CLINICAL ORTHOPAEDICS AND RELATED RESEARCH
Number 414, pp. 266–275

Patellar Tracking During Simulated Quadriceps Contraction

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The current study compared patella tracking during simulated concentric and eccentric quadriceps contractions in 12 knees from cadavers using a three-dimensional electromagnetic tracking system. The patella shifted (translated) and tilted medially during approximately the initial 22° tibiofemoral flexion. The patella then shifted and tilted laterally for the remaining arc of tibiofemoral flexion (90°). At 90° tibiofemoral flexion, the patella had an orientation of lateral patella shift and lateral patella tilt. Patella shift was significantly more lateral between 40° and 70° tibiofemoral flexion during concentric quadriceps action than during eccentric contraction. Patella tilt was significantly more lateral between 45° and 55° tibiofemoral flexion during concentric quadriceps contraction than during eccentric action. No other significant differences were seen between the quadriceps contraction conditions. The current study supports the hypothesis that patellar instability is most likely a result of various anatomic and physiologic factors causing a failure of the extensor mechanism to deliver the patella into the femoral sulcus and that a patellar dislocation rarely would occur in a normal knee.

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This investigation was done at the Department of Orthopaedic Surgery, Tulane University School of Medicine, New Orleans, LA.

Dr. Brunet received a research grant from Healthsouth Corporation in support of this study.

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Received: April 17, 2002.

Revised: October 4, 2002; November 7, 2002.

Accepted: November 14, 2002.

DOI: 10.1097/01.blo.0000079266.91782.11

One of the most common and difficult clinical problems in orthopaedic practice is the differential diagnosis of anterior knee pain. A large proportion of anterior knee pain is attributed to abnormal patellofemoral mechanics.[10,16,38,45] Although static patellar malalignment can be identified through various imaging studies, dynamic patellar tracking abnormalities are much more difficult to identify. As the patella glides over the femur during tibiofemoral motion, it simultaneously rotates about its own three anatomic axes, which introduces difficulty when attempting to describe patella tracking accurately in dynamic studies.[14]

Many terms have been proposed to describe patellar kinematics, but no common definitions have evolved. Descriptions of patellar motion depend explicitly on the conditions under which measurements are collected. Various authors have described patellar motion relative to either the mechanical or the anatomic axes of the knee or the patella.[21,24,27,30] Others have measured and described in vivo or in vitro patellar motion relative to the femur during tibiofemoral extension while using various quadriceps loads.[1,8,14,17,21,22,24,25,27,30,33,40,43,46,47] To date, no standard methodology for measuring patellar motion has been adopted.

Electromagnetic tracking,[19,21,22] magnetic resonance imaging (MRI),[5,32,42] radiographic techniques,[43,46,47] orthogonal grids,[33] dye contact techniques,[17] mechanical devices,[30] and cinematography[24] have been used to track patellofemoral motion in two or three dimensions. Most patella tracking studies have been static analyses in which patella position is recorded at specific intervals of knee flexion with the knee held in a stationary position as data are recorded, either with or without isometric quadriceps action.[1,15,30,33,42,43,46,47] Newer technologies allow dynamic three-dimensional studies that provide more information than simple two-dimensional or static measurements. Dynamic studies of patella tracking usually include concentric (muscle shortening) quadriceps action.[21,32,35,39] Only one previous study described patella tracking during eccentric (muscle lengthening) quadriceps action.[41] To the best of the authors' knowledge, no previous study has been done which compares patella tracking during concentric quadriceps action with patella tracking during eccentric quadriceps action.

In the current study, multiple normal knee specimens from cadavers were used to dynamically track the patella in vitro. The purpose of the current study was to compare the three-dimensional motion of the patella under simulated concentric quadriceps action with the motion of the patella under simulated eccentric quadriceps action.

MATERIALS AND METHODS

Twelve fresh frozen lower extremities from six male and six female cadavers were used in the current study. Four of the extremities from female cadavers and two of the extremities from male cadavers were paired specimens. Each knee was screened radiographically with anteroposterior (AP) and lateral radiographs to rule out evidence of any previous knee surgery, osteoarthritis, or apparent joint deformities. None of the specimens had previous surgery, substantial osteoarthritis, joint deformity, patella alta, or patella baja. None of the specimens had any gross radiographic evidence of trochlear dysplasia or patella malalignment, but no precise measurements were made.

