Journal of Biomechanics 58 (2017) 187–194

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Statistical shape modeling predicts patellar bone geometry to enable stereo-radiographic kinematic tracking

Lowell M. Smoger, Kevin B. Shelburne, Adam J. Cyr, Paul J. Rullkoetter, Peter J. Laz *

Center for Orthopaedic Biomechanics, University of Denver, Denver, CO, USA

ARTICLE INFO

Article history:
Accepted 8 May 2017

Keywords:
Statistical shape modeling
Patella
Stereo radiography
Fluoroscopy
Kinematics
Subject-specific geometry
Total knee replacement

ABSTRACT

Complications in the patellofemoral (PF) joint of patients with total knee replacements include patellar subluxation and dislocation, and remain a cause for revision. Kinematic measurements to assess these complications and evaluate implant designs require the accuracy of dynamic stereo-radiographic systems with 3D-2D registration techniques. While tibiofemoral kinematics are typically derived by tracking metallic implants, PF kinematic measurements are difficult as the patellar implant is radiotransparent and a representation of the resected patella bone requires either pre-surgical imaging and precise implant placement or post-surgical imaging. Statistical shape models (SSMs), used to characterize anatomic variation, provide an alternative means to obtain the representation of the resected patella for use in kinematic tracking. Using a virtual platform of a stereo-radiographic system, the objectives of this study were to evaluate the ability of an SSM to predict subject-specific 3D implanted patellar geometries from simulated 2D image profiles, and to formulate an effective data collection methodology for PF kinematics by considering accuracy for a variety of patient pose scenarios. An SSM of the patella was developed for 50 subjects and a leave-one-out approach compared SSM-predicted and actual geometries; average 3D errors were 0.45 ± 0.07 mm (mean ± standard deviation), which is comparable to the accuracy of traditional segmentation. Further, initial imaging of the patella in five unique stereo radiographic perspectives yielded the most accurate representation. The ability to predict the remaining patellar geometry of the implanted PF joint with radiographic images and SSM, instead of CT, can reduce radiation exposure and streamline *in vivo* kinematic evaluations.

1. Introduction

Patellofemoral (PF) joint complications continue to account for a significant percentage (up to 10%) of total knee replacement (TKR) revisions (Healy et al., 1995; Dalury and Dennis, 2003; Rhee and Haddad, 2008). Pathologies such as patellar subluxation and maltracking are characterized by medial-lateral (ML) translation and internal-external rotation of the patella (Singerman et al., 1997; Kawano et al., 2002) and remain a common cause of TKR revisions (D'Lima et al., 2003). Measuring dynamic *in vivo* PF joint kinematics to understand these complications and interactions between PF and tibiofemoral (TF) joints continues to be a challenge for patients with TKR because of the need for accuracy in multiple degrees of freedom (DOF) and difficulties in tracking the implanted patella. Current *in vivo* kinematic measurement techniques for the knee include static (Fellows et al., 2005; Pal et al., 2011; Freedman and Sheehan, 2013) and dynamic (Powers et al., 1998; Powers et al., 2003; von Eisenhart-Rothe et al., 2004; von Eisenhart-Rothe et al., 2007; Sheehan et al., 2009; Carpenter et al., 2009) magnetic resonance (MR) imaging. Static MR images have been unable to reproduce dynamic joint motion and dynamic MR studies have relied on combining scans from multiple cycles (Powers et al., 2003; Bey et al., 2008). Dynamic single-plane fluoroscopy has been used to evaluate primarily sagittal plane *in vivo* PF kinematics for TKR patients during flexion-dominated activities (Komistek et al., 2000; Stiehl et al., 2001; Argenson et al., 2005; Leszko et al., 2010). In particular, the sagittal angle of the patellar bone resection surface was measured relative to the tibial long axis and an estimate of the PF contact location was defined by the shortest perpendicular distance between the femoral component and patellar mass center.

Stereo radiography or biplane fluoroscopy has been utilized for *in vivo* kinematic measurements of the natural TF (You et al., 2001; Li et al., 2008; Bey et al., 2008; Baka et al., 2014) and PF (Nha et al., 2008; Bey et al., 2008), and implanted TF (Bingham and Li, 2006; Hanson et al., 2006) joints. Traditionally, the process

* Corresponding author at: Center for Orthopaedic Biomechanics, Mechanical and Materials Engineering, University of Denver, 2155 E. Wesley Ave, Denver, CO 80208, USA. Fax: +1 303 871 4450.

