Medical Engineering and Physics 37 (2015) 937–947

Contents lists available at ScienceDirect

Medical Engineering and Physics

journal homepage: www.elsevier.com/locate/medengphy

Validation of a method for combining biplanar radiography and magnetic resonance imaging to estimate knee cartilage contact

Eric Thorhauer, Scott Tashman*

Biodynamics Laboratory, Department of Orthopaedic Surgery, University of Pittsburgh, 3820 South Water Street, Pittsburgh, PA 15203, United States of America

ARTICLE INFO

Article history:
Received 17 February 2015
Revised 29 June 2015
Accepted 1 July 2015

Keywords:
knee biomechanics
Cartilage contact
Biplane radiography
Validation

ABSTRACT

Combining accurate bone kinematics data from biplane radiography with cartilage models from magnetic resonance imaging, it is possible to estimate tibiofemoral cartilage contact area and centroid location. Proper validation of such estimates, however, has not been performed under loading conditions approximating functional tasks, such as gait, squatting, and stair descent. The goal of this study was to perform an in vitro validation to resolve the accuracy of cartilage contact estimations in comparison to a laser scanning gold standard. Results demonstrated acceptable reliability and accuracy for both contact area and centroid location estimates. Root mean square errors in contact area averaged 8.4% and 4.4% of the medial and lateral compartmental areas, respectively. Modified Sorensen-Dice agreement scores of contact regions averaged 0.81 ± 0.07 for medial and 0.83 ± 0.07 for lateral compartments. These validated methods have applications for in vivo assessment of a variety of patient populations and physical activities, and may lead to greater understanding of the relationships between knee cartilage function, effects of joint injury and treatment, and the development of osteoarthritis.

1. Introduction

Estimation of in vivo knee joint contact is technically challenging, particularly during functionally relevant loading. Understanding the location and area of contact between the articulating joint surfaces can provide essential and clinically relevant insight into joint function of normal, injured, and surgically operative or rehabilitated knees. Articular cartilage contact has been assessed in the knee [1–9]. Methods for analyzing knee contact have typically utilized magnetic resonance imaging (MRI) to directly assess opposing cartilage and meniscal tissues in both unloaded supine conditions and simulated loading during low load static and dynamic flexion activities [2,8,10,11]. The low temporal sampling rates and physically restrictive environment of the MRI magnet, however, limit testing to loading magnitudes and ambulatory speeds that are far below those typically encountered during activities of daily living. Data of cartilage contact behavior during activities such as gait, stair climbing, hopping, and running are essential for a more complete understanding of the behavior of healthy and unhealthy joints [12].

Dynamic assessments of knee kinematics have been performed using motion capture, single-plane or biplane fluoroscopy or radiography [3,5–7,9,13–20]. Biplane radiographic and fluoroscopic systems have precisely quantified bone motion during functional activities [3,9,13,21,22]. These systems cannot directly assess cartilage contact within joints (because soft tissues do not appear on X-ray images), but simple approximations of articular surface interactions have been performed using three-dimensional (3D) bone models derived from computed-tomography (CT) scans while assuming uniform cartilage thickness [21,23,24]. For joint surfaces with varying cartilage thickness (such as the tibial plateau), cartilage contact estimations can be improved by combining kinematic data of bones with subject-specific cartilage models generated from MRI. This approach has been used to assess in vivo ankle and knee contact during squatting, quasi-static lunging, and low-speed gait [5,6,9,25,26]. These studies were performed using commercially available "C-arm" fluoroscopy systems, which are suitable only for relatively low-speed movements due to limitations in maximum frame rate and image acquisition time [27]. Bones were modeled from MRI and kinematics were determined by matching the projected external bony contours of the models onto the stereo fluoroscopic images. While both cartilage and bone can be modeled using MRI without ionizing radiation, MRI-derived bone models are subject to geometric distortion which has been previously reported to decrease kinematic accuracy [28] compared to models produced from CT that have low distortion and utilize full volumetric radiodensity information for the matching process [29].

High-speed biplane radiography systems [13,14,22] are designed specifically for dynamic imaging and are capable of sampling rates

* Corresponding author. Tel.: +1 412 586 3950.
E-mail address: tashman@pitt.edu (S. Tashman).

