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In vivo measurements of patellar tracking and finite helical axis using a static magnetic resonance based methodology

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ABSTRACT

Patellofemoral (PF) maltracking is a critical factor predisposing to PF pain syndrome. Many novel techniques of measuring patellar tracking remain research tools. This study aimed to develop a method to measure the in vivo patellar tracking and finite helical axis (FHA) by using a static magnetic resonance (MR) based methodology. The geometrical models of PF joint at 0°, 45°, 60°, 90°, and 120° of knee flexion were developed from MR images. The approximate patellar tracking was derived from the discrete PF models with a spline interpolation algorithm. The patellar tracking was validated with the previous in vitro and in vivo experiments. The patellar FHA throughout knee flexion was calculated. In the present case, the FHA drew an “L-shaped” curve in the sagittal section. This methodology could advance the examination of PF kinematics in clinics, and may also provide preliminary knowledge on patellar FHA study.

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1. Introduction

Patellofemoral pain syndrome (PFPS) is a common disease in human knee joint. The incidence of PFPS could reach to approximate 25% in the general population, and could be even higher in sports [1,2]. PFPS could affect the daily activities, and chronically lead to knee instability and osteoarthritis [3]. However, the pathophysiology of PFPS remains still unclear [4]. PFPS is correlated with the abnormal patellofemoral (PF) alignment and tracking (malalignment and maltracking) [5]. Previous studies reported significant differences in patellar lateral translation, spin, and tilt between symptomatic and asymptomatic individuals [6,7]. PFPS is also more prevalent in patients with patella alta, whose patella is high positioned [8]. As a common cause of PFPS, PF arthritis is also associated with incongruent sliding between the patella and femoral sulcus [9].

Restoring PF tracking has been considered as a critical principle in the treatment of PF diseases. Minor alterations in PF alignment could change the mechanics in both PF and tibiofemoral joints [10]. In the treatment of lateral patellar instability and subluxation, lateral retinacular release was performed with the aim to correct patellar tracking [11,12]. The realignment of PF joint is also a major concern in total knee arthroplasty. The rate of PF complications after knee arthroplasty ranged from 4% to 41% [13]. To improve the success rate, the design of prosthesis is still developing in terms of restoring the physiological PF kinematics [14].

The complex geometry and motion of the patella remains challenging to clinicians and technicians [15]. The advances in imaging technologies better enabled the measurement of PF kinematics. Dynamic MR techniques have been used to investigate the associations between joint kinematics and joint pathology [16–20]: Nha et al. measured the in vivo weight-bearing PF and tibiofemoral motion with MR imaging and dual orthogonal fluoroscopy [21]. However, many of these novel techniques remained research tools. And majority of these studies cannot accommodate deep flexion ranges [15–20], while clinical diagnosis commonly relies on static MR and CT. An efficient and sufficiently accurate method to assess the patella tracking using conventional imaging techniques is demanding [22].
Finite helical axis (FHA) is an important feature of joint kinematics. Although the method of calculating FHA has been mathematically well established and used in the kinematics analyses of tibiofemoral and ankle joints [23–26], the patellar FHA has not been thoroughly understood. The patellar FHA, which is closely associated with the quadriceps moment and knee extensor, plays an important role in the PF kinematics, and may serve as a potential reference in the PF realignment and replacement surgeries. Previous studies proposed the patella rotating around an approximate axis near the femoral epicondyle [27,28], yet no quantitative measurement has been conducted about the patellar FHA.

This technical note aimed to develop a methodology to quantify the in vivo patellar tracking and FHA by using the routine static MR scanning, which was of high practical and clinical relevance.

