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In Vivo Patellar Tracking and Patellofemoral Cartilage Contacts during Dynamic Stair Ascending

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Abstract

The knowledge of normal patellar tracking is essential for understanding of the knee joint function and for diagnosis of patellar instabilities. This paper investigated the patellar tracking and patellofemoral joint contact locations during a stair ascending activity using a validated dual-fluoroscopic imaging system. The results showed that the patellar flexion angle decreased from 41.9° to 7.5° with the knee extension during stair ascending. During first 80% of the activity, the patella shifted medially about 3.9 mm and then slightly shifted laterally during the last 20% of the ascending activity. Anterior translation of 13 mm of the patella was measured at the early 80% of the activity and then slightly moved posteriorly by about 2 mm at the last 20% of the activity. The path of the cartilage contact points was slightly lateral on the cartilage surfaces of patella and femur. On the patellar cartilage surface, the cartilage contact locations were about 2 mm laterally from heel strike to 60% of the stair ascending activity and moved laterally and reached 5.3 mm at full extension. However, the cartilage contact locations were relatively constant on the femoral cartilage surface (~5 mm lateral). The patellar tracking pattern was consistent with the patellofemoral cartilage contact location pattern. These data could provide baseline knowledge for understanding of normal physiology of the patellofemoral joint and can be used as a reference for clinical evaluation of patellofemoral disorder symptoms.

Keywords

Patellar tracking; Patellofemoral cartilage contact

INTRODUCTION

The knowledge of accurate kinematics of normal patellofemoral joint is important to provide accurate insight into the function of the knee joint, which can be further utilized to evaluate patellofemoral joint disorders and improve the treatment methods. Investigation of

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CONFLICT OF INTEREST STATEMENT

No potential conflict of interest is declared.

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patellofemoral joint biomechanics is a challenge in biomedical engineering. Traditional biomechanical research has reported patellar tracking that describes the patella motion along knee flexion path (Heegaard, et al., 1995; Reider, et al., 1981). For example, in-vitro studies have applied muscle loads to measure the corresponding patella motion using various techniques such as video-based motion analysis, magnetic tracking devices or optical systems, etc (Amis, et al., 2006; Fellows, et al., 2005; Goudakos, et al., 2009; Heegaard, et al., 1995; Nagamine, et al., 1995; Reider, et al., 1981). In-vivo studies have used intra-cortical pins (Koh, et al., 1992) and magnetic resonance imaging (MRI) techniques to examine the patellar tracking during flexion/extension of the knee (Brossmann, et al., 1993; Derasari, et al., 2010; Kujala, et al., 1989; MacIntyre, et al., 2006; Powers, et al., 1998; Sheehan, et al., 1999). In general, medial-lateral patellar shift and tilt have been widely reported in various patellar maltracking studies.

Fewer studies have investigated the patellofemoral articular cartilage contact kinematics. Earlier in-vitro studies have used pressure sensors (such as using Fuji pressure sensitive film, K-Scan pressure sensor, etc.) to measure the patellofemoral articular cartilage contact at different knee flexion angles (Beck, et al., 2005; Hsieh, et al., 2002). MRI has also been used to determine the patellofemoral cartilage contact (Brossmann, et al., 1993; Derasari, et al., 2010; Kujala, et al., 1989; MacIntyre, et al., 2006; Powers, et al., 1998; Sheehan, et al., 1999). Recently, dual-fluoroscopic imaging systems (DFIS) have been used to measure the patellofemoral contact kinematics as well as the cartilage contact deformation during weight-bearing knee flexion (Gill, et al., 2009; Nha, et al., 2008).

Despite these various studies on patellar tracking and patellofemoral articular cartilage contact biomechanics, no data has been reported on the patellar tracking and the corresponding articular cartilage contact kinematics during dynamic, functional activities of the knee. The intrinsic biomechanical relationship between patellar tracking and articular contact kinematics has not been reported in literature. Therefore, the objective of this study was to investigate the patellar tracking and the articular contact kinematics of the patellofemoral joint in living subjects while performing a stair ascending activity. Demanding physical activities, such as stair climbing, have been identified as risk factors for patellofemoral joint pain (Dye, et al., 2005). Since patellofemoral joint pain is frequently experienced during stair climbing –compared to other daily activities– (Goudakos, et al., 2009), this dynamic activity was considered suitable and selected for this investigation.

