Physiological sagittal plane patellar kinematics during dynamic deep knee flexion

Satoshi Hamai · Nicholas J. Dunbar · Taka-aki Moro-oka ·
Hiromasa Miura · Yukihide Iwamoto · Scott A. Banks

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Abstract

Purpose Lateral radiographic views can be easily taken and have reveal considerable information about the patella. The purpose of this study was to obtain sagittal plane patellar kinematics data through the entire range of knee flexion under weight-bearing conditions.

Methods Patellar flexion angles relative to the femur and tibia and anterior-posterior and proximal-distal translations of the patella relative to the femur and tibia were measured from 0 to 165° knee flexion in nine healthy knees using dynamic radiographic images.

Results The patella flexed relative to the femur and tibia by two thirds times and one third times the knee flexion angle, respectively. The patella translated in an arc relative to the femur and tibia as the knee flexed. In early flexion, the superior and centroid points translated anteriorly and then the patella translated posteriorly relative to the femur. All three points of the patella translated posteriorly relative to the tibia during a full range of flexion. An average of four and three millimetres proximal patellar translation relative to the tibia was demonstrated from 0 to 20° and 140 to 160° knee flexion, respectively.

Conclusions Physiological sagittal plane patellar kinematics, including patellar flexion angles and translations relative to the femur and tibia, showed generally similar patterns for each subject. Measurements of dynamic radiographic images under weight-bearing activities may enhance the opportunity to identify patellar pathological conditions.

Introduction

Patellofemoral disorders are common clinical problems and can result from abnormal patellar kinematics. Patellar kinematics will influence the contact patterns, contact areas and contact stresses in the patellofemoral joint [1–3]. Excessive patellofemoral forces will result in long-term cartilage degeneration [4, 5].

The sagittal plane patellar kinematics relative to either femur or tibia changes dramatically with increasing knee flexion. However, previous reports have only evaluated patellar flexion [6–8] or tendon angle [9, 10] during mid-flexion (~100°) using lateral radiographic images. Combined measurements of patellar flexion and translation relative to both the femur and tibia during deep flexion could enhance the opportunity to identify patellar pathological conditions. To our knowledge, no study has evaluated sagittal plane translation of the patella using a flat panel radiographic imaging system.

Biplane fluoroscopy [11–13] and magnetic resonance imaging (MRI)-based methods [5, 14] have explored the three-dimensional (3D) patellar kinematics. However, the methods used are either technically demanding or time-consuming. In contrast, a lateral radiographic view can be easily taken in the clinical setting and reveal considerable information about the patella [8]. Therefore, we have developed a 2D patella alignment measurement technique, which implemented a scaling tool of image measurements to physical dimensions,

S. Hamai · N. J. Dunbar · T.-a. Moro-oka · S. A. Banks
Department of Mechanical & Aerospace Engineering,
University of Florida, Gainesville, FL, USA

S. Hamai (✉) · T.-a. Moro-oka · Y. Iwamoto
Department of Orthopaedic Surgery, Faculty of Medical Sciences,
Kyushu University, 3-1-1 Maidashi, Higashi-ku,
Fukuoka 812-8582, Japan
e-mail: hamachan@ortho.med.kyushu-u.ac.jp

H. Miura
Department of Orthopaedic Surgery, Graduate School of Medicine,
Ehime University, Ehime, Japan

for quick and easy characterisation of patellar kinematics under dynamic conditions.

The purpose of this study was to obtain sagittal plane patellar kinematics data for the normal knee through the entire range of flexion under weight-bearing conditions. We sought to answer two specific questions:

1. How does the patella flex or translate in the sagittal plane during dynamic loaded deep knee flexion?
2. Are the accuracy and repeatability of the measurement technique sufficient to assess sagittal plane patellar kinematics?