Each lower limb was transected at midfemur and all skin and subcutaneous tissue were removed from midfemur to midcalf. The femur was clamped rigidly in a horizontal position to a test frame, rendering it motionless relative to the frame (Fig 1). The thigh musculature was stripped from the tendons and a nylon cable was sutured to the quadriceps central tendon to approximate the physiologic resultant vector of the quadriceps.[17,30] This arrangement simulates quadriceps activity in the normal knee, because the vastus lateralis and vastus medialis (including the obliquus) have simultaneous and equivalent electromyographic activity in the normal knee.[23,34,44,48] The net effect of this simultaneous and equivalent activity of the respective vastii is the resultant vector reproduced by the nylon cable in the current study. This approach has been used in similar in vitro models to simulate normal patellar movement.[30]

The nylon cable attached to the quadriceps was powered by a low-speed reversible electric motor that simulated the physiologic action of the quadriceps and moved the tibiofemoral joint at a rate of 20° per second. Concentric, or muscle shortening, quadriceps contraction was simulated by the electric motor exerting enough force through the cable to move the knee from 90° flexion to 0° flexion. Eccentric, or muscle lengthening, quadriceps contraction was simulated by reversing the electric motor to allow the knee to move from 0° to 90° flexion.

The position and orientation of the patella and tibia relative to the stationary femur were measured by an electromagnetic tracking system (3Space Tracker™ Systems, Polhemus, Colchester, VT). This device has been used in previous studies of in vitro patella tracking.[8,21,35] It showed an error less than 2% (< 0.9 mm position error or 0.3° rotation error) in conditions similar to that of the current study.[4,11,29] The electromagnetic tracking system consists of a signal source unit, which remains stationary, and two sensor units, which move with the

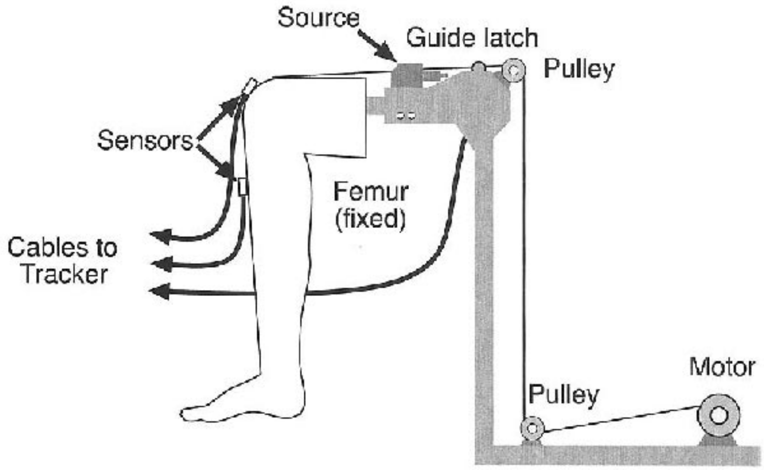

Fig 1. This schematic representation shows the electromagnetic tracking system and testing apparatus with sensors free to move in six-degrees-of-freedom relative to the source.

knee. A low-frequency electromagnetic field is emitted by the source unit to establish a static electromagnetic reference frame about the knee. The sensor units detect the intensity and orientation of the electromagnetic reference frame as they move through it. This system configuration acquires data at a rate of 12 samples per second (Fig 1).

A system electronics unit records the outgoing (source unit) signal and the incoming (sensor units) data. Using the appropriate software, the system electronics unit compares the source signal with the sensor data in three dimensions (six-degrees-of-freedom) and computes the motions of the sensor units (rotations about the X, Y, and Z axes of the patella) and orientations of the sensor units (azimuth, elevation, and roll) relative to the source signal unit's static reference frame. The software transforms the three-dimensional data into anatomic coordinates that correspond to the three patella axes. Mathematic transformation of three-dimensional motion data into anatomic coordinates has been described in detail.[7,19,21] This transformation provides a description of patella tracking as it moves in space and changes its orientation during tibiofemoral motion.