METHODS

Twelve healthy knees were investigated (7 males, 5 females; aged 35 ± 11 years, and with an average body mass index of 25.0 ± 2.4 kg/m²) in this study. Each knee was carefully screened for symptom of osteoarthritis, patellofemoral pain and previous injuries to ensure normal knee joint. An IRB approved consent form was signed by each subject before participating in this study.

Each knee was first scanned in a relaxed, extended position using a 3-T scanner (MANETOM Trio[®] Siemens, Malvern, PA) with a surface coil and a double-echo water-excitation sequence. The MR images were captured in sagittal plane with a 1 mm slice thickness and an image resolution of 512×512 pixels. The images were used to construct three dimensional (3D) bony models of the tibia, femur, patella and their corresponding cartilage surfaces using a solid modeling software (Rhinoceros[®], Robert McNeel & Associates, Seattle, WA). Thereafter, a dual fluoroscopic imaging system consisting of two C-arms (BV Pulsera[®], Philips, Bothell, WA) was used to capture the motion of the knee during ascending a step of 14 cm. The knee was imaged from the posteromedial and posterolateral directions using pulse images (8 ms pulse width) at 30 frames per second. The

time of heel strike on the stair was defined as the starting position and the time of full knee extension was defined as the ending position of the ascending activity.

The series of paired fluoroscopic images captured during the stair ascending activity and the 3D knee model were used to reproduce the in-vivo knee positions in Rhinoceros software (Gill, et al., 2009; Li, et al., 2007; Nha, et al., 2008; Van de Velde, et al., 2008). To do this, the relative positions of the fluoroscopes (including x-ray sources and image intensifiers) were created in the software to construct a virtual dual fluoroscopic system (Fig. 1A). Each pair of the captured fluoroscopic images was imported into the software and placed at the positions of the corresponding image intensifiers. The bony silhouettes of the tibia, femur, and patella were outlined on the fluoroscopic images. The 3D models of the femur, tibia, and patella were manipulated in the virtual fluoroscopic system until their projections matched the bony outlines on both fluoroscopic images (Fig. 1A). This process was repeated at every 10% of the entire ascending activity to reproduce the in-vivo knee positions along the ascending activity. The DFIS has been shown to have an accuracy of less than 0.1 mm and 0.3° to determine dynamic knee joint positions (Li, et al., 2008).

Joint coordinate systems and kinematics

Kinematics of the knee joint was quantitatively measured using coordinate systems assigned to the patella, femur and tibia. For the femur, its long axis was drawn through the middle of the femoral shaft. The transepicondylar axis (TEA) was defined by connecting the extremes of the medial and lateral condyles (Churchill, et al., 1998; Most, et al., 2004; Yoshino, et al., 2001). The anterior-posterior (AP) axis of the femur was drawn perpendicular to the long axis and TEA (Fig. 1B). The midpoint of the TEA was defined as the origin of femoral coordinate system. For the tibia, its long axis was drawn through the middle of tibial shaft. Knee flexion angle was defined as the angle between the long axes of the femur and tibia projected onto the sagittal plane of the knee. For the patella, its medial-lateral (ML) axis was drawn connecting the medial and lateral ridges of the patella. The superior-inferior (SI) axis was drawn perpendicular to ML axis and through the midpoint of the patella (origin of patellar coordinate system) in coronal view (Fig. 1B).

The patellar motion was measured relative to the femur in three translations (medial-lateral, anterior-posterior, and superior-inferior shifts), and three rotations (flexion-extension, medial-lateral tilt, and medial-lateral rotation) (Fig. 1B). Translation was measured as the distance between the origins of patellar and femoral coordinate systems. A positive shift corresponded to the lateral, anterior or superior translation of the patellar center along the femoral axes. Patellar flexion was defined as the angle between the SI axis of the patella and long axis of the femur projected onto the sagittal plane of the femur. Patellar tilt was defined as the angle between the ML axis of the patella and the TEA projected onto the transverse plane of the femur. Patellar rotation was defined as the angle between the ML axis of the patella and the TEA of the femur projected onto the coronal plane of the femur. A positive patellar rotation was corresponded to the flexion, lateral tilt, or lateral rotation of the patella with respect to the femoral axes (Fig. 1B).

Patellofemoral cartilage contact points

Cartilage surfaces of the patella and femur built from the MR images of the knee were mapped to the corresponding bones at each reproduced knee position. Intersection area of the patellar and femoral cartilage at each knee position was automatically outlined and the centroid of the area was calculated. This centroid was defined as the patellofemoral cartilage contact location (Van de Velde, et al., 2008).

