# A SYSTEM FOR TRACKING KNEE KINEMATICS WITH SEQUENTIAL MR IMAGES: ACCURACY OF COORDINATE SYSTEMS AND MOTION TRACKING

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## INTRODUCTION

Magnetic resonance (MR) imaging is an increasingly important tool for *in vivo* studies of the musculoskeletal system. Anatomic and geometric information may be coupled with other tools such as movement analysis and finite element modeling to test hypotheses regarding joint function and the effect of injuries. New techniques allow motion or loading within the MR scanner, thereby allowing investigation of kinematics or soft tissue deformations. Integration of MR imaging with these other tools requires manual or automated image analysis techniques to establish coordinate systems, segment objects or track motion. However, little is known about the reliability and accuracy of these techniques.

The purpose of this study was to evaluate reliability of establishing anatomic reference frames using landmarks from MR images and to assess the accuracy of a motion-tracking algorithm in quantifying knee motion. Techniques are demonstrated by tracking passive flexion of a human knee.

## METHODS

Image Collection, Digitizing and Coordinate System Definition:

Seven knee image sets from five adults were analyzed for this study. Subjects were positioned supine with the knee flexed to approximately 10°. 3-D gradient recalled echo (GRE) sequences were collected in the sagittal plane, with slice thickness of 1.5 to 1.7 mm, and in-plane resolutions between 0.58 and 0.66 mm/pixel. Sagittal and axial images were analyzed using NIH Image software. Two testers recorded coordinates for nine landmarks two times. Orthogonal anatomic reference systems were created for the tibia and femur, and the relative orientations expressed in clinical terms of flexion/extension (f/e), adduction/abduction (a/a), and internal/external (i/e) rotation (1). Distances between the two origins were also expressed in the anatomic systems. Intra- and inter-tester variations in digitizing, and their effects on the establishment of the coordinate systems were assessed by calculating the Pearson correlation and standard error of measurement (SEM) for each point and each of the three rotations and translations.

Automatic Image Segmentation and Motion Tracking:

The automated image segmentation algorithm uses a hierarchical approach of region growing, splitting and merging and statistical relaxation labeling (3). Analysis of a sequence of kinematic data sets starts with complete segmentation of a single volumetric data set. To track motion in subsequent volumes, point correspondences between feature points are predicted using a discrete deformable model formulation (3). The motion-tracking algorithm is based on minimization of the total energy, including the differences in voxel intensity, gradient magnitude, the Laplacian squared and the mesh deformation energy. For tracking of bones, these segmented structures are treated as rigid bodies and all other tissues are assigned low stiffness properties. A mesh is built connecting randomly selected node points on the boundary and interior of the segmented regions. A gradient minimization algorithm finds motion between rigid structures, and the optimal mesh configuration defining the nodes' displacements, continuing until all volumes in the series have been segmented. Results of the motion-tracking algorithm include definition of motion of the centroids and rotation matrices for the segmented structures relative to the global coordinate system for each image set of the motion series.

Validation of Bone Motion Tracking

The tibia and femur of a goat knee joint were mounted in a frame that held the femur fixed while the tibia was translated in a controlled manner. To allow unimpeded joint motion, the ACL, PCL and collateral ligaments were resected. Eight image sets were obtained with variations in tibia position including up to 6 mm out-of-plane translation and 9 mm in-plane translation, and two repeats of the original position. Image sequences were fast 3D GRE images, with a 12 cm FOV, 256 x 256 matrix, and 60 slices of thickness 0.9 mm, providing a spatial resolution equivalent to the human knees, relative to bony dimensions. Image data sets were processed to segment the tibia and femur in the original position, followed by motion tracking to the seven additional positions. Motion of the tibia centroid and orientations of the principal axes relative to the global reference frame were calculated for each test position and compared to the imposed motion. The root mean squared (RMS) difference and Pearson correlation were calculated.

Demonstration of Motion Tracking in Passive Flexion:

A series of six routine GRE image sequences were collected as a subject flexed his knee approximately 4° between each sequence from full extension to the limits of the MR scanner. The motion-tracking algorithm was used to quantify 3D motion of the tibia and femur. Tibio-femoral relative motion was calculated, and rotations and translations of the tibia and femur were used to predict new locations of the landmarks used to create the original coordinate system. These predicted points were compared to points digitized from the images in each flexed position, and RMS differences were calculated.

## RESULTS

The average SEM for nine digitized points was 0.51 mm for inter-tester, and 0.41 mm for intra-tester differences. Maximum SEMs of 3 mm were associated with points establishing m/l axes. Correlations for intra-tester and inter-tester identification of each landmark were above 0.95. The effect of these variations on coordinate axis definition resulted in inter-tester SEMs of 1.2, 1.0, and 2.6 degrees for f/e, a/a, and i/e rotation. Distances between the anatomic origins had inter-tester SEMs of 0.73, 0.65, and 0.34 mm for ant/post, med/lat, and inf/sup directions.

The motion-tracking algorithm confirmed the fixed position of the goat femur in the validation experiment. In the tibia, the estimated motion of the centroid was highly correlated to the imposed motion, with a Pearson correlation of 0.99, and an RMS error of 0.25 mm. Slight systematic underestimation of motion was identified, indicated by a regression slope of 0.93. No rotations of the tibia or femur were imposed in the validation experiment, as confirmed by estimated rotations averaging 0.19°, and less than 1° for both bones.

The motion-tracking algorithm quantified knee flexion of 19°. Average RMS difference between digitized points and the location of the points as predicted by the motion-tracking algorithm was 1.71 mm. The RMS errors averaged 1.9° for rotations and 2.3 mm for translations, with Pearson correlations above 0.95 only for flexion and inferior/superior translation.

## DISCUSSION

The use of MR images to establish anatomic reference systems improves reliability over the use of external landmarks (2). Repeatability required careful definition of points, and improved with training. Flexion of the knee made certain points difficult to identify, introducing increased differences between digitized points and those predicted by the tracking algorithm. Manual digitizing is sufficiently reliable for *initial* establishment of reference systems, however appears to be inadequate for motion tracking as input for finite element modeling where greater accuracy is needed. For example, error of 1 mm could predict an unrealistic 50% deformation of a 2 mm thick cartilage layer. The motion tracking algorithm provides excellent tracking ability (RMS error = ± 0.25 mm, < 1° rotation). This tool may be useful to non-invasively detect kinematic differences due to knee injuries, and to provide input for finite element models further investigating the patterns of stress associated with these differences.

## REFERENCES

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