Patellofemoral Joint Kinematics: The Circular Path of the Patella around the Trochlear Axis

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ABSTRACT: Differing descriptions of patellar motion relative to the femur have resulted from previous studies. We hypothesized that patellar kinematics would correlate to the trochlear geometry and that differing descriptions could be reconciled by accounting for differing alignments of measurement axes. Seven normal fresh-frozen knees were CT scanned, and their kinematics with quadriceps loading was measured by an optical tracker system. Kinematics was calculated in relation to the femoral epicondylar, anatomic, and mechanical axes. A novel trochlear axis was defined, between the centers of spheres best fitted to the medial and lateral trochlear articular surfaces. The path of the center of the patella was circular and uniplanar (root-mean-square error 0.3 mm) above 16 ± 3° (mean ± SD) knee flexion. In the coronal plane, this circle was aligned 6 ± 2° from the femoral anatomical axis, close to the mechanical axis alignment. It was 91 ± 3° from the epicondylar axis, and 88 ± 3° from the trochlear axis. In the transverse plane it was 91 ± 3° and 88 ± 3° from the epicondylar and trochlear axes, respectively. Manipulation of the data to different axis alignments showed that differing previously published data could be reconciled. The circular path of patellar motion around the trochlea, aligned with the mechanical axis of the leg, is easily visualized and understood.


Keywords: patellofemoral joint; kinematics; patellar tracking; trochlea; femur axis

Patellar maltracking is a common clinical problem that can be difficult to diagnose because of its many causes and because clinical features can be subtle.1,2 Axial radiography requires accurate positioning.3,4 Computed tomography (CT) and magnetic resonance imaging are better at visualizing the joint near full extension,5–7 a critical point in the range of motion where the patella enters the trochlear groove.

Many studies have described the motion of the patella relative to the femur, with differing results;8 the different methods and coordinate systems used make comparison difficult. Imaging studies often describe patellar motion relative to the femoral groove3,5–7,9 because it is relatively straightforward to identify the groove and measure this on cross-sectional 2D images. However, with 3D tracking studies, difficulties exist in defining the axis or plane of the trochlear groove, as it is curved and different definitions have been used.10 The behavior of the patellofemoral joint depends on articular geometry,11 although retinacular and muscle tensions also affect kinematics.12,13 Alteration of the alignment of the measurement axes leads to differing descriptions of patellar motion.10,14 A fundamental weakness of prior work has been the lack of 3D definition of the articular geometry or alignment of the coordinate systems, which is essential to understand how the kinematics of the patella relate to the shape and alignment of the knee.

Our primary aim was to measure patellar kinematics in normal knees and to relate the path of motion to models of the 3D geometry of the distal femur and the various femoral axes used by surgeons during knee arthroplasty. In the coronal plane, this includes the anatomical axis of the diaphysis, which is followed by intramedullary alignment rods, and the mechanical axis passing to the center of the femoral head used by navigation systems. In the transverse plane, it includes the epicondylar and posterior condylar axes and Whiteside’s line, which define internal–external rotation. We hypothesized that patellar motion could be related to the geometry of the trochlear articular surfaces, and that differing motion patterns reported in the literature could be reconciled by reference to their differing definitions of measurement axis alignment.

MATERIALS AND METHODS

Seven fresh-frozen cadaveric knees with no history of knee surgery or disease were used (mean age 65, range 41–83 years) obtained from the International Institute for the Advancement of Medicine ( Jessup, PA), who undertook screening and consent for the use of the knees for research. Ethical permission for the study was obtained from the Riverside Research Ethics Committee. The knees were stored at −20°C and thawed for a day prior to experimentation.

The skin and subcutaneous tissue were removed, whereas the deep fascia, retinacula, and iliotibial band (ITB) were preserved. The femur and tibia were cut about 20 and 15 cm above and below the knee, respectively. The fibular head was transfixed to theibia by two bone screws to maintain its anatomical position, and then the distal part was excised. An intramedullary sleeve and a rod were cemented into the femur andibia, respectively. The quadriceps was separated into six components: rectus femoris (RF), vastus intermedius (VI), vastus lateralis longus (VLL), vastus lateralis obliquus (VLO), vastus medialis longus (VML), and vastus medialis obliquus (VMO). Four fiducial marker screws were placed into each of the femur, patella, andibia. The knees were imaged by CT.