http://dx.doi.org/10.1016/j.medengphy.2015.07.002
1350-4533/

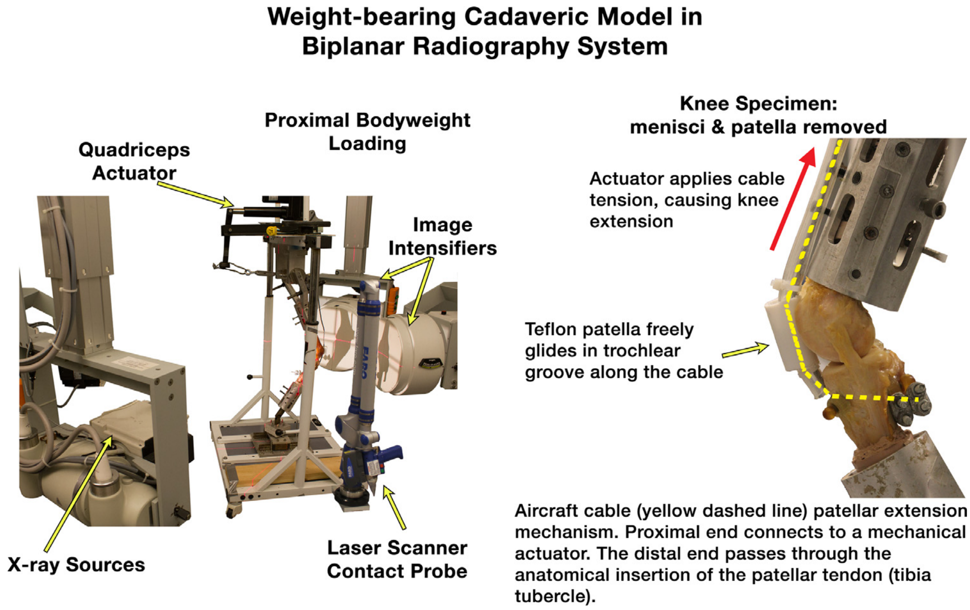

Fig. 1. Knees were posed in a weight-bearing flexion test rig with quadriceps loading within the capture volume of a biplane radiography system. Specimen menisci and patellae were removed to permit laser scanning and probing of the contacting cartilage regions. Quadriceps loading was applied through a stainless steel cable tendon and Teflon patella using a mechanical actuator.

(up to 180 frames/s of pulsed X-rays) and short exposure times (down to 1 ms) necessary for blur-free imaging of dynamic, functional activities such as gait, running, and hopping. When used with volumetric model-based tracking methods utilizing digitally reconstructed radiographic projections of CT bone models [29,30], high-speed biplane radiographic systems can accurately reproduce knee kinematics during such activities. With these systems, however, estimating cartilage contact requires the additional step of mapping cartilage surface models generated from MRI onto the CT bone models. The errors introduced by combining the MRI and CT modalities and the repeatability of multiple MRI segmentation operators and their cumulative effect on articular contact estimation error have not been assessed.

The purpose of this study was therefore to evaluate the accuracy of estimating of area, shape, and centroid of cartilage contact determined by combining subject-specific articular knee cartilage models from MRI with a previously validated CT model-based method of determining tibiofemoral kinematics using biplane radiography. This validation was performed using a load-bearing human cadaveric knee model with laser scan data of joint contact as a gold standard. Laser scanning has been established as an acceptable gold standard method for assessing cartilage geometry [31,32]. Repeatability analysis of contact estimation from multiple operators performing the cartilage modeling was performed to quantify the sensitivity to error of multiple technicians working cooperatively with a given dataset as would be required for large studies.

2. Methods

2.1. Specimen preparation

Three fresh-frozen knee cadaver specimens (three males, ages 54–61) were obtained after approval of the Institution's Office for Oversight of Anatomic Specimens. Specimens were screened using MRI and fluoroscopy for evidence of osteophytes, ligamentous injuries, osteoarthritis, or defects in articular cartilage and stored at −20°C prior to use. Three poly-ether-ether-ketone screws were bi-cortically fixed in each specimen's femur and tibia 35 mm distal and 50 mm proximal relative to the joint line to avoid damaging the articular cartilage. Plastic fiducial marker spheres (8 mm inner diameter, 10 mm outer diameter) were printed on a stereo lithography machine. The spheres were filled with multi-modality radiographic contrast fluid (Beekley Medical, Bristol CT), sealed with septum rubber, and rigidly attached to each screw head. Bone and cartilage volumetric data were acquired via CT scanning (GE LightSpeed Pro 16, voxel size: 0.589 × 0.589 × 1.25 mm, manufacturer's "bone" convolution kernel) and MRI scanning (Siemens 3T Magnetom Trio, near-isotropic 3D Dual Echo Steady State (DESS) with water excitation, CP Extremity knee coil, voxel size: 0.45 × 0.45 × 0.70 mm, TR: 16.32 ms, TE: 4.71 ms, Flip Angle = 25°, 140 × 140 mm field of view). These CT scanning parameters are identical to those used for in vivo studies assessing dynamic knee function with the biplanar radiography system and balance bone model accuracy and subject radiation exposure [29]. The 3D DESS MRI sequence provides enhanced contrast between cartilage tissue and bone, meniscus, and synovial fluid and permits accurate quantification of articular cartilage morphology [33,34]. Knees were held in position during scanning by use of a braided suture (#2 Ti-Cron, Covidien, Dublin, Ireland) whipstitched into the quadriceps tendon, passed through a 3 mm bicortical hole drilled into the femur bone shaft 15 cm proximal to the knee joint line, and knotted after the knee was placed into a normal extension position. During MRI scanning, knees were aligned near the magnet isocenter to reduce geometric distortions of the specimen tissues and fiducial spheres.

Skin and muscle tissues were carefully stripped from the knee specimens to expose the joint capsule. The capsule was dissected and the menisci and patella-quadriceps-tendon construct removed to facilitate direct visualization and laser scanning of tibiofemoral cartilage–cartilage contact during testing (Fig. 1). Caution was exercised to avoid disruption of the cruciate and collateral ligaments and damage to the articular cartilage. Femoral and tibial bone shafts were cut 15 cm from the joint line and potted in fiberglass resin cylinders aligned to the native anatomical axes.

Simulated quadriceps loading was applied through a stainless steel aircraft cable covered with polyethylene tubing. The cable acted as both the patella tendon and quadriceps tendon. The proximal cable end was routed over a pulley mounted to the testing frame and connected to the quadriceps mechanical actuator. The quadriceps