To quantitatively report the locations of the patellofemoral cartilage contact on the patellar cartilage, a symmetric coordinate system was defined by fitting an ellipse on the patellar cartilage (Fig. 2A). The medial-lateral and superior-inferior axes representing the axes of the ellipse were used to measure the contact locations on the patellar cartilage surface. The cartilage contact locations were normalized to the length of corresponding axes of the fitted ellipse.

To describe the path of the patellofemoral cartilage contact on the femoral cartilage, a previously described femoral coordinate system was used (Nha, et al., 2008). A rectangular cube was created with its axes parallel to the TEA and anterior-posterior axis of the femoral coordinate system and to enclose the distal part of the femoral condyles (Fig. 2B). This rectangular cube was limited by TEA and the most distal part of femoral condyles, the most medial and lateral points of the femoral condyles, and the most anterior and posterior points of the femur. The medial-lateral and superior-inferior coordinates of the contact points were normalized to the corresponding length of femoral rectangular cube (the dimensions of the rectangular cube in medial-lateral and superior-inferior directions). Distance between trochlear groove and contact path was also measured.

RESULTS

Tibiofemoral joint flexion

The flexion angle of the knee was $50.5^{\circ} \pm 12.7^{\circ}$ when the heel contacted on the step (Fig. 3). It reached a peak flexion of $51.2^{\circ} \pm 13.0^{\circ}$ at 10% of the activity. The knee was then continuously extended to full extension and reached $-1.7^{\circ} \pm 12.2^{\circ}$ of flexion at the end of the stair ascending.

Patellofemoral joint kinematics

The patellar flexion was monotonically reduced with extension of the knee during stair ascending (Fig. 4A). On average, the patellar flexion was reduced by 44° . The patella was tilted by $2.6^{\circ} \pm 3.5^{\circ}$ laterally at heel strike (Fig. 4B). The patellar tilt was approximately constant at the first 20% of stair ascending. Afterwards, the lateral patellar tilt was reduced. At 60% of the ascending (the knee was flexed at 21.8°), a slight medial tilt of the patella was observed. The patella tilted laterally again and reached $2.0^{\circ} \pm 3.1^{\circ}$ at full extension. On average, the patella rotation was rather constant during the stair ascending activity (Fig. 4C).

The patella was 5.1 ± 1.2 mm laterally to the femur at heel strike (Fig. 4D). With extension of the knee, it shifted by 3.9 mm medially up to 80% of the activity (the knee flexion was 7.8°). At the last 20% of the stair ascending, the patella shifted laterally and was 2.2 ± 3.3 mm lateral to the femur at full extension. In anterior-posterior direction, the patella moved anteriorly by 13 mm with extension of the knee from 0% to 80% of the activity (Fig. 4E). Thereafter, it slightly moved posteriorly by about 2 mm. In proximal-distal direction, the patella monotonically moved superiorly with extension of the knee from 26.2 ± 4.8 mm inferior to the femur at heel strike to 16.0 ± 9.3 mm superior to the femur at full knee extension (Fig. 4F). The patella moved in a range of approximately 42 mm in superior-inferior direction.

Patellofemoral cartilage contact points

In average, the contact points were at slightly lateral side of the patellar cartilage during the stair ascending activity (Fig. 5A). From heel strike to 60% of the ascending activity, the patellar contact was about 2 mm in lateral direction (Fig. 5B). With further extension of the knee, the contact point moved laterally and reached 5.3 ± 4.8 mm at full extension. In superior-inferior direction, the contact point was close to the center of the patellar cartilage

surface at heel strike (1.9 ± 3.2 mm, Fig. 5C). It moved constantly inferiorly with knee extension and reached -10.5 ± 2.2 mm at full extension. The contact point moved in a range of 12 mm in the superior-inferior direction during the stair ascending activity.

Patellofemoral contact locations on the femoral cartilage were also lateral to the femoral trochlea (Fig. 5D) with a relatively constant lateral position of 5 mm (Fig. 5E). As the knee getting close to full extension, the contact location moved more laterally. In superior direction, the contact point moved constantly superiorly with extension of the knee (Fig. 5F). The range of contact point motion was about 22 mm in superior direction during the stair ascending activity.

