DESIGN OF A MOTION PHANTOM FOR ACCURACY DETERMINATION IN THE MEASUREMENT OF JOINT KINEMATICS USING CINE-PHASE CONTRAST MRI DATA

Peter J Barrance, Glenn N Williams, Thomas S Buchanan

Center for Biomedical Engineering Research
University of Delaware
Newark, Delaware

INTRODUCTION

Accurate determination of *in vivo* musculoskeletal kinematics is important for assessing the subtle changes in joint function resulting from injury to joint-stabilizing structures. Cine-Phase Contrast (Cine-PC) MRI is a dynamic magnetic resonance imaging modality that acquires anatomical images and velocity maps of moving structures. It has been employed to determine musculoskeletal kinematics [1] using a Fourier based tracking algorithm [2]. Using a motor-driven cyclic motion phantom, the kinematic accuracy achievable has been established as less than 1mm [3]. We have developed a new kinematic tracking technique to register 3D surface models of bony anatomy with Cine-PC images [4]. A new motion phantom has been designed to establish the accuracy of this technique under typical experimental conditions. The phantom allows bone specimens to be moved in a precise and repeatable way; the known input kinematics may then be compared with the motion measured. All aspects of the data acquisition and tracking techniques in the human experiment are allowed by the phantom design.

METHODS

Cine-PC Data Acquisition and Kinematic Tracking Algorithm

Subjects perform a repetitive knee flexion/extension exercise within the MRI scanner (GE Signa LX) while lying supine (Fig. 1). A custom apparatus is used to elevate the thigh, and the knee angle varies between approximately 30° flexion and full extension. The subject voluntarily synchronizes repetitions of the exercise with a metronome at a rate of 35 cycles per minute. The duration of the imaging sequence is approximately 5.5 minutes. An optical sensor (*a* in Fig. 1), positioned under the subject's ankle, triggers data acquisition in each repetition. A sequence of 24 frames of Cine-PC MRI data, centered on the subject's knee joint, is collected through the motion cycle on a user-specified sagittal image plane. Each resulting data frame yields four separate images on the selected plane; one is an anatomical cross-section, and the others are encoded with velocity in three orthogonal directions.

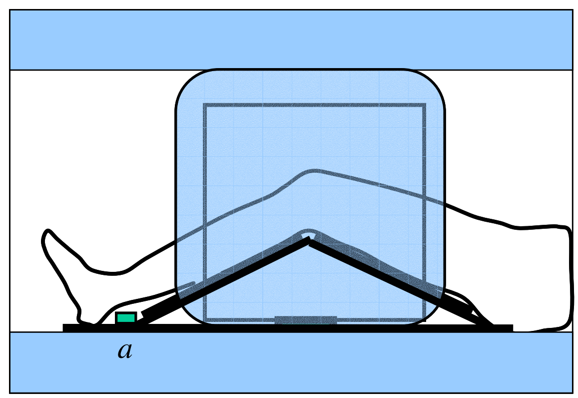

Figure 1. Human subject experiment

A sequence of high resolution axial plane MR images is also acquired, centered at the subject's knee joint. Three-dimensional graphical models of the surfaces of the distal femur and proximal tibia are created from digitized traces of these images. Custom developed software is used to reconstruct the polygonal graphical models.

The sagittal plane cine-PC MR images show lines of low signal around the edge of each bone's intersection with the image plane. An initial estimate of the location of the bone is made by manually varying the position and orientation of the geometric model relative to a virtual cutting plane. A region of interest (ROI) of the sagittal image is extracted which contains only points lying within the boundary of the bone of interest. Using the ROI velocity data and invoking the relationships between the motions of particles within rigid bodies, the angular and linear velocities of the bone are estimated. An iterative procedure minimizes the error between modeled velocities and cross-sections produced by the modeled trajectory of the rigid body, and those observed in the entire Cine-PC MRI magnitude and velocity data set. To quantify joint motion, anatomical coordinate systems are defined within each bone, and the relative motion is decomposed into kinematic rotation and translation parameters.

Motion Phantom for Kinematic Validation

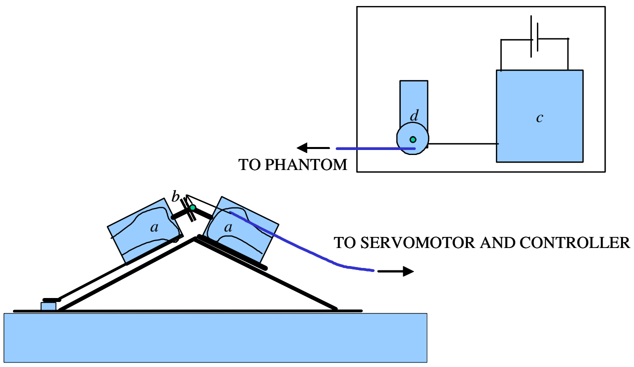

Figure 2. Schematic figure of motion phantom

Bovine femur and tibia bone specimens are enclosed in separate clear acrylic enclosures (*a* in Fig. 2). The enclosures are joined by a linkage that produces an axial rotation coupled with the primary flexion angle. This does not reproduce physiological kinematics; it does, however, test the ability to measure true 3D motion. Since the motion occurs over a similar range and at a similar speed to the knee motion in the human experiment, the magnitudes and directions of velocity data are similar in the two cases. The coupling of rotations is achieved using meshing bevel gears fixed to each axis of rotation (*b* in Fig. 2.) Multi-modality imaging markers (IZI Medical Products, Baltimore, MD) are attached to each enclosure; the centers of these can be accurately defined in the MR images. The distal enclosure has an extension, designed to trigger the data acquisition similarly to the human experiment.

