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Automatic Determination of an Anatomical Coordinate System for a Three-Dimensional Model of the Human Patella

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Abstract

Measuring the *in vivo* 3-D kinematics of the patella requires a repeatable anatomical coordinate system (ACS). The purpose of this study was to develop an algorithm to determine an ACS using the patella's unique morphology.

An ACS was automatically constructed that aligned the proximal/distal (PD) axis with the posterior vertical ridge. Inter-subject ACS repeatability was determined by registering all patellae and their associated ACSs to a reference patella.

The mean angle between the reference patella ACS and each subject's axes was less than 2.5° and the 95%CI was 1.0°–4.0.

Here, we presented an anatomical coordinate system that is independent of the observer's subjective judgement or orientation of the knee within the scanner.

Keywords

Patella; Kinematics; Biplanar Vidoradiography; Computed Tomography; Anatomical Coordinate System; In Vivo; Patellofemoral

Introduction

Patellofemoral pain (PFP) is one of the most common disorders of the knee, affecting up to 20% of the population (Laprade and Culham, 2003). However, the pathomechanics of PFP are not fully understood. Recent studies have evaluated *in vivo* patellofemoral kinematics statically (Noehren et al., 2011; Salsich and Perman, 2012) or during activities like deep knee flexion (Behnam et al., 2011; Kobayashi et al., 2012; Powers et al., 2003). These studies have computed patellofemoral kinematics using an anatomical coordinate system (ACS) that was determined using manual point selection methods (Fellows et al., 2005) or by fitting a bounding box (Li et al., 2007; Nha et al., 2008). Point selection methods depend

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on subjective identification of landmarks, and a bounding box depends on the orientation of the patella in the scanner. An ACS that takes advantage of the patella's unique surface features may extend these methods by removing dependence on subjective measures or scanner orientation.

The patella resembles a rounded triangle shape in the coronal plane. Distally, the patella forms an apex where the patellar tendon inserts. The posterior surface has medial and lateral facets that articulate with the trochlear groove of the femur. A distinct vertical ridge separates these medial and lateral facets. The ridge is a key landmark when measuring the motion of the patella with respect to the femur and has been used as a reference to take static radiographic measurements of patellar alignment (Laurin et al., 1978; Merchant et al., 1974). This prominent feature lends itself well to automatic identification using surface-based topography, a method that does not depend on subjective input from an observer.

The purpose of this study was to evaluate the repeatability, *in vivo*, of an automated algorithm for establishing an anatomic coordinate system for the patella, and to compare this algorithm to the commonly used bounding box method.

Methods

Following IRB approval and informed consent, one knee (distal femur to proximal tibia) each of ten healthy subjects (5M, 25±4.2yrs; 5F, 26±2.3yrs) was CT scanned (LightSpeed 16; GE, Piscataway, NJ: 80kVp, SMART mA, 0.381mm×0.381mm×0.625mm voxel size). A 3-D model of the patella was generated by segmentation using Mimics v14 (Materialise, Ann Arbor, MI).

The following procedure generated an ACS of the patella that was aligned with its posterior vertical ridge (ACS_A). The centroid and inertial axes of the patella model were computed (Crisco and McGovern, 1998). We note that the inertial axes are independent of scanner orientation. The centroid served as the origin of ACS_A. Due to the patella's near-circular shape in the coronal plane, the third inertial axis consistently defined the anterior/posterior (AP) axis, while the first and second inertial axes were variable across subjects. A rotation, θ , of the inertial coordinate system about the AP axis created a new, test coordinate system. The rotated axes of the test coordinate system were designated axis-1 and axis-2. The posterior surface was then iteratively scanned in 1mm slices along the axis-1 direction. At each slice, the axis-2 coordinate of the most posterior point on the patella was recorded, yielding a set of points across the surface that defined the vertical ridge. After the posterior surface was scanned, the standard deviation of all axis-2 coordinates of the vertical ridge points was computed (Figure 1A). The final coordinate system was determined after optimizing the rotation angle, θ . This was done by minimizing the standard deviation of the axis-2 coordinate of the vertical ridge points (Figure 1B,C). The minimization was performed using Matlab's nonlinear optimization function, *fmincon*, with an angular tolerance of 1e-8° (Mathworks, Natick MA). Following the minimization, axis-2 served as the medial/lateral (ML) axis, and axis-1 served as the proximal/distal (PD) axis. This procedure aligned the PD axis with the posterior vertical ridge (Figure 1D).