E-mail address: plaz@du.edu (P.J. Laz).

http://dx.doi.org/10.1016/j.jbiomech.2017.05.009

to obtain *in vivo* kinematics from stereo radiography involves two steps: representation of the bone, typically from segmentation of a CT or MRI scan, or metallic implant from a computer-aided-design (CAD) model, followed by manual or semi-automated tracking of the bone or implant in the image sequence of the dynamic activity (Ackland et al., 2011). Studies have used automated three-dimensional to two-dimensional (3D-2D) registration of virtual bone or implant models to fluoroscopic images for 3D pose extraction of the joint (Mahfouz et al., 2003; Bingham and Li, 2006). Feature-based methods work to align silhouette contours of the model projections to the X-ray images, while intensity-based methods work to align digitally reconstructed radiographs (DRRs) considering density (You et al., 2001; Yao and Taylor, 2003; Gollmer et al., 2007; Dworzak et al., 2010). Comparing a 3D-2D registration method between dual-plane and single-plane systems, Zhu and Li (2012) reported sub-millimeter and sub-degree accuracies for TF joint tracking with a dual-plane system; this amounted to 2x in-plane and 10x out-of-plane improvements in accuracy over their single-plane system. Recently, a high-speed stereo-radiographic imaging system was developed at the University of Denver to measure *in vivo* joint kinematics (Ivester et al., 2015). Using a semi-automated 3D-2D registration method of DRRs from a CT-based model with XROMM (Brown University; Brainerd et al., 2010), 3D tracking errors of 0.15 mm (S.D. 0.13 mm) in translation and 0.41° (S.D. 0.30°) in rotation were reported for motions of a human knee phantom containing cadaver bones (Ivester et al., 2015).

Stereo radiographic tracking of the implanted patella is challenging because the patellar implant is radiotransparent. While tracking embedded beads is accurate to <0.1 mm and 0.1° (Bingham and Li, 2006), this method would require custom modified implants and does not translate easily to larger, population studies. Without beaded implants, the resected patella requires either pre-surgical imaging of bones and precise implant placement or post-surgical imaging, which can be challenging due to imaging artifacts, expense, and increased patient exposure to radiation with computed tomography (CT).

Statistical shape models (SSMs) have become an accepted tool to describe anatomical variation and have characterized the morphology of individual bones and whole joints (Bryan et al., 2010; Yang et al., 2008; Rao et al., 2013; Smoger et al., 2015). SSMs offer an alternative means to obtain the 3D subject-specific bone geometry from stereo-radiographic images, thus avoiding the need for segmentation. Recently, automated approaches have utilized SSMs to *simultaneously* estimate 3D shape and 6-DOF pose from 2D image sets (Laporte et al., 2003; Zheng et al., 2009; Kurazume et al., 2009; Zhu and Li, 2011; Baka et al., 2011). Feature-based methods, utilizing contours of bone shape, have been applied to the rib cage (Dworzak et al., 2010), the distal femur using a deformable Kriging algorithm (LaPorte et al., 2003) or Canny edge detection (Zheng and Nolte, 2006), and the proximal femur using morphometric measurements (Schumann et al., 2010) or a level set method (Kurazume et al., 2009). Intensity-based methods, which are computationally expensive and benefit from more complex shapes to generate unique DRRs, have been previously applied in the pelvis (Yao and Taylor, 2003), as well as the femur and tibia (You et al., 2001). Recently, using an automated feature-based approach with multi-stage optimization, Baka et al. (2012, 2014) predicted both shape and pose of the tibia and femur from biplane fluoroscopic images of a gait cycle. Valenti et al. (2016) and Yu et al. (2017) applied similar techniques to obtain 3D representations of the distal femur with Gaussian Mixture Models and proximal femur with B-spline based statistical models, respectively. Schumann et al. (2016) simulated the proximal and distal portions of the femur as fragments; their fully automated image processing technique assessed bone alignment with applications to deformity correction and fracture repair. While these methods are advancing the state of the art and show promise, 3D-2D registration is challenging and in our experience, often requires manual intervention, leading to a semi-automated kinematic extraction process.