In general, a lateral and superior shift of the articular contact on the femoral cartilage surface was observed (Fig. 6). The closest distance of the contact location to the trochlear groove was 2.5 ± 5.0 mm at 10% of the ascending activity (when the knee was flexed maximally, Fig. 6). This distance was consistently increased with the extension of the knee. At 80% of ascending activity, the distance between the contact location and the trochlear groove was 8.2 ± 5.4 mm. Since the trochlear groove could not be recognized around the contact points corresponding to 90% and 100% of the activity, the distance between trochlear groove and contact path was not measurable at these data points.

DISCUSSION

Most previous studies on patellar kinematics have reported on the patellar tracking (Ahmed, et al., 1999; Heegaard, et al., 1995; Lin, et al., 2004; Reider, et al., 1981; Sakai, et al., 2000). Few data has been reported on the patellofemoral cartilage contact biomechanics during dynamic, functional knee joint motion (Derasari, et al., 2010; Seisler and Sheehan, 2007). This study investigated the patellofemoral tracking and the corresponding patellofemoral cartilage contact locations during a dynamic stair ascending activity using dual fluoroscopic imaging system. The data indicated that the patella rotates and tilts in a small range during the stair ascending extension. The patellofemoral articular contact path during extension of the knee showed similar trends with the observed patellar tracking.

There is a large variation in in-vivo and in-vitro patella tracking data in literature (Katchburian, et al., 2003). The patellar tracking was usually studied during knee flexion. In general, medial shift of the patella in early stage of knee flexion and lateral shift with increasing knee flexion were reported (Amis, et al., 2006; Heegaard, et al., 1995; MacIntyre, et al., 2006; Nagamine, et al., 1995; Nha, et al., 2008). Varadarajan et al. showed that the trochlear groove moves and twists laterally with flexion of the knee and the trochlear geometry had considerable effect on the patellar tilt (Varadarajan, et al., 2010). Consistent with this observation, our data indicated that by extending the knee during stair ascending, the patella shifted and tilted medially until about 20° to 30° of knee flexion, where the patella exited the sulcus and tilted laterally. These data are similar in trend to those reported in literature, but with lower magnitude.

The patellar tracking not only depends on the geometry of the bone, but also the magnitude and direction of muscle forces. For example, quadriceps forces greatly influence on the patellar movement (Lin, et al., 2004; Sakai, et al., 2000). Stair ascending requires higher quadriceps forces than other activities such as knee flexion or level walking (Morrison, 1969). The high quadriceps forces could cause the patella to engage within the trochlea at lower flexion angles of the knee, thus limiting the motion of the patella.

Few data has been reported on in-vivo patellofemoral joint contact biomechanics. A previous study on patellofemoral joint contact mechanics during a quasi-static single leg lunge (Van de Velde, et al., 2009) found that the contact points were on central or slightly

medial side of the patellar cartilage at low flexion angles. In this study, the data on contact points of patellofemoral articular cartilage surfaces during the stair ascending extension were found to be on the lateral side of the patellofemoral joint. The contact points shifted more laterally at final stage of the activity. These data indicated that the patellofemoral joint contact is more lateral during stair ascending than during the quasi-static single leg lunge. As the patellofemoral joint motion is affected by the loading environment of the joint, it is not surprising that the patellofemoral contact during stair ascending is different from that during the quasi-static single leg lunge. Although, it should be kept in mind that the definitions of the coordinate systems in our investigation and Van de Velde's study are slightly different. The various loading conditions and coordinate system definitions used in different studies of the patellofemoral joint kinematics made it impossible to objectively compare the data among these studies (Katchburian, et al., 2003; MacIntyre, et al., 2006; Nagamine, et al., 1995; Wilson, et al., 2009; Gill, et al., 2009; Nha, et al., 2008; Li, et al., 2007; Sheehan, et al., 1999). Future studies should investigate the patellofemoral joint contact kinematics during various functional activities such as walking, stair descending, etc. to examine the patellofemoral joint function under different loading conditions.

The path of the articular cartilage contact locations of the patellofemoral joint (Fig. 5E) showed a similar pattern to those of patellar shift and tilt (Figs. 4B and 4D), with contact location consistently on the lateral compartment of the femur. The patellofemoral cartilage contact points on the patellar cartilage shifted laterally at 60 % of the ascending activity (Fig. 5B), that was when the patellar tilt changed its direction from medial to lateral tilt (Fig. 4B). The contact location shifted more laterally when the patella tilted more laterally.

