Journal of Biomechanics 47 (2014) 122–129

Contents lists available at ScienceDirect

Journal of Biomechanics

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

Evaluation of automated statistical shape model based knee kinematics from biplane fluoroscopy

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ARTICLE INFO

Article history:
Accepted 26 September 2013

Keywords:
Tracking
SSM
Femur
Tibia
2D/3D reconstruction

ABSTRACT

State-of-the-art fluoroscopic knee kinematic analysis methods require the patient-specific bone shapes segmented from CT or MRI. Substituting the patient-specific bone shapes with personalizable models, such as statistical shape models (SSM), could eliminate the CT/MRI acquisitions, and thereby decrease costs and radiation dose (when eliminating CT). SSM based kinematics, however, have not yet been evaluated on clinically relevant joint motion parameters.

Therefore, in this work the applicability of SSMs for computing knee kinematics from biplane fluoroscopic sequences was explored. Kinematic precision with an edge based automated bone tracking method using SSMs was evaluated on 6 cadaveric and 10 in-vivo fluoroscopic sequences. The SSMs of the femur and the tibia–fibula were created using 61 training datasets. Kinematic precision was determined for medial–lateral tibial shift, anterior–posterior tibial drawer, joint distraction–contraction, flexion, tibial rotation and adduction. The relationship between kinematic precision and bone shape accuracy was also investigated.

The SSM based kinematics resulted in sub-millimeter (0.48–0.81 mm) and approximately 1° (0.69–0.99°) median precision on the cadaveric knees compared to bone-marker-based kinematics. The precision on the in-vivo datasets was comparable to that of the cadaveric sequences when evaluated with a semi-automatic reference method. These results are promising, though further work is necessary to reach the accuracy of CT-based kinematics. We also demonstrated that a better shape reconstruction accuracy does not automatically imply a better kinematic precision. This result suggests that the ability of accurately fitting the edges in the fluoroscopic sequences has a larger role in determining the kinematic precision than that of the overall 3D shape accuracy.

1. Introduction

Knee kinematics measurements are performed to describe normal joint function (Giphart et al., 2008; Li et al., 2005; Torry et al., 2010), to improve prosthesis designs (Kitagawa et al., 2010), and to characterize injury (Defrate et al., 2006; Dennis et al., 2005).

The most accurate method to assess joint kinematics is biplane fluoroscopy using metallic markers inserted in the bones to assess their pose through time (Tashman and Anderst, 2003). As marker insertion is invasive, this technique is not suitable in most cases. Skin marker-based kinematics on the other hand is prone to soft-tissue motion, resulting in errors larger than 10 mm (Garling et al., 2007; Stagni et al., 2005). More accurate kinematics can be obtained with model-based tracking in fluoroscopy (Fregly et al., 2005; Kitagawa et al., 2010; Li et al., 2008; Muhit et al., 2010; Nakajima et al., 2007; Pickering et al., 2009; Scott and Barney Smith, 2006; Tsai et al., 2010; You et al., 2001). These methods align a 3D bone model, segmented from CT or MRI, with calibrated fluoroscopic sequences. Alignment is achieved by minimizing either an image intensity distance through calculation of digitally

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http://dx.doi.org/10.1016/j.jbiomech.2013.09.022

reconstructed radiographs (DRR) (Anderst et al., 2009; Bey et al., 2008; Dennis et al., 2005; Mahfouz et al., 2003; Muhit et al., 2010; Nakajima et al., 2007; Pickering et al., 2009; Scott and Barney Smith, 2006; You et al., 2001), or an image edge to bone model silhouette distance (Defrate et al., 2006; Fregly et al., 2005; Gollmer et al., 2007; Hanson et al., 2006; Hirokawa et al., 2008; Kitagawa et al., 2010; Li et al., 2008; Tersi et al., 2013; Torry et al., 2011; Tsai et al., 2010). Kinematic analysis not requiring the subject-specific 3D model would, however, be preferred, as it would lower analysis costs and eliminate the prior 3D acquisition, resulting in lower radiation dose in the case of CT.

Statistical shape models (SSMs) could replace subject-specific shapes, as they are able to generate previously unseen shapes resembling the population they were built on. SSMs have been applied for reconstruction of bone shapes from single time-point biplane X-ray images (Baka et al., 2011; Gamage et al., 2009; Whitmarsh et al., 2011; Zheng et al., 2008; Zhu and Li, 2011). They have recently also been proposed for kinematic analysis differentiating between healthy and pathologic wrists (Chen et al., 2011), and assessing femur kinematics from in-vivo drop-landing sequences (Baka et al., 2012).

While first results with SSM based tracking were encouraging, the lack of evaluations of clinically relevant joint motion parameters makes the accuracy of SSM based joint kinematics yet unknown. Also, several studies indicated that the accuracy of the 3D bone surface may influence the kinematic accuracy (Moewis et al., 2012; Moro-oka et al., 2007). The aim of this study was, therefore, to explore the applicability of SSMs for calculating knee kinematics from biplane fluoroscopy. The following research questions were posed:

1. Does the 3D shape reconstruction accuracy influence the kinematic tracking precision?
2. What kinematic tracking precision can we achieve with the SSM using an automated edge based approach?