Limited work has been performed to generate subject-specific patellae or track implanted PF joint motions from fluoroscopic images, likely due to the issues with radiotransparency of the implant. Further, the resected patella may be occluded by the metallic femoral component depending on the activity, patient positioning and imaging planes. Most prior automated studies used images from an activity to develop the shape representation. Accordingly, the objectives of this study were to use a virtual platform of a stereo-radiographic imaging system to evaluate the ability of an SSM to predict subject-specific 3D patellar geometries from simulated target profiles, and to formulate an effective data collection methodology for *in vivo* PF kinematics by considering accuracy in a variety of patient pose scenarios. The emphasis of this study was to develop an approach to initially image the knee in controlled positions where the patella was clearly visible. Further, simulating the radiographic images, 2D profiles were used with the SSM to create the 3D representation of the resected patella, which can be used for subsequent semi-automated kinematic tracking. This approach is in contrast to more automated, combined (shape and pose) optimization studies, which have been applied in the femur and tibia (e.g. Baka et al., 2014; Yu et al., 2017). By utilizing a cohort of segmented patellar geometries and a computational platform, this study establishes a workflow for future experimental protocols without risk to patients.

2. Methods

An SSM of the healthy normal patellar bone was developed from a training set of 50 knees, derived from imaging on cadavers and the Osteoarthritis Initiative (OAI) database. The knees were from 25 males and 25 females whose average age was 64 years (range: 44–87), average weight was 73 kg (range: 43–127), and average body mass index (BMI) was 25.2 (range: 19.0–41.3). The OAI database is available for public access at http://www.oai.ucsf.edu/. The specific dataset used was 0. E.1, which consisted of baseline (initial healthy) scans. Subjects were included if they were deemed healthy and normal with no signs of osteoarthritis. The patellae were reconstructed from MR scans using ScanIP (Simpleware, Exeter, UK) and registered to a template mesh (Rao et al., 2013; Smoger et al., 2015). Registration was performed through an iterative closest point algorithm and provided nodal correspondence between all subjects in a common local coordinate system. The template mesh was developed for the median subject and consisted of 472 nodes with an average element edge length of approximately 3 mm (Fitzpatrick et al., 2011). The local coordinate system for the template patella was developed with the origin located at the geometric centroid and axes constructed from the proximal, distal and lateral points around the articular periphery (Rao et al., 2013).

The SSM was established by applying principal component analysis (PCA) to the training set of 50 subjects. Each subject's shape was represented by a 1416×1 vector of its registered 3D nodal coordinates (x, y, z). PCA is a statistical technique to decompose a large data set into its primary modes of variation or principal components (PCs). After applying PCA to the covariance matrix of the training set data, the modes of variation described the anatomic variation present in the dataset and enabled both training set subjects and new instances to be represented by the SSM with a series of PC scores. By reducing the dimensionality of a dataset, the subsequent optimization of patellar shape can be performed with a small set of PC scores.

A virtual model of the stereo-radiography system was developed to simulate an experimental data collection on a population of subjects. Leveraging prior data collections in the knee, the model was based on experimental images and projection parameters for a single subject participating in a larger IRB-approved study (Kefala et al., in press). To capture the resected bone of the implanted construct and avoid occlusion from the metallic implants and surrounding tissue, the patella was imaged in specific positions to capture the shape and resection plane. With the subject supine and knee flexed at 45°, images were collected in the sagittal and transverse directions with respect to cameras A and B, respectively (Fig. 1). Radiopaque markers were placed on the patella to locate the patella in the imaging volume of the system. A direct linear transform (DLT), which maps 3D objects onto the camera's 2D image plane, was calculated in a calibration process (Brainerd et al., 2010). Briefly, a DLT is estimated by identifying, in each camera image, points on a cube at known relative positions in the 3D object space. The markers were digitized on the radiographs and the DLT transformed the digitized points into the 3D object space to locate the virtual imaging volume. Marker digitization and camera calibration was conducted in XRayProject (XROMM, Brown University).