Materials and methods

Nine healthy male subjects, averaging 29 years (22–32), 170 cm (165–177) and 67 kg (53–80) gave informed consent to participate in this Institutional Review Board approved study, and they were informed of the risk of radiation exposure required. Continuous lateral radiographic images of dynamic single-leg lunge activity for each subject were taken using a flat panel detector, which provides higher-resolution distortion-free images (Clavis, Hitachi, Tokyo, Japan: 3 frames/s, image area 397×298 mm, 0.20×0.20 mm/pixel resolution). Each image was digitally analysed to measure knee flexion angle, patellar flexion angles relative to the femur and tibia and anterior-posterior and proximal-distal translations of the superior, centroid and inferior points of the patella relative to the femur and tibia using a custom program, which can be downloaded freely at <http://sourceforge.net/projects/jointtrack/files/> (Fig. 1).

A topology adaptive snake algorithm, based on a deformable active contour model [15], was implemented to determine the approximate silhouette of the patella. A set of seed points within the boundaries of the patella was used to initialise the contour. Numerical optimisation was used to ‘inflate’ the snake to best fit the radiographic outline of the patella, resulting in a uniformly sampled contour surrounding the patella. The centroid of this contour was defined as the origin of the patella, and the contour moments are computed to determine major/minor elliptical axes of the patella. Patellar flexion angles relative to the femur and tibia were defined as the angle between the major elliptical axis of the patella and distal femoral axis and between the major elliptical axis of the patella and proximal tibial axis, respectively (Fig. 1). Knee flexion angle was defined as the angle between the anatomical axis of the distal one third of the femur and proximal one third of the tibia [16].

The origin of the femur was defined as the midpoint of the medial and lateral centres of the circular profiles of the posterior femoral condyles [17, 18]. Anterior patellar translation perpendicular to the distal femoral axis was defined as

Fig. 1 Lateral radiograph of a knee joint showing measurement landmarks for determining patellar kinematics: *L1* and *L2* the longitudinal axis of the distal femur and proximal tibia, *L3* the axis parallel to the tibial plateau, *L4* the patellar axis, *P1*, *P2* and *P3* the superior, centroid and inferior points of the patella, *Fo* and *To* the origin of the femur (midpoint between the centres of *R1* and *R2*) and tibia (intersection of *L2* and *L3*), α knee flexion angle, β and γ patellar flexion angle relative to the femur and tibia, *R1* and *R2* circles that were fit to the contours of the medial and lateral posterior femoral condyles

positive relative to the origin of the femur. Proximal patellar translation parallel to the distal femoral axis was defined as positive relative to the origin of the femur. The origin of the tibia was defined as the intersection of the tibial plateau with the tibial longitudinal axis. Anterior patellar translation parallel to the tibial plateau was defined as positive relative to the origin of the tibia. Proximal patellar translation perpendicular to the tibial plateau was defined as positive relative to the origin of the tibia.

Computed tomography (CT) scans used a 512×512 image matrix, a 0.35×0.35 pixel dim and a 1.00-mm thickness (Aquilion, Toshiba, Tochigi, Japan). Cortical bone edges were segmented from CT images using commercial software (sliceOmatic, TomoVision, Montreal, QC, Canada) and these point clouds were converted into polygonal surface models (Geomagic Studio, Raindrop Geomagic, Research Triangle Park, NC, USA) [19]. The best-fit radius of a sphere fit to the lateral posterior femoral condyle was measured for each subject by radiographic images and CT-derived 3D model, and this ratio was used to provide a physical scale for the radiographic images (subjects’ knees were at an unknown distance from the X-ray source). The average diameter of the lateral posterior femoral condyle was 42 mm (range 40–46 mm).

The average maximum knee extension/flexion angle was 4° (range –10 to 19)/158° (range 137–170) using the current kinematic measurement technique. Continuous cubic polynomial curves were fit to each individual’s data, and these curves were sampled in 5° flexion increments to create average kinematics for the group. Linear and polynomial regression

analyses were performed to characterise the trends in patellar flexion and translation, respectively, as a function of knee flexion.