The signal source unit was secured to the test frame in parallel to the fixed femoral shaft, thereby providing a fixed reference against which to compare the sensor unit data. The first sensor unit was fixed to the central aspect of the anterior surface of the patella using small nylon screws. The first sensor unit provided information about the position and orientation of the patella. The second sensor unit was fixed rigidly with nylon screws to the medial aspect of the proximal tibia. The second sensor unit provided information about the position and orientation of the tibia.

Definitions of patella tracking and orientation and the anatomic patella axes are shown in Figure 2. Patella shift was defined as medial or lateral patella translation that occurred along the Z axis of the patella. Patella tilt was defined as the elevation of the medial or lateral patellar pole, rotating about the Y axis of the patella. Medial patella tilt occurs when the anterior surface of the patella is oriented toward the medial aspect of the knee. Patella flexion was defined as anterior movement of the superior patellar pole, rotating about the Z axis of the patella. Patella rotation was defined as the medial or lateral movement of the superior patellar pole about the center of the patella, rotating about the X axis of the patella. All patella tracking parameters and orientations are described from its neutral reference point with the tibiofemoral joint in full extension (0° flexion). These definitions of patella tracking are similar to the conventions used by several previous investigators.[20,21,33]

Each knee specimen was flexed and extended for three cycles before tracking to condition the soft tissues of the joint. After conditioning, the knees were flexed and extended for five cycles during data collection, providing 60 sets of data. Patella tracking was analyzed separately during the tibiofemoral

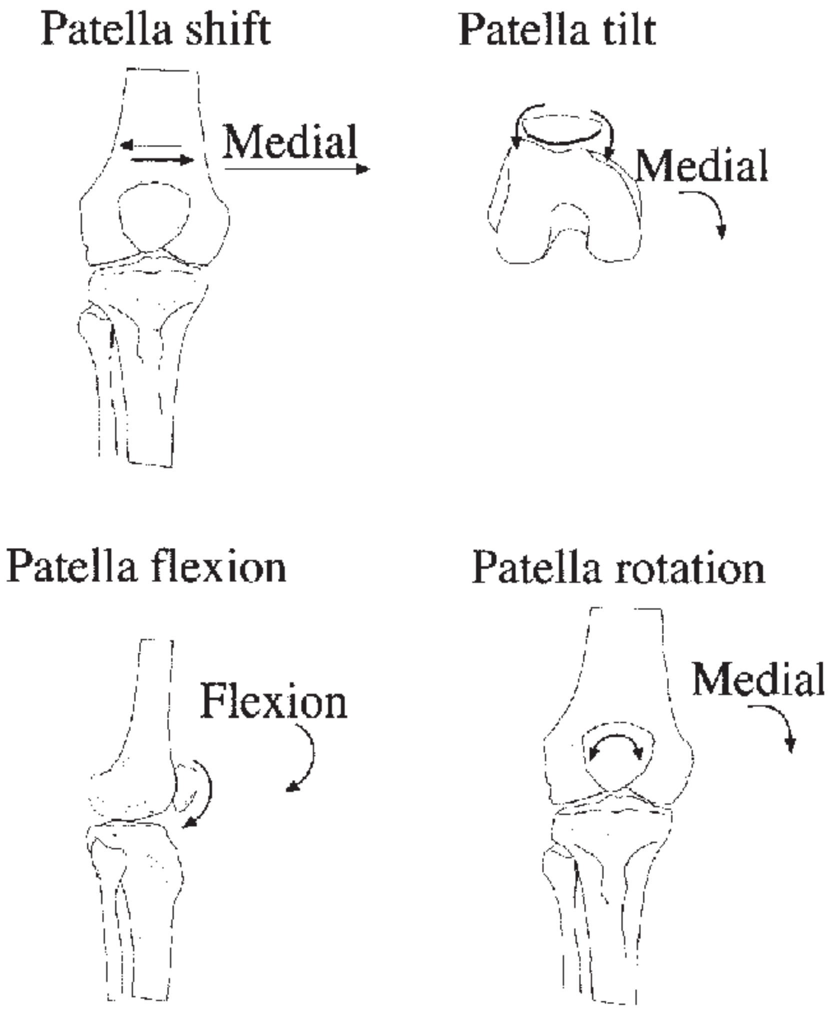

Fig 2. These schematic illustrations define the patella axes and patella tracking parameters used in the current study.