The phantom has one controllable degree of freedom- the flexion angle between the enclosures. In the human experiment, the flexion angle is ideally controlled in a repeated cycle in synchronization with the metronome; in reality, subjects only maintain an approximation to a cyclic trajectory. Investigation of the influence of this variability in cycle trajectory on the measurement technique is made possible by moving the phantom's degree of freedom according to a sequence of motion data recorded from a human subject. The motion data sequences used to drive the phantom were recorded in a separate experiment, using an electrogoniometer (Penny and Giles, Cwmfelinfach, UK) and 64-bit data acquisition card (National Instruments, Austin, TX) in a PC computer. The measured kinematics can be compared when using motion profiles of differing cycle variability, as well as an idealized case of perfect cycles.

The sequence of data must be restored in real time and used to control a electromechanical device to effect motion of the phantom. This must be done in the vicinity of the strong magnetic field (1.5 T) of the MR machine. Use of a desktop or laptop computer in this environment raises safety issues, as well as the possibility of damage to the computer. In addition, metallic objects near the magnet may compromise the fidelity of the data acquired. The data is therefore stored on a 32KB memory chip incorporated in a microcontroller board (Oopic-II, Savage Innovations, CA) (*c* in Fig.2) The motion data are processed and downloaded from a desktop computer to the memory before the experiment. The microcontroller board then reads the motion data and produces a pulse-width modulated signal to drive a rotary servo motor (FP-S28, Futaba Corporation, Schaumburg, IL) (*d* in Fig. 2)

The small amount of metal in the controller, batteries, and servo motor are kept remote from the center of the magnet by the means of a rigid frame. A long flexible pushrod is used to connect the linkage to the servo motor arm.

The femoral enclosure is attached via an adjustable connection to a base plate, which is rigidly clamped to the portion of the knee elevating apparatus. The alignment of the phantom may thus be varied in a precise way relative to the axis of the scanner. The measured components of velocity data change, but the measured joint kinematics should be independent of the alignment of the specimen.

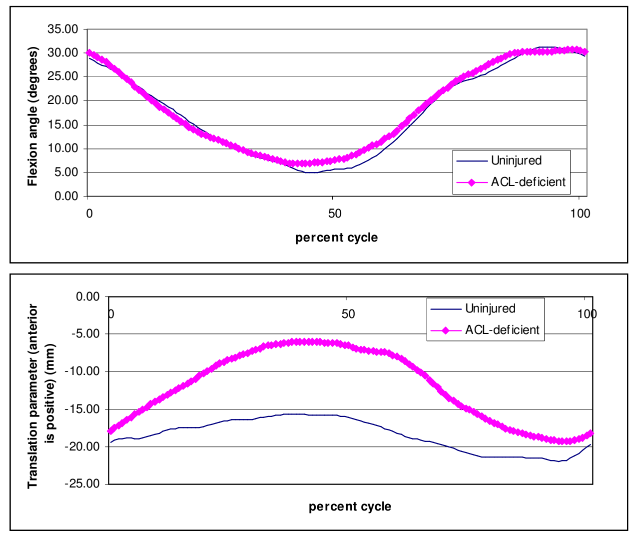

Figure 3. Comparison of ACL-D joint parameters

RESULTS AND DISCUSSION

The Cine-PC MRI and registration technique is being applied in a study of the effects of anterior cruciate ligament deficiency on the kinematics of the tibiofemoral and patellofemoral joints. Figure 3 compares the anterior/posterior positions of the tibia in intact and ACL knees of the same subject. The overall excursion is clearly increased in the ACL deficient knee. Investigation of the technique's accuracy under varying experimental conditions promises to support such results and open the technique to further areas of applicability.

REFERENCES

1. Sheehan, F. T., Zajac, F. E., and Drace, J. E., 1999, "In vivo tracking of the human patella using cine phase contrast magnetic resonance imaging", J Biomech Eng, Vol. 121, pp. 650-6
2. Zhu, Y., Drangova, M., and Pelc, N. J., 1996, "Fourier tracking of myocardial motion using cine-PC data", Magn Reson Med, Vol. 35, pp. 471-80
3. Sheehan, F. T., Zajac, F. E., and Drace, J. E., 1998, "Using cine phase contrast magnetic resonance imaging to non-invasively study in vivo knee dynamics", J. Biomech, Vol. 31, pp. 21-6
4. Barrance, P.J., Williams, G.N., and Buchanan T.S., 2002, "Registration of 3D bone geometry with cine phase contrast MRI data for the determination of in vivo joint kinematics," Proceedings, World Congress of Biomechanics, Calgary, Canada,

ACKNOWLEDGMENT

This work is supported by NIH grant R01AR46386