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Short communication

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.

1. 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 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.

2. Methods

Following IRB approval and informed consent, one knee (distal femur to proximal tibia) each of ten healthy subjects (5M, 25 ± 4.2 yr; 5F, 26 ± 2.3 yr) was CT scanned (LightSpeed 16; GE, Piscataway, NJ: 80 kVp, SMART mA, 0.381 mm × 0.381 mm × 0.625 mm 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

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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 1 mm 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 (Fig. 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 (Fig. 1B and 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 (Fig. 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) (Fig. 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 ($P<0.05$).

3. Results

The variability in axis orientation was substantially less for the automated ACS algorithm (ACS_A) compared to the bounding box method (ACS_B) ($P<0.001$) (Fig. 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 (Fig. 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 (Fig. 2C).

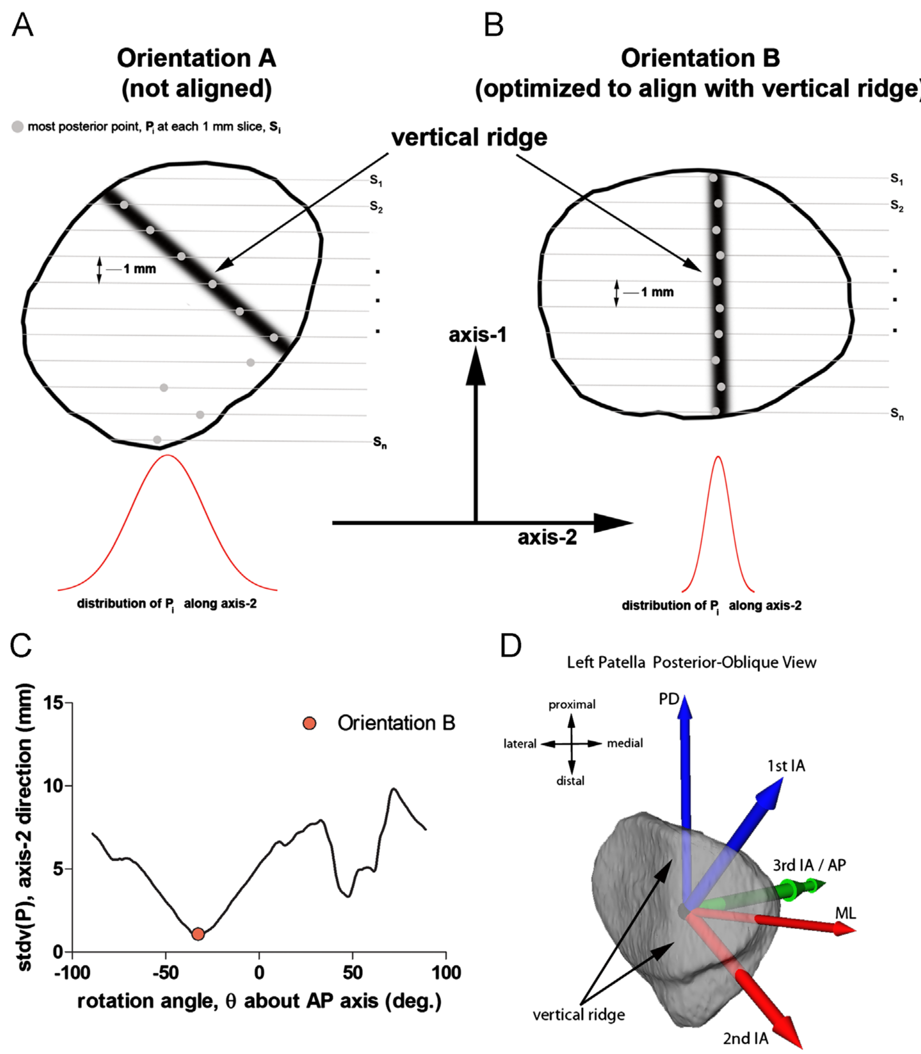

Fig. 1. Algorithm to compute the anatomical coordinate system (ACS_A) of the patella. The 3rd inertial axis was well defined and served as the anterior/posterior axis (AP). A test coordinate system was created by rotating the 1st and 2nd inertial axes by θ° about the AP axis. The rotated axes were designated axis-1 and axis-2. A. Axis-1 and axis-2 at an arbitrary rotation angle (θ) about the AP axis. For visualization purposes, we rotated the patella rather than the axes. Here, the patella's vertical ridge is not aligned with axis-1. When the patella is scanned in the axis-1 direction the axis-2 locations of the most posterior points, P_i are variable across the posterior surface of the patella. B. Rotation, θ, where the standard deviation of the axis-2 coordinates across the surface of the patella is minimized. C. An example of an explicitly computed cost function. The standard deviation (stdv) of the axis-2 location of all points, P_i for all rotations about the AP axis. Each rotation angle represents a different test coordinate system. The red circle indicates the rotation, θ, where the standard deviation is minimized and axis-1 is aligned with the posterior vertical ridge. D. Representative patella from a single subject. The 1st, 2nd, and 3rd inertial axes (IA) (shorter, heavier arrows) served as an initial guess. The longer, thinner vectors represent the final coordinate system that is aligned with the vertical ridge. The proximal/distal (PD) axis was aligned with the vertical ridge and the medial/lateral (ML) axis was perpendicular to the PD axis. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)