flexion and tibiofemoral extension phases of each cycle. Patella tracking during tibiofemoral extension (simulated concentric quadriceps contraction) was compared with patella tracking during tibiofemoral flexion (simulated eccentric quadriceps contraction). Patella shift, tilt, flexion, and rotation were reported with the concurrent degree of tibiofemoral flexion that was present.

The data for patella shift, patella tilt, patella flexion, and patella rotation for all 12 knees were fit to ordinary least square linear regression equations (TableCurve™, Jandel Scientific, San Rafael, CA). The linear regression equations with the highest r^2 values, which therefore best fit the data, provided the average values (± standard errors) for each patella tracking parameter across the range of tibiofemoral motion. The patella tracking parameters (shift, tilt, flexion, rotation) during concentric quadriceps action was compared with the respective patella tracking parameter during eccentric quadriceps action at every 5° tibiofemoral range of motion (ROM) using Student's t tests. A probability value of 0.05 or less was interpreted as statistically significant.

RESULTS

Patella tracking during eccentric quadriceps action is described and compared with patella tracking during concentric quadriceps action. Patterns of patella shift, patella tilt, and patella flexion were consistent across the 12 knee specimens. Patella rotation did not present a consistent pattern across knee specimens. The patella tracking patterns during concentric quadriceps action were similar, but not identical, to those during eccentric quadriceps action. During eccentric action, the patella shifted and tilted medially from 0° to approximately 20° tibiofemoral flexion. From 20° to 90° tibiofemoral flexion the patella shifted and tilted laterally during eccentric action.

An initial medial shift of the patella occurred at tibiofemoral flexion angles less than 20°, followed by an overall net lateral shift as the tibiofemoral angle increased (Fig 3). The maximum medial patella shift position (2.1 ± 0.4 mm) occurred at 22° ± 1.5° tibiofemoral flexion. The maximum lateral shift position (8.0 ± 1.2 mm) occurred at 90° tibiofemoral flexion. During concentric quadriceps action at tibiofemoral angles between 40° and 70°, patella shift was significantly ($p < 0.05$) more lateral (1.2 ± 0.1 mm) than during eccentric quadriceps action in that range.

An initial medial patella tilt was observed at flexion angles less than 20° followed by a lateral patella tilt as tibiofemoral flexion angle increased (Fig 4). The maximum medial patella tilt position (1.5° ± 0.4°) occurred at 23.3° ± 1.7° tibiofemoral flexion. The maximum lateral patella tilt position (9.5° ± 1.0°) occurred at 90° tibiofemoral flexion. During concentric quadriceps action at tibiofemoral angles between 45° and 55°, patella tilt was significantly ($p < 0.05$) more medial (0.7° ± 0.1°) than during eccentric quadriceps action in that range.

The patella flexion angle lagged the tibiofemoral flexion angle in a linear manner (Fig 5). Patella flexion increased an average of 0.75° ± 0.01° for every degree of tibiofemoral flexion. At 20° tibiofemoral flexion, the degrees

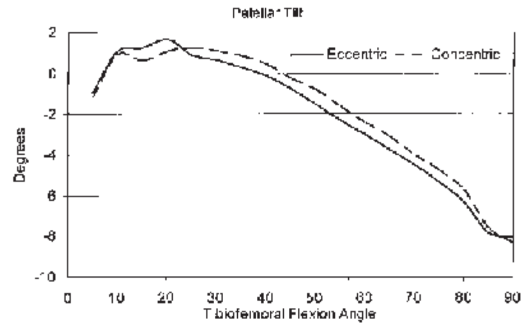

Fig 4. This graph shows the average patellar tilt progressing from medial (positive) to lateral (negative) with increasing tibiofemoral angle.