The knee was mounted in a kinematics rig by sliding the femoral sleeve onto a fixed rod. Femoral rotation was adjusted and fixed with the most posterior parts of the condyles horizontal in a distal–proximal view (Fig. 1). The components of the quadriceps and the ITB were each loaded with hanging
weights using cables and pulleys with a total of 175 N\textsuperscript{12,15} and 30 N\textsuperscript{16,17} respectively, according to the directions and physiological cross-sectional areas of the muscles\textsuperscript{18} relative to the femoral axis. The direction of pull of the ITB was 0° lateral and 6° posterior.\textsuperscript{16}

The kinematics of the patellofemoral and tibiofemoral joints were measured dynamically. A Polaris optical tracking system (Northern Digital Incorporated, Waterloo, Canada) was used with active optical trackers (Traxtal Technologies, Toronto, Canada). One tracker was secured to each of the femur, tibia and patella (Fig. 1). With the knee immobilized, a Traxtal probe was used to digitize the heads of the fiducial screws on the three bones. The knee was moved into two cycles of flexion-extension, against the extending moment of the quadriceps tension, using a rod within a freely rotating PTFE low-friction sleeve held transversely against the anterior surface of the tibial intramedullary rod, allowing the tibia to rotate freely during flexion. Patellar kinematics was calculated as the mean of the two knee extension motions. The Traxtal tracker used for the patella was rotated by a known angle; the accuracy and precision both averaged 0.03°. It was also displaced a known amount of 3 and 6 mm, 24 times each, and the average accuracy was 0.04 mm with a precision of 0.03 mm.

Custom software was used to reconstruct 3D images and determine the coordinates of the fiducial markers and landmarks used for the construction of the femoral, tibial, and patellar coordinate systems. For each knee, the femoral condylar axis was defined as a line connecting the centers of spheres fitted to the posterior aspects of the femoral condyles. The anatomic femoral axis (line passing along the center of the femoral shaft) was used to define flexion. The condylar axis was used to align the 3D model in the transverse and coronal planes. Spheres could also be fitted to the medial and lateral articular facets of the trochlea with a low root-mean-square (RMS) error (0.3 mm). The trochlear axis was defined as a line connecting the centers of these spheres, similar to the condylar axis. The epicondylar axis was defined as a line from the medial epicondylar sulcus to the most prominent point of the lateral epicondyle. The proximal point of the trochlear groove was also determined (Fig. 2).

Rotation of the patella in its transverse plane (patellar tilt) was defined from the flat central portion of its anterior surface. Rotation in the coronal plane was defined using the median ridge of the patella (Fig. 3). After aligning the patella, the transverse image at the level of the proximal–distal midpoint of the median ridge was used to define the center of the patella as the midpoint of the greatest AP thickness in that image. Thus, a coordinate system was constructed with its origin at the center of the patella, aligned to the central portion of the anterior surface in the transverse plane and the median ridge in the sagittal and coronal planes (Fig. 3). The proximal–distal midpoint and the distal end of the median ridge were also determined.
For the tibia, the center of the medullary canal was located at two levels in the CT scan, and a line joining these points defined the tibial anatomic axis. The tibial coordinate system was based on this axis and the mediolateral axis of the tibia, which was defined as a line joining the centers of circles fitted to the medial and lateral tibia plateaux.\textsuperscript{19}

These CT-based landmarks and coordinate systems were transformed to the Polaris coordinate system by coregistration of the relevant sets of fiducial screws. The CT position of a fiducial screw transformed to the Polaris position by coregistration of the three other screws was compared to the actual position of that screw as determined by the Traxtal stylus. This gave a mean error of registration of 1.2 \pm 0.5 mm.

The raw kinematic data was processed with Visual3D (C-Motion Inc., Germantown, MD). The points that defined the local coordinate system of each bone were used to create bone segments. The motion of each segment was then linked to the motion of the tracker attached to that bone. During the motion cycle, the transformations required to relate the patella and the tibia to the femur were calculated by a series of rotations and translations in three orthogonal planes, equivalent to the joint coordinate system described previously.\textsuperscript{20}

Patellar motion was described using a standard convention.\textsuperscript{10} Patellar lateral tilt was defined as a rotation about the longitudinal axis of the patella, positive values indicating that the lateral patella approached the femur. Patellar lateral rotation was analogous to abduction, a rotation of the patella in its coronal plane. Lateral translation was defined along an axis parallel to the condylar axis in the transverse plane and perpendicular to the anatomic axis of the femur in the coronal plane.

To determine the effect of the coordinate system when measuring patellar kinematics, three more coordinate systems were used such that the femoral transverse axis was aligned to the distal surfaces of the femoral condyles and to the condylar and trochlear axes in the coronal plane. The patellar kinematics was recalculated for each of these sets of femoral axes.