To determine the accuracy of the measurement technique, the knee specimen was mounted on radiolucent fixtures such that the knee joint could be manually moved through a range of motion during radiographic observation. Series of images were taken at three frames per second using a stereo flat panel radiographic imaging system (Allura Xper FD20/20, Philips Medical Systems B.V., Best, Netherlands), and ten image pairs were selected randomly (Fig. 2). The 3D surface geometries of the femur, tibia and patella were reconstructed and aligned in the same manner as the 2D measurement technique. Model-image registration was performed to measure patellar kinematics, which were taken as reference values, using custom open-source software (JointTrack, Gainesville, FL, USA, www.sourceforge.net/projects/jointtrack) [20]. Differences in the root-mean-square (RMS) errors between biplane images with 3D bone models and sagittal plane patellar kinematics measurements were less than 2.0° and 3.0 mm, for in-plane rotation and translations, respectively.

Two observers, an orthopaedic surgeon and an engineer, performed patellar kinematic measurements on a random sample of 40 radiographic images and also measured one image ten times over a time period of five days. A power analysis determined these sample sizes would give a 5 % probability of type I errors ($\alpha=0.05$) and a 20 % probability of type II errors ($\beta=0.20$). The assumed effect size was 1° and 1 mm. The intra-observer RMS errors ($\sqrt{\text{bias}^2 + \text{variance}}$) were approximately one millimetre and one degree, and inter-observer RMS errors were approximately two millimetres and two degrees. The errors were not significantly biased ($\text{bias} < 1 \text{ mm}$, $p < 0.05$, two-tailed t test).

Results

Patellar flexion angles relative to the femur and tibia increased with increasing knee flexion (Fig. 3). The ratios of patellar flexion relative to the femur and tibia versus knee flexion averaged 0.66:1 and 0.34:1, respectively. Linear regression showed the knee flexion angle predicted 99 % of patellar flexion with respect to the femur ($R^2=0.992$, $p < 0.0001$) and 97 % of patellar flexion with respect to the

Fig. 3 Patellar flexion angles with respect to the femur (circles) and tibia (squares) from 0 to 165° of loaded knee flexion for 5° flexion increments. The lines represent linear regressions in patellar flexions relative to the femur (black solid) and tibia (grey grid)

tibia ($R^2=0.971$, $p < 0.0001$). Inter-subject variability in patellar flexion angles relative to the femur and tibia was $2.4 \pm 0.2^\circ$. A consistent increase in patellar flexion angles was observed throughout the flexion cycle, even in deep knee flexion beyond 140°. The mean patellar flexion angles relative to the femur and tibia were approximately 100 and 65°, respectively, at 160° of knee flexion.

The three patellar reference points were positioned an average of 51 mm (range 46–54 mm) anterior to the distal femoral origin at 0° of knee flexion (Fig. 4). The patellar centroid translated 2 mm anteriorly from 0 to 20° knee flexion and then 69 mm posteriorly beyond 20° knee flexion. The inferior patellar point translated 93 mm posteriorly from extension to 160° knee flexion. The superior patellar point translated 57 mm distally from extension to 160° knee flexion. The three patellar reference points were positioned an average of 20 mm (range –22 to –18 mm) inferiorly to the distal femoral origin at 160° of flexion. Translations with flexion of all points were well modelled by quadratic regression curves (superior point: $R^2=0.789$, $p < 0.0001$; centroid: $R^2=0.840$, $p < 0.0001$; inferior point: $R^2=0.895$, $p < 0.0001$).

