# ACCURATE MEASUREMENT OF THREE-DIMENSIONAL NATURAL KNEE KINEMATICS USING SINGLE-PLANE FLUOROSCOPY

**Haseeb Rahman (1), Benjamin J. Fregly (1,2,3), and Scott A. Banks (4)**

(1) Department of Biomedical Engineering
University of Florida
Gainesville, FL

(2) Dept. of Mechanical & Aerospace Engineering
University of Florida
Gainesville, FL

(3) Department of Orthopaedics & Rehabilitation
University of Florida
Gainesville, FL

(4) Orthopaedic Research Lab
The Biomotion Foundation
West Palm Beach, FL

## INTRODUCTION

Single-plane fluoroscopy (i.e., dynamic x-rays) is a valuable research tool for studying *in vivo* kinematics of knee replacements [1,2]. By matching static three-dimensional (3D) geometric models of the metallic implant components to their segmented outlines in dynamic two-dimensional (2D) x-ray images, fluoroscopy eliminates skin and soft-tissue artifacts associated with video-based motion analysis. The result is dynamic measurement of joint motion accurate to within 1º for all rotations and 0.5 mm for in-plane translations [1]. The method facilitates comparison of the *in vivo* function of different knee designs [3], evaluation of function during different activities [4], and evaluation of different surgical decisions and alignments [5].

Fluoroscopic measurement of natural knee motion has potential for understanding arthritis progression and planning surgical procedures (e.g., high tibial osteotomy) to treat arthritis. However, this approach has not been used extensively in practice, primarily because bones rather than metallic components are needed for image matching. Bones edges are less sharp than those of implants in fluoroscopic images. Furthermore, subject-specific geometric bone models for image matching are not readily available. Thus, studies using static x-ray procedures to measure joint orientations have utilized geometric bone models derived from CT scan data of the same subject [6,7].

This study evaluates the accuracy of using bone surface models derived from CT data for single-plane fluoroscopic image matching in the knee. Synthetic fluoroscopic images created by placing the bone models in known positions and orientations are used to quantify the theoretical errors in the matching procedure.

## METHODS

One subject gave informed consent to perform stair rise/descent activities during fluoroscopic motion analysis and to undergo CT scans of the same knee. A fine scan was performed in the knee region using a slice thickness of 1 mm while a course scan covering the entire lower extremity was performed with a slice thickness of 5 mm. Both scans used a 512 x 512 image resolution.

The CT images were segmented semi-automatically with SliceOmatic (Tomovision, Montreal, CA) using a watershed algorithm. By finding intensity changes in the images, this algorithm produces more objective and repeatable segmentation results than standard thresholding methods. For the femur and tibia/fibula, the exterior and interior cortical bone boundaries were segmented, while for the patella, only its exterior surface was segmented.

Point clouds defining the segmented bone surfaces were input into Geomagic Studio (Raindrop Geomagic, Research Triangle Park, NC) for polygonal surface model creation. First, the course and fine scans of the femur were automatically aligned and the course points in the knee region replaced with the fine points. A similar procedure was followed for the tibia/fibula. This produced full femur and tibia/fibula point clouds with high resolution only in the knee region. Next, the point clouds were automatically converted into watertight 3D polygonal surface models. After automatic cleaning of the polygons to eliminate unrealistic bumps in the surface geometry, the tolerance between the original points clouds and final polygonal models was evaluated for each bone (Table 1). Maximum distance errors were on the order of 1 to 3 mm with average distance errors less than 0.2 mm.

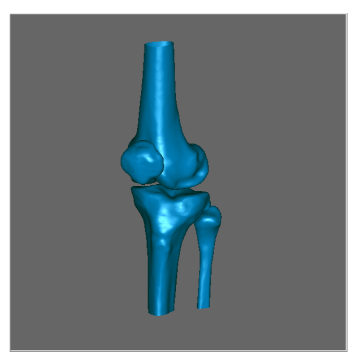

**Figure 1. Accurate polygonal surface model of the femur, tibia/fibula, and patella created from CT scan data.**

| Distance Errors (mm) | Femur | Tibia/Fibula | Patella |
|---|---|---|---|
| Maximum | 2.00 | 3.00 | 1.52 |
| Mean | 0.14 | 0.14 | 0.17 |
| SD | 0.14 | 0.15 | 0.19 |

**Table 1. Distance errors produced by converting point clouds into smooth polygonal bone models.**

In preparation for fluoroscopic image matching, anatomic coordinate systems were created in each bone model. The mechanical axis of the full femur and tibia/fibula surface models was used to define the first axis of these bones, with the remaining axes defined using conventions reported in the literature [8]. The coordinate system for the patella was derived from the femur.

