis obliquus is significantly delayed and has a smaller amplitude compared to the other components.[27] This imbalance in quadriceps activation onset could result in a more lateral patellar orientation during the supine, knee extension task (open-chain) compared to the closed-chain squat. Additionally, the relationship between quadriceps force and knee flexion angle differs between activities. During the squat, quadriceps force is highest at deeper angles of knee flexion, whereas during a leg raise, quadriceps force is highest at full extension.[28,29] The differences in quadriceps loads likely have the largest effect on patellar motion near full extension when the patella is not constrained by the trochlea. This may explain the increased lateral patellar translation near full extension during the non-weight-bearing movement.

While it is difficult to compare results due to loading condition, these results are consistent with some previous results investigating patellofemoral motion in patients with patellofemoral pain. Active quadriceps contraction[10] and loaded joint motion[17] have resulted in more lateral patellar translation and tilt compared to passive or unloaded joint motion. These previous investigations did not study weight-bearing loading conditions, but we observed similar trends we detected with increased lateral translation during the supine task only near full extension where the quadriceps force was highest. Conversely, we did not detect changes in patellar tilt with weight-bearing, which may be due to the different loading conditions used in our study compared to those in previous investigations. One study comparing patellofemoral alignment between upright, weight-bearing and seated, loaded conditions in patients with lateral patellar subluxation found that lateral displacement of the patella was increased during the seated task compared to the weight-bearing condition for knee flexion angles between 21° and 27°.[18] This differs from our results and is likely due to the increased

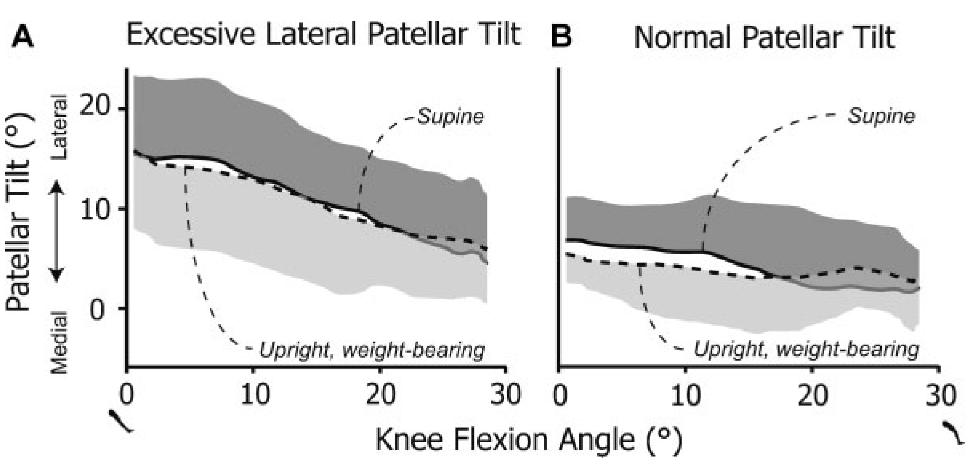

Figure 5. Comparison of patellar tilt between upright, weight-bearing (dashed line), and supine, non-weight-bearing (solid line) knee extension. The shaded region = ±1 SD. (A) Subjects with excessive lateral tilt during weight-bearing. (B) Subjects with normal tilt during weight-bearing. No differences between weight-bearing and supine patellar tilt were detected for either group.

quadriceps contraction required during the loaded, seated task compared to the supine, unloaded task used in the current study.

Our second hypothesis that patellofemoral kinematics respond differently to weight-bearing in maltrackers compared to normal trackers was also supported. The knee flexion angles over which changes between weight-bearing and non-weight-bearing patellar translation occur differed between those with excessive versus normal bisect offset. Non-weight-bearing motion produced more lateral patellar translation than weight-bearing motion in normal trackers, but the opposite was found in patients with excessive lateral patellar translation. Thus, patients with normal patellar translation during functional, weight-bearing tasks may present with excessive lateral patellar translation near terminal extension during a supine, non-weight-bearing clinical assessment task. As a result, they could be prescribed a treatment for maltracking, when in fact, they do not exhibit weight-bearing kinematics any different from controls. Conversely, in subjects with excessive lateral patellar translation, the weight-bearing and non-weight-bearing kinematics were similar near full extension, suggesting that misdiagnoses are less likely in these patients. While previous studies only investigated patients with patellar maltracking, our results suggest that weight-bearing affects patellofemoral kinematics differently in maltrackers compared to nonmaltrackers. Future research investigating the underlying causes of maltracking may help explain why the kinematics of maltrackers and normal trackers respond differently to weight-bearing.