The three patellar reference points were positioned an average of 34 mm (range 32–36 mm) anterior to the tibial origin at 0° of knee flexion (Fig. 5). All points translated posteriorly over the full range of weight-bearing flexion. The superior/inferior points of the patella showed the largest/smallest posterior translations (73/33 mm) from 0 to 160° knee flexion. The inferior patellar point was positioned close

Fig. 2 Bi-plane images at near extension (a) and deep flexion (b) of the knee specimen mounted to radiolucent fixtures for accuracy assessment of the measurement technique

Fig. 4 Anterior-posterior and proximal-distal translations of the patella (black circle superior point, dark grey triangles centroid point, light grey squares inferior point) with respect to the origin of the femur from 0 to 160° of loaded knee flexion for 10° flexion increments. The black (superior point), dark grey (centroid point) and light grey (inferior point) curves represent quadratic regressions

to the proximal tibial origin at 160° of flexion. The patellar centroid translated 9 mm proximally from 0 to 70° knee flexion and then 4 mm distally beyond 70° knee flexion. Especially from 0 to 20° knee flexion, the patella showed an average of 4 mm (range 4–5 mm) proximal translation. Beyond 140° knee flexion, the inferior point of the patella showed 3 mm proximal translation relative to the tibia. All three points translated in an arc as the knee flexed, but quadratic regression curves did not fit the patellar

Fig. 5 Anterior-posterior and proximal-distal translations of the patella (black circles superior point, dark grey triangles centroid point, light grey squares inferior point) with respect to the origin of the tibia from 0 to 160° of loaded knee flexion for 10° flexion increments. The black (superior point), dark grey (centroid point) and light grey (inferior point) curves represent quadratic regressions

translations well (superior point: $R^2=0.314$, $p<0.0001$; centroid: $R^2=0.082$, $p=0.0029$; inferior point: $R^2=0.077$, $p=0.0043$).

Discussion

In this study, we evaluated the in vivo normal patellar kinematics during a single-leg lunge using lateral radiographic images with sufficient accuracy and repeatability. The patella flexed relative to the femur and tibia by two thirds times and one third times the knee flexion angle, respectively. A consistent increase in patellar flexion angles was observed throughout the flexion cycle, even in deep knee flexion beyond 140°. The superior, centroid and inferior positions of the patella translated in an arc relative to the femur and tibia as the knee flexed. In early flexion, the superior and centroid points translated anteriorly and then posteriorly relative to the femur. All three points of the patella translated posteriorly relative to the tibia over the full range of weight-bearing flexion. The patella translated an average of four and three millimetres proximally relative to the tibia from 0 to 20° and 140 to 160° knee flexion, respectively.

Only 2D patellar kinematics, including patellar flexion angles and translations relative to the femur and tibia, were analysed in this study. However, several studies have shown abnormal sagittal plane kinematics in pathological knees [3, 5, 8, 21] and knees replaced by total knee arthroplasty [6, 7, 9, 10]. Tyler et al. [8] demonstrated that patients with patellar tendinitis have abnormal patellar tilt in the sagittal plane. Luyckx et al. [3] reported that patella alta was associated with higher maximal patellofemoral contact force and contact pressure than normal patellar positions and thereby gives rise to anterior knee pain. Komistek et al. [6] and Stiehl et al. [7] demonstrated that the angle between the longitudinal axes of the patella and tibia were statistically different in total knee arthroplasties from those in normal knees. Therefore, this measurement method could be used to diagnose or investigate patellar motions and pathomechanics.

Because alternations in the position and movement of the patella could change the co-ordinated motion of the femur/tibia and patella, previous studies have evaluated the ratio of patellar flexion relative to either femur or tibia. Matthews et al. [22] used serial lateral X-rays of cadaver specimens and fitted the relationship between the quadriceps-patellar tendon angle and the knee flexion angle to a linear regression. Amis et al. [23] used fresh-frozen cadaver knees and reported the patella relative to the femur flexed by 0.66 times the tibiofemoral flexion angle as the knee flexed up to 100°. In our study, the patella flexed relative to the femur by 0.66 times the knee flexion angle as the knee flexed from 0 to 165°. This finding was also very consistent with previous in vivo studies that used different measurement methods [6, 7, 12–14]. Therefore, the ratio of the patella flexion to the knee flexion, two thirds for relative to the

femur and one third for relative to the tibia, is a reliable indicator of normal patellar function in both static postures and continuous weight-bearing motion [24]. Few studies have explored the patellar kinematics in deeply flexed postures [12, 13]. Since an increase in knee flexion angle or quadriceps muscle force during weight-bearing activities will be accompanied by elevated patellofemoral joint reaction forces [22, 25], it is important to understand normal patellar mechanics at the higher ranges of flexion.