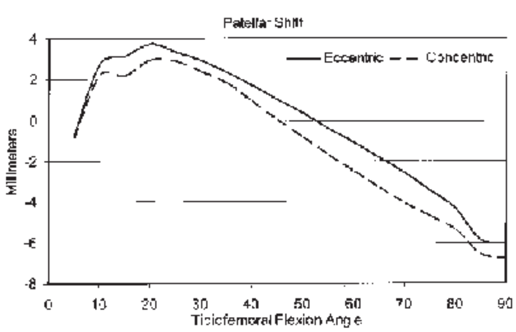

Fig 3. A graph shows the average patellar shift progressing from medial (positive millimeters) to lateral (negative) with increasing tibiofemoral angle.

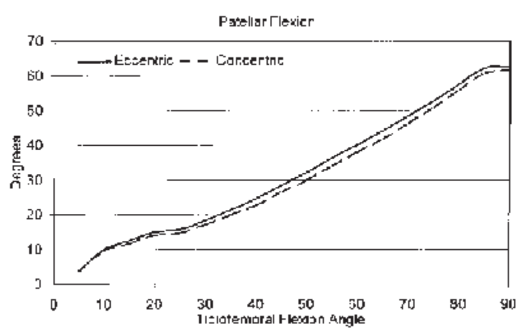

Fig 5. A graph shows the average patellar flexion increasing as tibiofemoral angle increases.

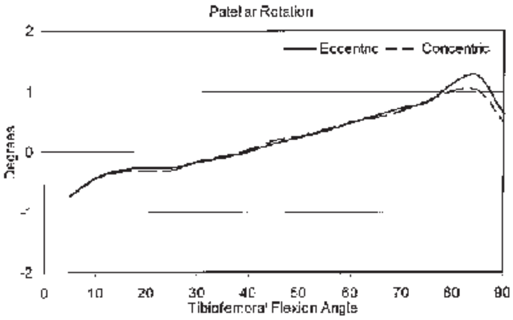

Fig 6. This graph shows the average patellar rotation medially (positive) with increasing tibiofemoral angle.

of patella flexion per degree of tibiofemoral flexion increased slightly. No significant differences in patella flexion patterns were seen between eccentric quadriceps action and concentric quadriceps action.

Patella rotation patterns were not consistent across specimens. The superior role of the patella rotated medially (3.4° ± 0.8°) between 45° and 90° tibiofemoral flexion in nine specimens, rotated laterally (1.9° ± 0.3°) between 0° and 90° tibiofemoral flexion in two specimens, and produced negligible net rotation in one specimen. Six of the 12 specimens had less than 1° terminal lateral rotation between 85° and 90° tibiofemoral flexion. No significant differences in patella rotation patterns were seen between eccentric quadriceps action and concentric quadriceps action (Fig 6).

DISCUSSION

The current study measured in vitro patella tracking through six-degrees-of-freedom during tibiofemoral motion under simulated quadriceps activity. The average net patella tracking during eccentric quadriceps action (as the tibiofemoral joint moved from 0° to 90°) was lateral patella shift, lateral patella tilt, and patella flexion. Patella rotation patterns were inconsistent.

Differences in patella shift and patella tilt between concentric quadriceps action and eccentric quadriceps action occurred only in the middle of the tibiofemoral ROM. During concentric quadriceps action, patella shift was more lateral between 40° and 70° tibiofemoral motion than during eccentric quadriceps action. During concentric quadriceps action, patella tilt was more medial between 45° and 55° tibiofemoral motion than during eccentric quadriceps action. Patella flexion and patella rotation did not show any differences between the concentric quadriceps action and eccentric quadriceps action conditions.

Beginning from a neutral patella orientation at 0° tibiofemoral flexion, the initial 20° tibiofemoral flexion was accompanied by the motions of medial patella shift and medial patella tilt, ending with the patella in a medial orientation. From approximately 20° to 90° tibiofemoral flexion, the patella displayed the motions of lateral patella shift and lateral patella tilt, beginning from the medial patella orientation observed at 20° tibiofemoral flexion and ending in a lateral orientation at 90° tibiofemoral flexion. When patella rotation was present, it occurred between 45° and 90° tibiofemoral motion. On average, patella flexion increased 0.75° for every degree of tibiofemoral flexion.