To improve treatment for patellofemoral pain, a more comprehensive understanding of patellofemoral kinematics and patellar maltracking is necessary. Most experiments measuring kinematics have been performed during supine knee flexion,[16] and often under static conditions.[1130] Based on our results, conflicting descriptions of maltracking may be obtained when examining patients under different movement or loading conditions. For example, using the kinematics measured during supine, non-weight-bearing knee extension, we would be unable to distinguish males with weight-bearing maltracking from those with normal weight-bearing tracking whereas a clear difference between groups is found during weight-bearing movement. This suggests that not only is weight-bearing movement necessary to accurately understand patellar motion during painful activities, but it may also more convincingly differentiate maltrackers from nonmaltrackers. Furthermore, this implies that while the measured differences in patellar translation between loading conditions were small (2–3 mm), these motions were large enough to potentially affect the clinical assessment of patients. Based upon our results, measurements of movement abnormalities in patients with patellofemoral pain and evaluations of treatment efficacy should be performed during weight-bearing activities to obtain the most clinically relevant results.

This study provides insight into the effects of weight-bearing on dynamic patellar motion, but it was limited by the measurement accuracy of the real-time images. To achieve a frame rate fast enough for dynamic, weight-bearing imaging, the pixel size of real-time images from the open-bore scanner was set to be 1.88 mm; thus, changes in joint kinematics <1.9 mm were unable to be detected. For instance, small variations in tilt ($<2°$) may have occurred that we were unable to visualize given the image pixel size. Furthermore, we could only acquire a single image slice instead of a volume, preventing us from measuring 3D patellofemoral joint motion. The kinematics in the other image planes are relevant in this patient population.[16] In the future it will be valuable to understand how 3D patellofemoral kinematics are affected by upright, weight-bearing. Also, 3D measurements will be less susceptible to variations in scan plane. Finally, the thresholds used to classify patients were based upon a group of pain-free, female subjects. Gender-specific thresholds are possibly warranted, and some patients might be defined differently if other classifications were used.

This is the first study to quantitatively compare upright, weight-bearing, dynamic patellar motion with supine, nonweight bearing, dynamic patellar motion in patients with patellofemoral pain. Our results establish the importance of assessing patellofemoral kinematics during weight-bearing tasks when studying patients with patellofemoral pain. Furthermore, clinical assessments incorporating weight-bearing joint alignment are needed to improve the diagnosis of maltracking. This remains challenging, as dynamic, weight-bearing MRI is not used in routine clinical practice. One promising alternative is a standing X-ray,[31–33] which could be performed in most clinics. Future research is needed to evaluate the efficacy of this technique in diagnosing and treating patellofemoral pain.

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REFERENCES

1. Devereaux MD, Lachmann SM. 1984. Patello-femoral arthralgia in athletes attending a Sports Injury Clinic. Br J Sports Med 18:18–21.
2. LaBella C. 2004. Patellofemoral pain syndrome: evaluation and treatment. Primary Care 31:977–1003.
3. Fulkerson JP. 2002. Diagnosis and treatment of patients with patellofemoral pain. Am J Sports Med 30:447–456.
4. DeHaven KE, Lintner DM. 1986. Athletic injuries: comparison by age, sport, and gender. Am J Sports Med 14:218–224.
5. Draper CE, Besier TF, Santos JM, et al. 2009. Using real-time MRI to quantify altered joint kinematics in subjects with patellofemoral pain and to evaluate the effects of a patellar brace or sleeve on joint motion. J Orthop Res 27:571–577.