Our analysis during a functional weight-bearing knee flexion newly demonstrated that three reference points of the patella translated in an arc relative to the femur as the knee flexed from 0° to maximum knee flexion. Our data showed that anterior translation of the superior and centroid points was demonstrated in early flexion. The healthy patella lies proximal to the trochlea at knee extension, enters the trochlear groove as flexion proceeds and translates along the nearly circular arc formed by the patellofemoral groove in the sagittal plane [26, 27]. This patellar movement is guided by multiple factors, including the geometry of the trochlear groove, the relative position of the femur with respect to the tibia, contractions of quadriceps muscles and patellar tendon constraints [9, 21, 22]. Using a biplanar image-matching technique, Asano et al. [11] demonstrated movement of the patellar centre point relative to the femur from 0 to 120° flexion in the lateral view, which is consistent with our data. However, they measured a single point, the patellar centre point, and showed only representative data for the first subject.

This in vivo dynamic study found that the patella also translated in an arc relative to the tibia as the knee flexed from 20 to 140° knee flexion, with the patellar tendon acting as a connecting link. Our results showed that the patella showed four millimetres proximal translation relative to the tibia below 20° knee flexion, which is consistent with a previous in vivo study by Jacobsen et al. [28] and a report on elongation of the patellar tendon during a single-leg lunge [29]. DeFratre et al. [29] demonstrated that the length of the patellar tendon increased sharply as the knee flexed from full extension to 30° of flexion, then remained relatively constant until 110° of flexion. This is the first report showing that the inferior point of the patella showed three millimetres proximal translation relative to the tibia beyond 140° knee flexion. The activation of the quadriceps muscles, which are required to resist a flexion moment, might extend the tension and length of the patellar tendon and cause this proximal patellar translation near extension [28] and very deep flexion. The patella moved from anterior to posterior relative to the tibia during dynamic weight-bearing flexion, in large part because the patella tracks with the femur with flexion. Li et al. [12] showed posterior femoral translation was strongly correlated with the posterior patellar translation during static weight-bearing flexion.

The accuracy of measuring sagittal plane patellar kinematics using the measurement technique was less than 2.0° for rotation and three millimetres for in-plane translations. Both observers, an orthopaedic surgeon and an engineer, were highly repeatable and had low intra-observer errors. Inter-subject variability in patellar flexion was extremely low (<3°). When comparing the single-plane measurements to the biplane measurements using projected 3D bone models, Tang et al. [30] reported RMS differences of 2.1° for rotations and 1.8 mm for in-plane translations in terms of patellofemoral joint kinematics. Although 2D evaluation potentially includes the out-of-plane movement, the accuracy and repeatability of our custom program were sufficient to evaluate sagittal plane patellar kinematics. We have developed a simple-to-use program for quantifying knee and patellar kinematics that does not require specialised equipment, expertise or expensive software licenses. The CT method is useful for accurate calibration to measure the patellar position, but other scaling approaches, e.g. calibration grid [31] or skin-mounted marker [32], are easily implemented. Thereby, patients can avoid additional radiation exposure needed for CT scan. Otherwise, the ratio of patellar position to diameter of the lateral posterior femoral condyle could be used without any calibration. The program is written using MATLAB (MathWorks, Inc., Natick, MA, USA), an almost ubiquitous platform for computation, and is available for free download.

In conclusion, our data revealed physiological sagittal plane patellar kinematics during weight-bearing deep knee flexion. Patellar kinematics, including patellar flexion angles and translations relative to the femur and tibia, showed generally similar patterns for each subject. These kinematic data will be used to investigate and diagnose patellar motion and pathomechanics.

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