The patella moved superiorly by 42 mm during the stair ascending extension of the knee. The contact point on the patellar articular surface moved inferiorly by 12 mm. However, the corresponding contact location on the femoral articular surface moved superiorly by 22 mm. The length of the contact path on the femoral condyle is almost 1.8 times of that on the patellar surface. Therefore, the patellar cartilage and the femoral cartilage may experience different articular contact kinematics during the dynamic motion of the patellofemoral joint. These data also imply that description of the patellofemoral joint kinematics should include quantification of both the patellar tracking as well as the articular contact kinematics in order to understand the overall joint function.

Certain limitations of the current study should be noted. Gender differences may exist in the tibiofemoral rotation kinematics and trochlear groove orientation (Varadarajan, et al., 2009). However, due to the small number of subjects, the gender differences in the stair ascending kinematics were not included in this study. Further, the kinematics of the patellofemoral joint during stair descending should also be studied and compared with those of stair ascending in future works. Comparing knee joint motion with other activities, such as walking, standing up from chair or running, is necessary.

In conclusion, this study determined 6DOF in vivo kinematics of the patellofemoral joint of the knee during stair ascending using the dual orthogonal fluoroscopic system. The patella was shown to shift and tilt in a small range, but vary in a similar pattern with the patellofemoral joint contact path during the stair ascending activity. The rotation of the patella was found small during the ascending extension. The path of patellofemoral cartilage contact points was located on lateral side of patellar and femoral cartilage surfaces. These data provide baseline knowledge for understanding of normal function of the patellofemoral joint and can also be used as a reference to evaluate the abnormal joint kinematics caused by various joint pathologies, to improve the contemporary surgical treatments, and to validate the data of in-vitro experiments and computational simulations.

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Figure 1.

(A) A virtual dual fluoroscopic imaging system was used to reproduce in vivo knee kinematics. The 3D MR-based bony models were matched to their outlines on the fluoroscopic images, (B) Definition of the coordinate systems used to quantify motions of the patella and femur. Femoral coordinate system consists of the transepicondylar axis (TEA) and long axis intersecting at the origin of the femur (midpoint of TEA). Patellar coordinate system consists of superior-inferior (SI), anterior-posterior (AP), and medial-lateral (ML) axes. Lateral shift, anterior shift, superior shift, flexion, lateral tilt, and lateral rotation of patella were considered positive, as shown in the figure.

Figure 2.

Definition of the coordinate systems used to quantify the translation of patellofemoral cartilage contact points on the patellar and femoral cartilages (used for normalization of data). **(A)** An ellipse fitted to the patellar cartilage mesh in posterior view: the ellipse's axes were used to define the axes of the patellar coordinate system, **(B)** Rectangular cube of femur: its axes were parallel to the TEA and anterior-posterior axis of femoral coordinate system and it enclosed the distal part of femoral condyles.

Tibiofemoral flexion

Figure 3.

Tibiofemoral flexion angle measured during stair ascending. The kinematics reported here represents the motion of the tibia relative to the femur. One ascending motion is defined from heel strike on the stair to full knee extension.

Figure 4.

6 degrees-of-freedom kinematics of the patellofemoral joint measured during stair ascending. The kinematics represents the motion of the patella relative to the femur. (A) flexion angle, (B) lateral tilt angle (C) lateral rotation angle, (D) medial-lateral shift, (E) anterior-posterior shift, (F) superior-inferior shift.

Figure 5.

The average values of translation of the patellofemoral cartilage contact points during the stair ascending activity. (A) The path of the patellofemoral contact points on the patellar cartilage, (B) medial-lateral shift on the patellar cartilage, (C) superior-inferior shift on the patellar cartilage, (D) the path of the patellofemoral contact points on the femoral cartilage, (E) medial-lateral shift on the femoral cartilage, (F) superior-inferior shift on the femoral cartilage.

The values on the left side of the figures are absolute kinematic values. The values on the right side of the figures are the normalized kinematic values reported as a percentage (absolute values normalized to their corresponding characteristic lengths). The characteristic lengths were chosen as the length of the main axes of the ellipse fitted to the patellar cartilage and the main axes of the rectangular cube fitted to the femoral condyles for the contact points on the patellar cartilage and the femoral cartilage, correspondingly.

Distance between trochlear groove and the patellofemoral contact points

Figure 6.

Distance between trochlear groove and the path of the patellofemoral contact points on the femoral cartilage.