2. Materials and methods

2.1. MR scanning

A male subject (age: 30 years; mass: 65 kg; height: 172 cm) volunteered for this study. The knee pathology was ruled out with the physical and MR examinations. The right knee was scanned with the MR machine (Siemens, Sonata 1.5 T, Germany) at 0°, 45°, 60°, 90°, and 120° of knee flexion. To accommodate the flexed knee in the magnetic field, subject was required to lie on the right side under no-weightbearing condition. A knee brace of thermoplastic sheet (ORFIT Eco, ORFIT, Inc., Belgium) was utilized to maintain the right knee static in the certain flexion angle during the scanning. The left leg was out of touch with the right knee. The following scanning parameters were used: magnetic field = 1.5 T, field of view = 180.5 × 149.5 mm², pixel resolution = 0.47 × 0.47 mm², slice thickness = 2 mm, echo time (TE) = 43 ms, repetition time (TR) = 7170 ms. Ethical approval was granted from the authority and the subject signed the consent with the experimental procedures explained.

2.2. Geometry reconstruction

The geometries of the PF joint at different knee flexion angles were reconstructed from the MR images using the medical image processing software, Mimics (version 8.0 Materialise, Inc., Belgium). The segmentations of the patella and femur were performed based on different grayscales among tissues. The developed 3D models of PF joint were shown in Fig. 1(a)–(e). These five models were placed in a common coordinate system by matching the femurs through a geometry registration technique in Rapidform (version 2006, 3D Systems, Inc., Korea), as shown in Fig. 1(f).

2.3. Patellar tracking interpolation and validation

The approximate patellar tracking was derived from the above-mentioned patella models. The patella in this study was considered rigid, and its position could be determined by three non-collinear points. Therefore, points at apex, medial, and lateral sites of patella were selected as the reference points (Fig. 2(a)). Since the positions of these reference points at 0°, 45°, 60°, 90°, and 120° of knee flexion were known (the red points in Fig. 2(b) and (c)), the approximate tracking of the points throughout knee flexion (the blue dash curves in Fig. 2(c)) could be calculated with the order-three spline interpolation method [29] (Supplementary material 1). With the tracking of the reference points, the patellar tracking can be determined as follows:

As shown in Fig. 2(d), let points A, B, C denote the three reference points on patella, A’, B’, and C’ denote their positions at θ degree of

![Fig. 1. 3D models of PF joint at different angles of knee flexion. (a–e) PF joints at 0°, 45°, 60°, 90°, and 120° of knee flexion. (f) Five models were placed in a common coordinate system by matching the femurs through a geometry registration technique in Rapidform (Version 2006, 3D Systems, Inc., Korea).](image-url)
knee flexion. The patella was translated and rotated so that point A coincided with point A', axis AB parallel with axis A'B', and plane ABC paralleled with plane A'B'C'. Finally, the patellar position at any degree of knee flexion could be determined with this process (Fig. 2(e)).

The calculated patellar tracking was compared with the in vitro and in vivo experiments in literature [17,30]. To facilitate the comparison, the patellar motion was re-described by a floating axis coordinate system, which has been widely used in the previous studies [30,31]. The patellar flexion was characterized by a femoral medial-lateral axis perpendicular to the femoral shaft and parallel to the plane containing the most-posterior points of the femoral condyles, the patellar longitudinal axis characterized the patellar tilt, and the third axis, perpendicular to the above axes, characterized the patellar rotation.

2.4. Determination of patellar FHA

The patellar FHA is a 3D instantaneous axis, which moves with knee flexion. Patella motion could be described as a rotation around the FHA and a slight translation parallel to the FHA. Based on the patellar tracking obtained, the patellar FHA throughout knee flexion was determined with the widely used mathematical process [23,24]. The patellar movement from one position to another could be characterized by a translation vector and an orthogonal rotation matrix. Let \( \alpha, \beta, \) and \( \gamma \) denote three linearly independent vectors on patella at \( \theta \) degree of knee flexion, and \( \alpha', \beta', \) and \( \gamma' \) denote these vectors at \( \theta + \Delta \theta \) degree of knee flexion. The rotation matrix \( T \) satisfies:

\[
T \alpha = \alpha', \quad T \beta = \beta', \quad T \gamma = \gamma'
\]  

(1)