The distances from the midpoint and the distal end of the patellar median ridge to the proximal entrance of the femoral trochlear groove were calculated during knee motion. These values were used to determine the flexion angles when the distal end and the midpoint of the patellar median ridge entered the trochlear groove.

In addition to computing patellar kinematics in relation to the femur, the movement of the center of the patella in space was exported as a stream of coordinate points. Using the reverse matrix, these coordinates were transformed to the CT coordinate system, and a circle was fitted to them using a least-square-fitting algorithm\textsuperscript{21} in Microsoft Excel. The coordinates of the center and the radius of the fitted circle and the RMS errors from this circle were calculated, both radially and perpendicular to the plane of the circle. Plotting the deviations against the tibiofemoral flexion angle gave an indication of the angle of knee flexion where the center of the patella deviated from the circle. The angles between the plane fitted to the circular path of the center of the patella and various axes in the distal femur were measured in the coronal and transverse planes.

RESULTS

Relative to the position in the extended knee, the patella translated 2.2 \pm 2.9 mm medial at 20° knee flexion, then moved to 1.3 \pm 1.7 mm lateral at 100° knee flexion (Fig. 4). The patella was tilted laterally by 6.9 \pm 3.4° relative to the femoral condylar axis in the extended knee. This increased to 13 \pm 3° at 100° knee flexion. Patellar flexion increased and the lateral rotation decreased with knee flexion. The knee flexion angles at which the distal end and then the midpoint of the patellar median ridge crossed the proximal limit of the femoral trochlear groove were 6 \pm 2.8° and 22 \pm 5.3°, respectively.

When the long axis was aligned close to the mechanical axis of the femur, defined as passing from the midpoint of the condylar axis at the knee to the center of the head of the femur, the patellar-medial–lateral translation was reduced to an initial medial translation in early knee flexion, followed by almost zero translation thereafter (Fig. 5).

The path of the center of the patella was circular (RMS error 0.3 mm) above 16 \pm 3.6° of knee flexion. The radius of the circle fitted to the center of the patella was 44 \pm 2.9 mm.

The plane of the circle fitted to the path of the center of the patella was oriented 6.4 \pm 1.6° from the femoral anatomic axis in the coronal plane, so that it was close to the femoral mechanical axis (Fig. 6). The angles between this circle and the epicondylar, condylar, and trochlear axes in the coronal plane were 91.2 \pm 3.4°, 88.9 \pm 2.4°, and 88.3 \pm 3°, respectively. The angles in the transverse plane were 92.3 \pm 4.6°, 88.8 \pm 3.8°, and 89.4 \pm 3.2°, respectively. Angles >90° mean that the circle was abducted and internally rotated in the coronal and transverse planes, respectively.

A plane could also be fitted to the path of the center of the patella near extension before it became circular. This plane was oriented 17.5 \pm 8° from the circle in the coronal view: the patella moved 5.0 \pm 2.0 mm lateral to the circle in terminal knee extension. This path occurred from 0 to 16 \pm 3.6° knee flexion, after which the patella followed the circular path (Fig. 6).

DISCUSSION

For most of the arc of knee flexion, the patella followed a simple circular path around the trochlea. This path was perpendicular to a newly defined trochlear axis, which joined the centers of spheres fitted to the articular surfaces of the medial and lateral facets of the trochlea. In the coronal plane, the path of motion of the patella was aligned to the mechanical axis of the femur, toward the center of the hip. The finding of this simple and intuitive relationship supports the initial hypothesis that the motion of the patella would follow the articular geometry of the trochlea. The patella was pulled proximally and laterally in terminal knee extension, lateral to the circular path, as it disengaged from the trochlea. Conversely, in early knee flexion, the patella translated medially, reflecting its initial contact against the prominent proximal part of the lateral rim of the trochlea. The patella followed the circular path of motion beyond 16° knee flexion, reflecting its engagement with the trochlea; the distal end of the median ridge of the patella entered the groove at 6° knee flexion, and the midpoint at 22°.
When the patellar motion was measured in relation to the femoral anatomic axis, it had an initial medial translation, followed by a progressive lateral translation with knee flexion. When this motion was recalculated in relation to the condylar, epicondylar, and trochlear axes, the initial medial translation was followed by a constant medial–lateral position. These axes were approximately 6° abducted from being perpendicular to the femoral

Figure 4. (a) Lateral rotation (°), (b) lateral tilt (°), (c) lateral translation (mm), and (d) flexion (°) of the patella versus knee flexion (°) in the seven experimental knees.