6. Fredericson M, Yoon K. 2006. Physical examination and patellofemoral pain syndrome. Am J Phys Med Rehabil 85: 234–243.
7. Noehren B, Pohl M, Barrance P, Davis I. 2008. Relationship between tibio-femoral and patellofemoral alignment during a single leg squat: a preliminary MRI study. Med Sci Sports Exerc 40:S119.
8. Nha KW, Papannagari R, Gill TJ, et al. 2008. In vivo patellar tracking: clinical motions and patellofemoral indices. J Orthop Res 26:1067–1074.
9. Wilson NA, Press JM, Koh JL, et al. 2009. In vivo noninvasive evaluation of abnormal patellar tracking during squatting in patients with patellofemoral pain. J Bone Joint Surg Am 91:558–566.
10. Brossmann J, Muhle C, Schroder C, et al. 1993. Patellar tracking patterns during active and passive knee extension: evaluation with motion-triggered cine MR imaging. Radiology 187:205–212.
11. MacIntyre NJ, Hill NA, Fellows RA, et al. 2006. Patellofemoral joint kinematics in individuals with and without patellofemoral pain syndrome. J Bone Joint Surg Am 88: 2596–2605.
12. O'Donnell P, Johnstone C, Watson M, et al. 2005. Evaluation of patellar tracking in symptomatic and asymptomatic individuals by magnetic resonance imaging. Skeletal Radiol 34:130–135.
13. Powers CM. 2000. Patellar kinematics, part II: the influence of the depth of the trochlear groove in subjects with and without patellofemoral pain. Phys Ther 80:965–978.
14. Wittstein JR, Bartlett EC, Easterbrook J, Byrd JC. 2006. Magnetic resonance imaging evaluation of patellofemoral malalignment. Arthroscopy 22:643–649.
15. Shellock FG, Mink JH, Deutsch AL, Fox JM. 1989. Patellar tracking abnormalities: clinical experience with kinematic MR imaging in 130 patients. Radiology 172:799–804.
16. Sheehan FT, Derasari A, Fine KM, et al. 2009. Q-angle and J-sign: indicative of maltracking subgroups in patellofemoral pain. Clin Orthop Relat Res 468:266–275.
17. Shellock FG, Mink JH, Deutsch AL, et al. 1993. Patellofemoral joint: identification of abnormalities with active-movement, "unloaded" versus "loaded" kinematic MR imaging techniques. Radiology 188:575–578.
18. Powers CM, Ward SR, Fredericson M, et al. 2003. Patellofemoral kinematics during weight-bearing and non-weight-bearing knee extension in persons with lateral subluxation of the patella: a preliminary study. J Orthop Sports Phys Ther 33:677–685.
19. McWalter EJ, Hunter DJ, Wilson DR. 2010. The effect of load magnitude on three-dimensional patellar kinematics in vivo. J Biomech 43:1890–1897.
20. Kujala UM, Jaakkola LH, Koskinen SK, et al. 1993. Scoring of patellofemoral disorders. Arthroscopy 9:159–163.
21. Draper CE, Santos JM, Kourtis LC, et al. 2008. Feasibility of using real-time MRI to measure joint kinematics in 1.5T and open-bore 0.5T systems. J Magn Reson Imaging 28:158–166.
22. Santos JM, Wright GA, Pauly JM. 2004. Flexible real-time magnetic resonance imaging framework. Conf Proc IEEE Eng Med Biol Soc 2:1048–1051.
23. Riederer SJ, Tasciyan T, Farzaneh F, et al. 1988. MR fluoroscopy: technical feasibility. Magn Reson Med 8:1–15.
24. Besier TF, Draper CE, Gold GE, et al. 2005. Patellofemoral joint contact area increases with knee flexion and weight-bearing. J Orthop Res 23:345–350.
25. Stanford W, Phelan J, Kathol MH, et al. 1988. Patellofemoral joint motion: evaluation by ultrafast computed tomography. Skeletal Radiol 17:487–492.
26. Fulkerson JP, Schutzer SF, Ramsby GR, Bernstein RA. 1987. Computerized tomography of the patellofemoral joint before and after lateral release or realignment. Arthroscopy 3:19–24.
27. Stensdotter AK, Hodges PW, Mellor R, et al. 2003. Quadriceps activation in closed and in open kinetic chain exercise. Med Sci Sports Exerc 35:2043–2047.
28. Cohen ZA, Roglic H, Grelsamer RP, et al. 2001. Patellofemoral stresses during open and closed kinetic chain exercises. An analysis using computer simulation. Am J Sports Med 29: 480–487.
29. Escamilla RF, Fleisig GS, Zheng N, et al. 1998. Biomechanics of the knee during closed kinetic chain and open kinetic chain exercises. Med Sci Sports Exerc 30:556–569.
30. Fellows RA, Hill NA, Gill HS, et al. 2005. Magnetic resonance imaging for in vivo assessment of three-dimensional patellar tracking. J Biomech 38:1643–1652.
31. Ahlback S. 1968. Osteoarthrosis of the knee. A radiographic investigation. Acta Radiol Diagn (Stockh): Suppl 277:7–72.
32. Boegard T, Rudling O, Petersson IF, et al. 1998. Joint-space width in the axial view of the patello-femoral joint. Definitions and comparison with MR imaging. Acta Radiol 39:24–31.
33. Baldini A, Anderson JA, Cerulli-Mariani P, et al. 2007. Patellofemoral evaluation after total knee arthroplasty. Validation of a new weight-bearing axial radiographic view. J Bone Joint Surg Am 89:1810–1817.