With Eq. (1), \( T \) could be calculated as:

\[
T = \begin{bmatrix}
\alpha_1 & \beta_1 & \gamma_1 \\
\alpha_2 & \beta_2 & \gamma_2 \\
\alpha_3 & \beta_3 & \gamma_3 \\
\end{bmatrix}^{-1}
\]

(2)

where \( \alpha_i, \beta_i, \gamma_i, \alpha_i', \beta_i', \) and \( \gamma_i' \), are the vector components of \( \alpha, \beta, \gamma, \alpha', \beta', \) and \( \gamma' \). The patellar FHA could be described by an unit orientation vector \( \mathbf{n} \) and a point on the FHA. Let \( s \) denote the radius vector of a point on FHA at \( \theta \) degree of knee flexion, and \( \mathbf{p} \) denote an arbitrary point on patella. \( s \) and \( \mathbf{p} \) moved to \( s' \) and \( \mathbf{p}' \) at \( \theta + \Delta \theta \) degree of knee flexion. Since \( \mathbf{p} \) and \( \mathbf{p}' \) are known from the patellar tracking, \( \mathbf{n}, s, \) and \( s' \) could be calculated by satisfying:

\[
T \mathbf{n} = \mathbf{n}, \quad ||\mathbf{n}|| = 1
\]

(3)

\[
(s' - s) \times \mathbf{n} = 0
\]

(4)

\[
\mathbf{s}' = \mathbf{p}' + T(s - \mathbf{p})
\]

(5)

where \( ||\mathbf{n}|| \) is the modulus of \( \mathbf{n} \), “\( \times \)” is the cross product of two vectors.

Since the continuous patellar tracking has been calculated, the patellar FHA at any degree of knee flexion (\( \theta \) ranged from 0 to 120, \( \Delta \theta = 1 \)) was determined. The spatial relationships between FHA trajectory and the femoral anatomic axes including condylar axis, epicondylar axis, and trochlear axis were analyzed. The definitions of anatomic axes were quoted from literature [27]. Briefly, the condylar axis was defined as an axis linking the two centers of spheres fitted to medial and lateral posterior femoral condyles; the epicondylar axis was defined as an axis linking the medial and lateral epicondyles; and the trochlear axis was defined as an
axis linking the two centers of spheres fitted to medial and lateral trochlea. The instantaneous patellar rotational radius was also defined as the perpendicular distance from the patellar center to the FHA. The patellar center was defined as the midpoint of the line linking the basis patellae and apex patellae. The calculations of patellar tracking and FHA were accomplished with C++ program (Visual C++ 6.0, Microsoft, Inc., USA).

3. Results

3.1. Validation of patellar tracking

The comparison between the obtained patellar tracking and the experiments in literature were shown in Fig. 3 and Supplementary material 2. The obtained patellar tracking was within the range of experimental measurements.

3.2. Trajectory of patellar FHA throughout knee flexion

As shown in Fig. 4, the patellar FHA moved with knee flexion and generated a surface. In the view of sagittal section through the midpoint of epicondylar line, the trajectory drew an “L-shaped” curve (Fig. 4(b)). As shown in Fig. 4(c), patellar rotational radius experienced four stages throughout knee flexion: (1) increasing to a peak value, (2) decreasing to the minimum, (3) remain approximately level, and (4) increasing to the maximum. These four stages corresponded to four stage of FHA trajectory: (1) migration in the proximal-distal direction, (2) migration in the posterior–anterior direction, (3) approximately maintained near the femoral epicondyles, and (4) migration in the distal–proximal direction (Fig. 4(d)).

3.3. Relationship between FHA and femoral anatomic axes

Fig. 5 shows the distances in the sagittal section and angles between FHA and the anatomic axes. With regard to the angle, the condylar axis was the most parallel axis to FHA during 10° to 120° knee flexion (Fig. 5(b)). With regard to the distance in the sagittal section (the sagittal plane through the midpoint of femoral epicondylar line), the condylar axis was the closest axis to FHA during 0° to 35° knee flexion; the trochlear axis was the closest axis to FHA during 45° to 120° knee flexion (Fig. 5(c)).

