Development of a Novel Combined Tibial and Femoral Bone Registration Method for Reliable Quantification of MR-based Knee Joint Kinematics

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Purpose:

Measuring knee joint kinematics using magnetic resonance images (MRI) is appealing, as it is non-invasive and leads to reduced errors in determining bony landmarks and defining joint coordinate systems [1]. Reliable quantification of knee kinematic measurements from MRI requires (a) reproducible segmentation of bone geometry from MR images and (b) an accurate geometric registration method. The objective of this study was to examine the inter-user and intra-user reliability in quantifying knee joint kinematics employing a novel method of using both tibia and femur bones for registering the extended and flexed positions as compared to a tibial based method [2,3]. We hypothesize that a tibial-femoral based registration method will provide more reliable inter-user and intra-user measurements of knee kinematics compared to a tibial only based registration method.

Methods:

Image Acquisition: MR images were acquired for 5 subjects with no history of prior knee injury on a General Electric 3T Signa HDx MR scanner using an 8-channel phased array knee coil. Sagittal T2-weighted fast spin echo images of the knee were obtained in full knee extension and flexion (30^0) using a custom-made axial loading device with 25% of total body weight applied through a footplate. Imaging parameters included: FOV 16 cm, 512x512 matrix, slice thickness of 1.5 mm, resolution of 0.39 x 0.39 mm, TR: 4000 ms, TE: 49.3 ms, gap 1.5 mm, ETL 9. Image segmentation was performed using an in-house software program based on a spline-based semi-automated (automated edge detection and manual correction) segmentation algorithm in MATLAB (Mathworks Inc, Natick, MA). Femur and tibia bone regions of interest (ROIs) were defined with Bezier splines for each subject in flexion and extension.

Tibia-Based Registration and Coordinate system: The following ROIs were used to register and define tibial and femoral coordinate systems for quantifying tibio-femoral joint kinematics: tibia, an arc along the posterior aspect of the medial and lateral femoral condyles, and tibial and femoral shaft axes drawn along the diaphysis of the tibia and femur on a mid-sagittal slice. The flexed tibia point cloud is rigidly registered to the extended tibia point cloud using an iterative closest point-matching algorithm. The most posterior points (P_T) of the medial and lateral tibial plateaus (mP_T and lP_T) are automatically localized. A line connecting the mP_T and lP_T is defined as the medio-lateral (ML) axis of the tibia and the mid-point of this line served as the origin of the tibial coordinate system. Anterior-posterior (AP) axis of the tibia is defined by taking the cross product between the ML axis and the tibial shaft axis. The superior-inferior (SI) axis of the tibia is then defined by taking the cross product between the ML and AP axes, providing a mutually orthogonal set of anatomic axes for the tibial coordinate system. The femoral condyles are modeled as spheres with a least-squares fitting algorithm, based on the defined arc of the posterior aspect of the medial and lateral femoral condyles. A line connects the center of each sphere, defining the epicondylar axis of the femur in the ML direction. The mid-point between the two spheres is the origin for the femoral coordinate system. The SI axis is an orthogonal line to the epicondylar axis, in line with the diaphysis of the femur. The AP axis is set as the cross-product of the ML/SI axes. A coordinate system is established for both extended and flexed positions independently. After rigid registration of the tibiae, the tibia is held fixed and kinematic measurements are made by analyzing the relative position of femur in both the extended and flexed positions.

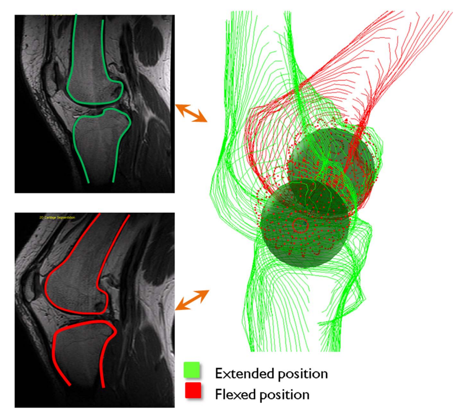

Figure 1: 3D reconstruction of the registered tibia and femur following segmentation from MR images obtained in the extended and

Combined Tibial-Femoral Registration Method: Registration of the tibia proceeds as described above. Similarly, the femur in the flexed position is registered to the femur in the extended position. Coordinate systems are established in the extended position for both the tibia and femur and then transferred to the tibia and femur in the flexed position using the transformation matrix obtained with the registration. Thus, the tibia is held fixed allowing for translational and rotational kinematic measurements to be made by analyzing the relative position of the femur in both the extended and flexed positions (Figure 1).

Algorithm Reliability Analysis: Kinematic MR images for 5 subjects were segmented independently by two researchers with minimum segmentation experience of twenty prior studies. All images were re-segmented by the same individuals after a minimum of two weeks in order to assess reproducibility. Inter-user and intra-user reliability was calculated for anterior tibial translation (ATT) and internal tibial rotation (ITR) values using a Single Measures Intra-class Correlation Coefficient (ICC) as well as a standard error of measures (SEM) value.

Results:

The tibial-femoral based method of registration provided excellent inter-user and intra-user reliability when measuring knee kinematics. For all measures of ATT and ITR, the combined tibial-femoral based registration method provided better inter-user and intra-user reliability compared to the tibial based registration method (Table 1). For Trial 1, the ICC between users was 0.94 (p=0.03) and 0.97 (p<0.01) for ATT and ITR measures respectively. Trial 1 SEM values were 0.34 mm for ATT and 0.78 degrees for ITR. ICC between users during Trial 2 was 0.90 (p=0.007) and 0.99 (p<0.01) for ATT and ITR respectively. For Trial 1, SEM values were 0.62 mm for ATT and 0.48 degrees for ITR. ICC values for User 1 between trials were 0.99 (p<0.01) for ATT and 0.96 (p=0.01) for ITR while for User 2, ICC values between trials were 0.79 (p=0.031) and 0.97 (p=0.01) for ATT and ITR respectively. SEM values for intra-user measurements were 0.17 mm for ATT and 1.04 degrees for ITR in User 1, and 0.83 mm for ATT and 0.92 degrees for ITR in User 2.

Table 1: Inter and Intra-user reliability of a Tibial-Femoral based registration method in measuring anterior tibial translation

		ICC Tibia	ICC Tibia/Femur Combined
Inter-User	Trial 1 ATT	0.71	0.94*
	Trial 2 ATT	0.77*	0.90*
	Trial 1 ITR	0.92*	0.97*
	Trial 2 ITR	0.97*	0.99*
Intra-User	User 1 ATT	0.90*	0.99*
	User 2 ATT	0.73*	0.79*
	User 1 ITR	0.89*	0.96*
	User 2 ITR	0.86*	0.97*

* Indicates p < 0.05

Conclusion:

We have described a novel combined tibial and femoral algorithm for determining MR-based knee kinematics that improves reliability and reproducibility. Additionally, the proposed method eliminates the need of the shaft axes for both tibia and femur in flexed position as well as the arc defining the posterior aspect of femoral condyle, the latter of which has proven to be a major source of inter-user and intra-user variability. The combined tibial-femoral based registration method exhibits excellent inter-user and intra-user reliability with acceptable standard error of measure values. This method offers the potential to detect smaller changes in kinematics, which is important when evaluating knee kinematics after injury or surgical procedures.

References:

[1]. Scheys et al., *Gait Posture*. 2011 Feb;33(2):158-64.
[2] Carpenter et al., *Arthroscopy*. 2009 Jul;25(7):760-766
[3] Shefelbine et al.,*J Orthop Res*. 2006 Jun;24(6):1208-17