Various measuring techniques and naming conventions have been used to describe patella tracking in two and three dimensions.[1,3,5,8,21,24,27,30–33,39,43,46,47,49] Lack of standard measurement methods and terminology for patellar motion and orientation makes comparing the results of different studies difficult. In the current study, patella tracking was described relative to tibiofemoral flexion during simulated eccentric quadriceps contraction. The authors have described the results of previous studies using the same definitions of patellar motion and orientation to make comparisons with the current results.

Numerous previous studies have measured the patella's position using multiple static positions of the tibiofemoral joint.[1,15,30,33,42,43,46,47] Previous dynamic patella tracking studies have used isometric or concentric quadriceps action.[21,32,35,39] Only one previous study measured patella tracking during eccentric quadriceps action, but tibiofemoral motion was limited to 0° to 45° in that study.[41] To the current author's knowledge, no previous study has compared patella tracking during tibiofemoral motion under concentric quadriceps action with patella tracking during tibiofemoral motion under eccentric quadriceps action.

The patella shift patterns observed in the current study generally agreed with those described by others.[1,3,5,20,21,24,25,27,30,33,46] Specifically, as the tibiofemoral joint moves from 0° to 90° flexion, the patella shifts slightly medially in the initial 20° and then laterally for the remainder of the motion. The magnitude of lateral patella shift is larger than the magnitude of medial patella shift, so the patella ends in a lateral patella shift orientation at 90° tibiofemoral flexion. Some previous studies report magnitudes of net lateral patella shift similar to the current results (8 mm),[3,20,46] whereas others have reported the magnitude of lateral patella shift to be either larger[27,33] or smaller.[1,21,24,30] In comparison with eccentric quadriceps action, concentric quadriceps action in the midrange of tibiofemoral motion caused a slightly larger lateral patella shift, but the net orientation of the patella remained lateral under both quadriceps action conditions.

Patella tilt patterns observed in the current study also generally agreed with those described by others.[3,5,13,20,21,24,25,32,33,39,46] The patella has a slight medial patella tilt (1.5°) in the initial 20° tibiofemoral flexion and an increasing lateral patella tilt with increasing tibiofemoral flexion greater than 20°. Maximum lateral patella tilt in the current results (9.5°) was similar to that of previous studies.[3,20,24,39,46] Others have reported the magnitude of lateral patella tilt to be either larger[33] or smaller[21,30] than the current results. In comparison with eccentric quadriceps action, concentric quadriceps action between 45° and 55° tibiofemoral motion caused a slightly more medial patella tilt, but the overall orientation of patella tilt was lateral for both quadriceps action conditions.

Patella rotation patterns were less consistent than the other patella tracking parameters. The lack of consistency for patella rotation patterns is evident in the literature. The pattern of medial patella rotation with increasing tibiofemoral flexion that was observed in most of the current specimens was similar to those previously reported by Reider et al,[33] but the magnitude was considerably less than in several other studies.[14,27,46] Some authors have reported a net medial patella rotation during tibiofemoral flexion,[14,33,35] others have reported a net lateral patella rotation,[3,30,46] and others have reported negligible patella rotation.[24,39] Although a pattern of normal patella rotation remains elusive, it did not seem to be affected by either the concentric or eccentric quadriceps conditions in the current study.

The 0.75° patella flexion for every degree of tibiofemoral flexion during eccentric quadriceps action in the current study was similar to that of previous studies. Previous authors have reported that patella flexion occurs at an average rate of 0.60° to 0.75° for every degree of tibiofemoral flexion.[1,20,21,24,46]

The patella ligaments and quadriceps muscles control patella tracking in the initial 20° to 30° tibiofemoral flexion.[17,20] The patella contacts the femur and the articular surface of the femoral sulcus between 20° and 25° tibiofemoral flexion, which influences the motion of the patella directly.[2,14,17,26,28] In addition, as tibiofemoral flexion increases, the patellofemoral joint compression forces increase as a result of the quadriceps tendon and patellar tendon, which also directly affects patella mechanics.[13]