We evaluated the variability in ACS_A with the morphology of the whole patella using a previously established method (Miranda et al., 2010). Briefly, we scaled (by volume) and registered all patellae and their associated ACS_A to a single reference patella using the alignment algorithm in Geomagic (Raindrop Geomagic, Research Triangle Park, NC) (Figure 2A). We then computed the resultant AP, ML, and PD axis from the vector sum of all AP, ML, and PD axes, and the centroid of all ACS_A origins. Inter-subject variability was

determined by calculating the angle between the resultant axis and each subject's axis and the distance between the centroid of all ACS_A origins and each subject's origin.

Finally, we computed a second patella ACS for each subject using the bounding box method (ACS_B) described by Li et al. (2007). Variability in ACS_B was computed as described above and then compared to the variability of ACS_A. These variables were reported as the mean and 95% confidence interval (CI). A two-way ANOVA evaluated differences for each axis (AP, ML, and PD) between ACS_A and ACS_B. A Students t-test evaluated differences in variability between the origin of ACS_A and ACS_B ($p < 0.05$).

Results

The variability in axis orientation was substantially less for the automated ACS algorithm (ACS_A) compared to the bounding box method (ACS_B) ($P < 0.001$) (Figure 3). ACS_A variability for the AP, ML, and PD axes was 1.3° (CI: 0.8°- 1.7°), 2.5° (CI: 1.1°- 3.9°), and 2.5° (CI: 1.0°- 4.0°), respectively (Figure 2B). ACS_B variability was 8.6° (CI: 4.7°- 12.4°), 9.0° (CI: 5.4°- 12.6°), and 6.1° (CI: 2.9°- 9.2°), for the AP, ML, and PD axes respectively (Figure 2C).

There was a trend of less variability in origin location of ACS_A than ACS_B ($P = 0.051$). The mean distance between the centroid of all origins and individual origins was 0.7 mm (CI: 0.5mm–0.9mm) and 1.2 mm (CI: 0.69mm-1.6mm) for ACS_A and ACS_B respectively.

Discussion

The aim of this study was to describe an automatic ACS algorithm for the patella that is aligned with the posterior vertical ridge. The vertical ridge is important because it separates the medial and lateral facets that articulate within the trochlear groove of the femur. We found that the coordinate system is consistent across subjects when compared to a whole bone registration method. Whether the small variability between subjects is due to the algorithm or differences in patellar morphology cannot be answered with these methods. However, inter-subject variability in patellar shape is visually noticeable. Therefore, we postulate that the ACS algorithm fully aligns the proximal-distal axis with the vertical ridge of each patella, but between subjects, the vertical ridge is oriented slightly differently with respect to other features of the patella, such as the apex. The low inter-subject variability of the ACS_A suggests that this morphology based method is robust.

The variability in axis orientation and location of this new method is markedly lower compared to the bounding box method of ACS determination. The bounding box method automatically defines an ACS, but relies on repeatable positioning of the knee within the CT or MRI scanner (Li et al., 2007; Nha et al., 2008). Manual point selection methods do not rely on knee posture to define the patella ACS, but they are inherently subjective and may vary within and among raters (Della Croce et al., 2005). While evaluating kinematics was beyond the scope of this study, we postulate that the bounding box method or subjective methods using manual point selection, may be responsible for some of the high inter-subject variability reported in studies of patellofemoral motion (Nha et al., 2008; Patel et al., 2003; Seisler and Sheehan, 2007). Since the presented ACS is more consistent across subjects, its application to patellofemoral kinematics may reduce inter-subject variability, and facilitate a better understanding of patellofemoral joint mechanics.

The automated coordinate system can be used to quantify local features of the patella and, when combined with a femoral coordinate system, clinically relevant patellofemoral kinematics can be interpreted. We sought to establish an ACS that follows standard terminology for patellar motion. Previous recommendations define *tilt* as rotation of the

patella about its own proximal distal axis, flexion as rotation of the patella about the flexion axis of the femur, *rotation* as rotation of the patella about its AP axis which is tethered to the femoral flexion axis, and *shift* as translation of the patella's origin with respect to the flexion axis of the femur (Bull et al., 2002). This new ACS follows these recommendations when combined with a previously established algorithm that computes an ACS of the femur (Miranda et al., 2010). These algorithms remove variability associated with subjective identification of anatomical landmarks, knee posture, or orientation of the leg in the scanner. Automatic ACS definition also allows for more consistent comparisons across subjects and studies. Moreover, intra-subject ACS variability will be zero provided a new CT or MRI scan is not required for a repeated measures experiment with multiple visits. These methods represent an important step to study *in vivo* patellofemoral kinematics using skeletal motion capture technology such as biplanar videoradiography or dynamic MRI.

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Figure 1.

Figure 2.

Figure 3.