Custom software was used to match the bone models to 29 fluoroscopic images collected from the subject [1]. One image in the middle of the set was approximately matched manually and the automatic matching algorithm allowed to fine-tune the final positions and orientations of each bone model. These results were used as the starting guess for the two adjacent images, with the automatic matching procedure being propagated forward and backward through the image sequence from there.

a  b 

**Figure 2. (a) Actual fluoroscopic image. (b) Synthetic fluoroscopic image with known bone positions and orientations.**

To evaluate the accuracy of automated image matching using CT-based bone models, 29 synthetic fluoroscopic images were generated with the bones in known positions and orientations (Fig 2b). For each image, Rhinoceros (Robert McNeel & Associates, Seattle, WA) was used to place the bone models in the same position and orientation measured fluoroscopically (Fig 2a). After setting up the viewing properties to simulate the fluoroscope, a rendering algorithm with attenuation was used to generate synthetic fluoroscopy images. The final synthetic image sequence mimicked the original stair data. These images were input to the image matching software and each bone model automatically re-matched to the synthetic images. Since the actual positions and orientations of the bones were known, this approach permits quantification of errors due to image matching alone.

## RESULTS

For the 29 images analyzed in this study, the automated image matching procedure reproduced the known bone positions and orientations accurately (Table 2). Rotations for all bones were reproduced to within 1º while in-plane translations were reproduced to within about 1 mm, similar to the results obtained in [1] for knee replacement components. The two primary differences with [1] were that Z (i.e., out-of-plane) translational errors were 3 to 4 times larger here while the patella could not be tracked in [1]. Overall, in-plane translational errors are of the same order of magnitude as mean surface geometry errors in the bone models (Table 1).

| RMS Errors | Femur | Tibia/Fibula | Patella |
|---|---|---|---|
| X translation (mm) | 0.90 | 0.58 | 1.19 |
| Y translation (mm) | 0.67 | 0.66 | 0.86 |
| Z translation (mm) | 24.17 | 22.11 | 16.58 |
| X rotation (deg) | 0.48 | 0.81 | 0.51 |
| Y rotation (deg) | 0.57 | 0.66 | 0.63 |
| Z rotation (deg) | 0.64 | 0.78 | 0.50 |

**Table 2. RMS matching errors calculated from 29 synthetic stair rise images for the femur, tibia/fibula, and patella.**

## DISCUSSION

Single-plane fluoroscopic image matching using bone models derived from CT data appears to be highly accurate. Though the exterior borders of bones are less well defined than those of metallic implants, bones possess interior contours that show up well in fluoroscopic images using edge detection algorithms. This additional contour information allows the bone models to be aligned with the fluoroscopic images to roughly the same accuracy as metallic knee components. Since errors in the bone surface geometry relative to the original point cloud data are uniformly distributed over the surface, small errors in one region are approximately cancelled by small errors in the other region. Overall, this approach holds significant potential for improving our understanding of the detailed mechanics of the natural knee. Use of MRI rather than CT data to generate accurate bone models would further improve the procedure by reducing the total radiation exposure of the subject.

## REFERENCES


1. Banks, S.A. and Hodge, W.A., 1996, “Accurate measurement of three-dimensional knee replacement kinematics using single-plane fluoroscopy,” IEEE Transactions on Biomedical Engineering, 43, pp. 638-649.
2. Hoff, W.A., Komistek, R.D., Dennis, D.A., Gabriel, S.M., and Walker, S.A., 1998, Three-dimensional determination of femoral-tibial contact positions under in vivo conditions using fluoroscopy, Clinical Biomechanics, Vol. 13, pp. 455-472.
3. Banks, S.A., Markovich, G.D., and Hodge, W.A., 1997, “The mechanics of knee replacements during gait: in vivo fluoroscopic analysis of two designs,” American Journal of Knee Surgery, Vol. 10, pp. 261-267.
4. Walker, P.S., Komistek, R.D., Barrett, D.S., Anderson, D., Dennis, D.A., and Sampson, M., 2002, “Motion of a mobile bearing knee allowing translation and rotation,” Journal of Arthroplasty, Vol. 17, pp. 11-19.
5. Banks, S.A., Markovich, G.D., and Hodge, W.A., 1997, “In vivo kinematics of cruciate-retaining and –substituting knee arthroplasties, Journal of Arthroplasty, Vol. 12, pp. 297-304.
6. Asano, T., Akagi, M., Tanaka, K., Tamura, J. and Nakamura, T., 2001, “In vivo three-dimensional knee kinematics using a biplanar image-matching technique,” Clinical Orthopaedics and Related Research, Vol. 388, pp. 157-166.
7. Neu,, C.P., Crisco, J.J., and Wolfe, S.W., 2001, “In vivo kinematic behavior of the radio-capitate joint during wrist flexion-extension and radio-ulnar deviation,” Journal of Biomechanics, Vol. 34, pp. 1429-1438.
8. MacWilliams, B.A., DesJardins, J.D., Wilson, D.R., Romero, J., and Chao, E.Y.S., 1998, A repeatable alignment method and local coordinate system description for knee joint testing and kinematic measurement,” Journal of Biomechanics, Vol. 31, pp. 947-950.