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In vivo determination of normal and anterior cruciate ligament-deficient knee kinematics

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Abstract

The objective of the current study was to use fluoroscopy to accurately determine the three-dimensional (3D), in vivo, weight-bearing kinematics of 10 normal and five anterior cruciate ligament deficient (ACLD) knees. Patient-specific bone models were derived from computed tomography (CT) data. 3D computer bone models of each subject's femur, tibia, and fibula were recreated from the CT 3D bone density data. Using a model-based 3D-to-2D imaging technique registered CT images were precisely fit onto fluoroscopic images, the full six degrees of freedom motion of the bones was measured from the images. The computer-generated 3D models of each subject's femur and tibia were precisely registered to the 2D digital fluoroscopic images using an optimization algorithm that automatically adjusts the pose of the model at various flexion/extension angles. Each subject performed a weight-bearing deep knee bend while under dynamic fluoroscopic surveillance. All 10 normal knees experienced posterior femoral translation of the lateral condyle and minimal change in position of the medial condyle with progressive knee flexion. The average amount of posterior femoral translation of the lateral condyle was 21.07 mm, whereas the average medial condyle translation was 1.94 mm, in the posterior direction. In contrast, all five ACLD knees experienced considerable change in the position of the medial condyle. The average amount of posterior femoral translation of the lateral condyle was 17.00 mm, while the medial condyle translation was 4.65 mm, in the posterior direction. In addition, the helical axis of motion was determined between maximum flexion and extension. A considerable difference was found between the center of rotation locations of the normal and ACLD subjects, with ACLD subjects exhibiting substantially higher variance in kinematic patterns.

Keywords: Kinematics; Helical axis; Registration; Anterior cruciate ligament deficient; Fluoroscopy; Normal knee

1. Introduction

The "in vivo" measurement of dynamic knee kinematics is important for understanding the effects of joint injuries, diseases, and evaluating the outcome of surgical procedures. Researchers have used "in vitro" (cadavers), (Fukubayashi et al., 1982; Goldberg and Henderson, 1980; Hsieh and Walker, 1976; Mahoney et al., 1994; Markolf et al., 1976, 1979; Muller, 1983; O'Connor et al., 1990; Singerman et al., 1994) noninvasive (gait laboratories), (Andriacchi et al., 1986, 1994; Andriacchi, 1993; Draganich et al., 1987; Lafortune et al., 1992; Murphy et al., 1995; Wilson et al., 1996) and in vivo (roentgen stereophotogrammetry and fluoroscopy) (Chao, 1980; Dennis et al., 1998a,b. Kharrholm et al., 1994; Nilsson et al., 1991; Sarojak, 1998; Stiehl et al., 1995, 1997) approaches to assess human knee motion. Cadaveric and static X-ray measurement methods often do not accurately reflect loads encountered during typical movements, and often fail to reliably predict outcome. Therefore, treatments aimed at improving knee function should be evaluated using data obtained from dynamic measurement methods. This requires the determination of six degrees of freedom (DOF) pose (position and orientation) of objects to be measured during dynamic activities.

The most commonly used methods for assessing dynamic movement rely upon skin-mounted markers or bone-implemented markers. However, external skin-markers are often unable to accurately represent motion of the underlying bone due to movement of soft tissue relative to bone. To overcome the inherent inaccuracy of the skin-mounted markers, markers have been mounted

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on skeletal pins inserted into the underlying bones (Murphy, 1990), or inserted directly into the bones (Lafortune et al., 1992) to measure skeletal kinematics. Though these studies provide some of the best available quantitative data during movement, the requirement of skeletal pins or radio-opaque markers has limited application for human studies. The objective of the current study was to accurately determine the three-dimensional (3D) kinematic patterns of normal and anterior cruciate ligament (ACL)-deficient (ACLD) knees, under in vivo weight-bearing activities using a novel intensity-based 3D-to-2D image registration method, similar to that previously utilized to analyze kinematics of total knee arthroplasty (TKA) (Banks, 1992; Banks and Hodge, 1996; Dennis et al., 1996,1998a,b; Hoff et al., 1998; Mahfouz, 2002; Mahfouz et al., 2003; Sarojak 1998; Stiehl et al., 1995; Zuffi et al., 1999.).

Fig. 1. Volume rendered images (top) showing both knees of a normal subject. The bottom images show the segmented bone models superimposed on the volume data.

2. Materials and methods

2.1. Model creation

The computer software packages used in the current study were developed by the current authors with the aid of software development languages (Open Inventor C++ library, and C++ Qt GUI development library; TGS, San Diego, CA). Ten healthy normal volunteers with an average age of 37 years (range, 22–44 years), and average body mass of 76 kg participated in the study. The volunteers were scanned with MRI (Fast Spin Echo T2 FSE) and exhibited no lower extremity pathology or had any measurable ligamentous instability on clinical examination (pivot shift and Lachman exams). In addition, five patients with recently isolated ACL tear (4–6 weeks) with an average age 39 years (range, 25–47), and average body mass of 65 kg were also included in the study to compare their kinematics to the normal subjects. The five ACLD patients performed a KT-1000 test for laxity measurement and the manual max score was limited to 3 mm or less.

Spiral computed tomography (CT) scans of the subjects' (normal and ACLD) knees were made at levels ranging from 120 mm proximal to the joint to 120 mm distal to the joint. These scans were made at 1–2 mm intervals and the volumetric data of the knee joint was constructed at 0.5 mm interpolation in the transverse plane. Segmentation of the CT-scanned bone was automatically performed by applying a thresholding filter to the slices which isolated the bone from soft tissues. Manual intervention was conducted only when the thresholding filter failed. On completion of the segmentation process, the resulting data were used to create full 3D polygonal surface models for the distal femur (approximately 12 000 polygons), the proximal tibia and the proximal fibula (combined approximately 18 000 polygons) (Fig. 1).

2.2. X-ray fluoroscopy

The subjects were analyzed using a high-frequency pulsated video fluoroscopy unit (Radiographic and Data Solutions, Minneapolis, MN). All subjects gave informed consent to participate in this study. The study has been approved by an institutional research review board (IRRB #0607). Each subject subsequently performed weight-bearing deep knee bend activity while under fluoroscopic surveillance. During the deep knee bend activity, subjects were asked to begin in full extension and flex the knee of interest to maximum flexion (Fig. 2). The fluoroscope maximum frame rate is 30 frames/s. This frequency puts a limitation on the maximum frequency content of the kinematics data to 15 Hz to avoid aliasing (Nyquist criteria (Jain, 1989). In practice, all the activities that were analyzed with video fluoroscopy in the authors' research have much lower bandwidth. The fluoroscopic images of the deep knee bending activity were downloaded to a workstation for processing.

The fluoroscope is modeled as a perspective projection image formation model. The perspective projection model treats the fluoroscope sensor as consisting of an X-ray point source and a planar phosphor screen upon which the image is formed (Fig. 3). Although image distortion and non-uniform scaling can occur, these can be compensated for by careful calibration (Mahfouz et al., 2003).

2.3. 3D-to-2D registration

Registering 3D models using 2D fluoroscopy images has been the subject of much research. Generally,