The average tibiofemoral angles at which maximum patella shift (22.0°), maximum patella tilt (23.3°), and increase in the rate of patella flexion (20.0°) occurred in the current specimens were similar. This reflects changing of the anatomic relationship between the patella and the femoral sulcus at 20° and 90° tibiofemoral flexion as compared with 0° to 20° tibiofemoral flexion. The buttressing effect of the sulcus walls serves to stabilize and guide patella tracking when the tibiofemoral joint is flexed greater than 20°.[2,18,28,46] Anatomically, the femoral sulcus becomes deeper and more laterally directed as tibiofemoral flexion increases, primarily because of the larger and more anteriorly prominent medial femoral condyle.[46] This anatomic feature is reflected in the patella shift and patella tilt results of the current study. Lateral patella shift and lateral patella tilt began at approximately 22° tibiofemoral flexion and continued to increase in magnitude through 90° tibiofemoral flexion.

Most weightbearing activity takes place with the tibiofemoral joint oriented at less than 60° flexion.[12,18] The quadriceps use concentric contractions (ascending stairs) and eccentric contractions (descending stairs) during weightbearing activities.[12] Lateral patella shift increases as tibiofemoral flexion angle increases from 0° to 60° during simulated sitting and squatting maneuvers with simulated concentric quadriceps contractions in specimens from cadavers.[35] During these same maneuvers, a medial patella tilt occurs with increasing tibiofemoral flexion angle through 30°, whereupon a lateral patella tilt is initiated and continues until a net lateral patella tilt orientation is achieved at 90°.[35] These parameters are similar to the current observations of patella tracking during tibiofemoral motion under eccentric quadriceps action, thereby lending evidence as to the validity of the in vitro model.

The results of the current study showed that a patella dislocation is not likely to occur in a normal knee. The current study showed that the patella in a normal knee has a medial tilt and medial shift between 0° and 20° tibiofemoral flexion, up to the point where the patella engages the femoral sulcus. Several anatomic and physiologic conditions can affect the patellofemoral relationship, including a dystrophic vastus medialis obliquus, a vastus medialis obliquus inhibited by pain, a shallow trochlea, a flattened or dysmorphic patellar articulating surface, laxity of the patellotibial ligaments, laxity of the patellar retinaculum, femoral-tibial varus, and external tibial torsion.[2,6,9,15,20,21,26,36,37] These conditions may produce a neutral or lateral patellar position between 0° and 20° tibiofemoral flexion rather than the normal medial position. A forceful quadriceps contraction with the knee extended to 20° or less under these conditions may laterally displace the patella enough to prevent it from properly engaging the femoral sulcus as the knee flexes beyond 20°.[6,28] Once the knee has flexed beyond 20° with the patella displaced lateral to the lateral femoral condyle such that it cannot enter the sulcus, a frank patellar dislocation occurs. Therefore, the current study supports the hypothesis that patellar instability is most likely to result of various anatomic and physiologic factors causing failure of the extensor mechanism to deliver the patella into the femoral sulcus in a congruent manner, as normally occurs.

The results of the current study are limited primarily by the use of an in vitro model. Specimens from cadavers cannot simulate the reflexive action of the quadriceps that may occur in response to patella motion or environmental stimuli in a living subject. In addition, no precise radiographic measurements were made to determine whether the patella in any of the specimens was malaligned. Also, the activity of other muscles surrounding the knee were not simulated in the model. The patella tracking patterns observed, however, were similar to those obtained in previous in vitro and in vivo studies of patella tracking during various simulated activities such as squatting and stair climbing.[3,20,21,24,33,39,46] This suggests that, although imperfect, the in vitro model yields useful information about patella tracking.

Patella tracking data were collected through six-degrees-of-freedom during tibiofemoral motion and simulated concentric and eccentric quadriceps loading. Patella tracking in reference to tibiofemoral flexion during eccentric quadriceps action, which represents a common mode of function of the knee and the extensor mechanism was described. In general, the patella tracking patterns observed during the concentric and eccentric quadriceps actions were similar. The authors' description of patella tracking during eccentric quadriceps action is comparable with the majority of recent literature describing patella tracking during concentric quadriceps action. The current results support the hypothesis that patellar dislocation rarely occurs in a normal knee.

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