4. Discussion

PF malalignment is a critical factor predisposing to PFPS [5], the patellar tracking could potentially serve as a reference for the diagnosis and treatment of the PF malalignment [10]. In this light, the present study developed a method to measure the in vivo patellar tracking and FHA with five static MR scanning. In comparison
with the previous studies [16,17,32], this technique was based on the routine MR scanning in clinics, and did not involve complicated operating requirement for the subject. Nearly full knee flexion range (0°–120°) could be measured with this method.

The obtained patellar tracking was compared with the in vitro and in vivo experiments in the literature [17,30]. Both the present study and the in vivo experiment were conducted under the non-weighting bearing condition. The subject’s age (30 years), weight (65 kg), and height (172 cm) in the present study were within the range of the in vivo experiment (age: 26.7 ± 2.8 years, weight: 67.5 ± 12.7 kg, 172.3 ± 7.5 cm). The present result was within the range of experimental measurements, which consolidated the accuracy of the measurement method. The difference between the obtained results could be caused by inter-subject variation, loading condition, and coordinate system configuration. Therefore, the kinematics analysis with patellar FHA was recommended. The FHA was independent of coordinate system, thus could reduce the inter-subject variations. Furthermore, in the third stage of FHA trajectory, the patellar rotational radius remained at approximate 45 mm, the FHA remained near the femoral trochlear axis and at the anterior-proximal side of epicondylar axis. These phenomena were also in agreement with the previous studies [27,33]. The present method was precisely derived from the mechanical theory. The measuring process was also implemented with the program, which ensured the repeatability and the certainty of the method.

In the present case, the FHA trajectory drew an “L-shaped” curve in the sagittal plane. This phenomenon is similar to the tibiofemoral kinematics, in which the tibial FHA draws a “J-shaped” curve on femur during knee flexion [33,34]. The patellar FHA and rotational radius experienced four stages during knee flexion. These four stages corresponded to four contact status in PF joint [35]. In stages one and two, patella partially engaged with femoral trochlea. Most patella dislocation often occurred in these two stages in patients with PF malalignment [36,37]. In stage three, high interaction forces often occurred in the PF joint during daily activities, such as cycling, stair ascent, stair descent, and jogging [35]. Most cartilage defects also occurred in the articular contact regions in this stage [38]. The last stage corresponded to the deep knee flexion. Patella was astride the medial and lateral femoral condyles, leading to two divided contact regions.

There are some limitations in this study. Firstly, the present study focused on the method to measure the in vivo patellar tracking and FHA. Although the patellar tracking was validated with the previous studies, more subjects should be enrolled to consolidate the present findings. Secondly, the knee flexion angles for MR scanning may influence the results. Further study is required to optimize the scanning process, and to advance the accuracy of this method. Thirdly, the MR scanning was performed on the knee free from any external loadings. The effects of loading conditions on the FHA trajectory need to be further investigated. Finally, to facilitate the comparison with the other studies, only the data of healthy subject was reported in this study. In spite of this, the present method could be applied on both healthy people and patients with different PF diseases. The correlations between the patellar FHA and different

![Fig. 4. Patellar FHA trajectory and rotational radius throughout knee flexion. (a) FHA trajectory in medial view, (b) FHA trajectory in sagittal section. FHA draws an “L-shaped” curve. (c) Patellar rotational radius throughout knee flexion. (d) Four stages of the FHA trajectory.](image)
types and severities of PF disease will be investigated in our future studies.

5. Conclusions

This study developed a method to measure the in vivo patellar tracking and FHA in full knee flexion range using a static MRI-based methodology. The obtained patellar tracking was validated with the previous in vitro and in vivo studies. In the present case, the FHA trajectory drew an “L-shaped” curve in the sagittal plane. This methodology could advance the examination of PF kinematics in clinics, and could also provide preliminary knowledge on patellar FHA study.

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Ethical approval

An ethical approval was given by the Medicine and Life Sciences Ethics Committee of Tongji University (No. 2011–121).

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.medengphy.2014.08.014.

Conflict of interests

None declared

References