Figure 5. (a–d) Patellar medial–lateral translation (mm) versus knee flexion (°) after aligning the femur to the transcondylar (CD), trochlear (EF), distal femoral surfaces (GH), and femoral anatomic (AB) axes, respectively. (e) The femur is aligned to the femoral anatomic axis. Positive values indicate lateral translation (mean + SD, n = 7).
anatomic axis, so the circular path of motion of the patella and the trochlea itself were aligned parallel to the mechanical axis in the coronal plane. The differing results in the literature may often be reconciled by reorientation to the different axes that have been defined, as we had hypothesized.

This study has limitations. As with most other in vitro studies, it used knees obtained from the elderly. Although care was taken to distribute the tension among the individual heads of the quadriceps physiologically, their relative contributions vary from knee to knee, and the overall tension in the quadriceps was limited by tearing the muscle fibers in these elderly specimens. This study simulated non-weight bearing extension of the knee. A similar pattern of patellar translation was reported in vivo during non-weight bearing knee motion. However, although a similar pattern of patellar tracking was found in weight-bearing activity in vivo, the kinematics may be influenced by the distal ground contact. For example, tibial rotation has an influence on patellar kinematics. A further limitation was that patellar kinematics could not be measured in deep knee flexion due to the design of the test rig. We speculate that the patella might move away from the circular pathway in deep flexion, when it moves from the trochlea and onto the femoral condyles.

This study defined and accurately identified the center of the patella after the orientation of the patellar coordinate system had been visualized on CT scans. The axes were oriented to the flat anterior surface because that would not be affected by arthritic changes when degenerated joints are studied. For the proximal–distal and medial–lateral position, the center of the patella was at the midpoint of the median ridge. This is a reasonable location for the definition of the center because tilting of the patella is likely to be related to this ridge. At this level the midpoint of the thickness of the patella was selected as its center. Previous studies used a point 10 mm deep from the center of the anterior surface of the patella as the datum. Our 3D analysis allowed more rigorous and automatic definition of axes than is possible via planar imaging or surgical identification and palpation; this can lead to large errors even with experienced surgeons.

When the anatomical axis of the femur was used to align the coordinates, an initial medial translation occurred and then a lateral translation. A similar pattern of patellar translation was shown in previous in vitro studies. However, other studies described an initial medial translation without a subsequent lateral translation. This pattern was found in relation to the transcondylar axis in this study, in agreement with Blankevoort et al. Comparing these with the uniplanar and circular path of the center of the patella, the orientation of the femoral coordinate system clearly affects the description of the patellar medial–lateral translation. Our study shows the effect of using different coordinate systems on reporting the patellar translation (Fig. 5). Choosing a femoral reference that is more in line with the plane of the circular path of motion and the trochlear groove in the coronal plane diminished the reported subsequent lateral patellar translation. Once the frame of reference had been aligned to the trochlear axis, medial–lateral translation of the patella was minimal.

The circular path and deviations from the circle complement the information provided by the more standard descriptions of patellar tracking and provides a clear datum when investigating the kinematic effect of a surgical intervention. A prosthesis that is designed to replace the native knee should mimic this aspect of patellar tracking, but several factors may affect this. First, the engagement of the patella into the trochlea may occur at a different flexion angle due to a change in the proximal–distal level of the prosthesis, patellar height, or length of the anterior flange. Second, the circularity of the patellar path may be altered by the choice of the sagittal geometry of the anterior–distal
aspect of the femoral component. Similarly, overstuffing or understuffing the joint will affect the radius of the circle. A change observed in the pattern of patellar translation can be further interpreted by relating it to any change in the position or orientation of the circle. This may help determine how much the abnormal motion is due to implant positioning versus implant design.

Past articles looked at patellar motion using axes that were not aligned to the plane of patellar motion, leading to complex kinematic descriptions. Our study makes it easier for surgeons to visualize the motion by describing it as a simple uniplanar circle aligned with the mechanical axis in the coronal plane. Knowing the relationships between the different femoral axes, differing published results can be reconciled. In particular, we have shown that the patella moved in a circle around a newly defined trochlear axis that was close to parallel to the femoral epicondylar and condylar axes. This knowledge allows maltracking to be identified if 3D analysis is available, allows the correct alignment to be set up during arthroplasty even if parts of the geometry have been eroded, and supports implant design and alignment instruments.

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