We performed experiments on high-speed biplane fluoroscopic sequences analyzing the drop-landing motion of 6 cadaveric and 10 in-vivo knees.

2. Data

2.1. Kinematic data

The in-vivo dataset consisted of 10 drop-land sequences acquired with a high-speed (500 frames/s), high resolution (1024×1024 pixels), custom built biplane fluoroscopic setup. The sequences were part of earlier studies (Torry et al., 2011, 2010), where the acquisition setup was described in detail. Briefly, subjects were asked to perform a drop-landing from a 40 cm high box, and land on their dominant leg in the field-of-view (FOV) of the biplane fluoroscopic camera system. The average sequence length was 74 frames. All subjects were also scanned by CT to attain the subject-specific knee shape.

The cadaver dataset consisted of 6 intact cadaveric knees, which were dropped in the FOV of the bi-plane fluoroscopic system to simulate the drop-landing motion. The sequences were part of an earlier study (Giphart et al., 2012), which contains more detail on the experimental setup. The bones were implanted with tantalum beads to enable marker-based kinematic analysis. All cadaveric knees were also scanned by CT.

2.2. Training set of the SSM

The training set of the SSM of the femur and the combined tibia–fibula consisted of 62 knee CT images, from which 10 were subjects from the in-vivo kinematic dataset, 47 were subjects scanned for other medical reasons than arthritis, and 5 were cadavers from the kinematic dataset. The population contained both sexes with a wide age range (subjects were 21–66 years old, the cadavers' age was unknown). The CT images were acquired on different scanners with in-plane voxel sizes between 0.6 and 0.78 mm, and slice thickness between 0.5 and 0.8 mm.

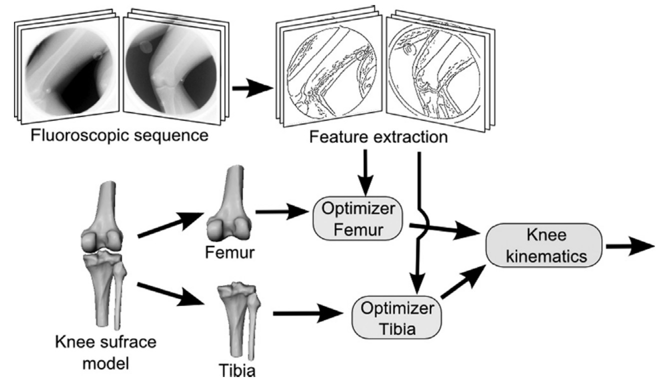

Fig. 1. The diagram of a general feature based knee kinematics method. First, the features (edges) in the fluoroscopic images are extracted in every frame. Second, a surface model of the femur and the tibia is aligned in 3D space to best match the features in the fluoroscopic frames. Finally, the pose estimates of the femur and tibia through time are converted into knee kinematic measurements.

3. Method

Fig. 1 depicts the diagram of a general feature-based knee kinematics method. First, the features (edges) in the fluoroscopic frames are extracted. Second, the femoral and tibial surface models are aligned in 3D space to best match the extracted features. Finally, the pose estimates of the femur and tibia over time are converted into knee kinematics by expressing the recovered motion in the anatomical coordinate-system of the knee.

Variations of this framework include the traditional knee kinematics system using manual edge extraction and subject-specific knee surfaces, as well as the automated, 3D acquisition-free system using automatic edge extraction and SSM-generated knee shapes. We describe our implementation of the automated system below.

3.1. Statistical shape model

The CT images in the training set of the SSM (Cootes et al., 1992) were segmented using level-sets, and were converted to triangulated surfaces with the same number of corresponding landmark points (femur: 4250 points, tibia–fibula: 4778 points). Correspondence within the training set was achieved using B-spline registrations (Elastix; Klein et al., 2010), by deforming every bone segmentation to match the bone with the smallest FOV, and subsequently propagating the surface points of this shortest bone back to every bone in the training set. Bones were then aligned by Procrustes analysis (translation, rotation, and isotropic scaling), and principal component analysis (PCA) was employed to derive the statistical shape model consisting of the mean shape and its main modes of variations. New shapes can be generated with the model by varying the parameters along the modes. First and second modes of both models are shown in Fig. 2. The models were created containing 95% of the variance, resulting in 33 modes for the femur, and 32 modes for the tibia–fibula.

3.2. 2D/3D bone reconstruction and tracking

Knee kinematics were recovered by optimizing the shape and the pose of the SSM through time to best fit the automatically extracted edges in the fluoroscopic frames. Edges were extracted with a Canny edge detector (Canny, 1986), employing hysteresis thresholding on the gradient magnitude. The optimization algorithm was derived from Baka et al. (2012), [1] consisting of three stages: 1) a crude alignment of the mean shape calculated frame-by-frame; 2) shape and pose estimation on a

[1] Due to the high frame rate of our fluoroscopic sequences, we omitted the edge appearance terms proposed to enable tracking from low frame-rate sequences.