A registration-based MR method for calculating in-vivo 3-D knee joint motion: Validating finite element simulations

A. D. McCarthy[1], S. Wood[2], D. C. Barber[1], D. R. Hose[2], D. Chan[3], D. R. Bickerstaff[3], G. Darwent[1], I. D. Wilkinson[2]

[1]Sheffield Teaching Hospitals Trust, Sheffield, Yorkshire, United Kingdom, [2]University of Sheffield, Sheffield, Yorkshire, United Kingdom, [3]Sheffield Centre of Sports Medicine, Sheffield, Yorkshire, United Kingdom

Abstract

A registration-based method to calculate *in-vivo* knee joint motion from MR data has been developed. Its purpose is to permit validation of finite element (FE) simulations of knee joint motion. High resolution T2* volumes, and quasi-dynamic T1-weighted cine images of the knee under load, were acquired and segmented. A rigid transformation method was developed to map the segmented volume onto the sparse dynamic segments and the Levenberg-Marquardt non-linear least squares minimisation method used to decompose the resultant matrix into its Euler rotation components. Calculated joint angles of the tibia relative to the femur demonstrate the knee's screw-home mechanism.

Introduction

This research focuses on the simulation of knee joint kinematics using finite element (FE) analysis and the validation of the simulated motion. It forms part of the Simbio European project, which aims to develop a generic simulation environment. It is important to validate the FE model with respect to *in-vivo* behaviour reliably and with good resolution, which is difficult with existing methods due to kinematic cross-talk[1] and surface marker motion artefacts[2]. Ultimately, a validated FE model of the knee will aid in virtual prototyping of test designs, such as for a meniscal implant.

Methods

MR imaging was performed at 1.5T (Edge Eclipse, Philips Medical Systems). Two sets of MR images of volunteer knees were acquired using a general purpose flexible receive-only RF coil. A volume scan (60 high resolution images) was acquired using a T2* weighted sequence (TE=47ms, TR=15ms, Flip angle=30º) with an acquisition matrix of 512 x 512, resulting in an in-plane pixel resolution of 0.35mm. In addition, a quasi-dynamic T1 weighted cine sequence (TR=10ms, TE=2ms, Flip angle=90º) consisting of 42 sagittal slices (7 evenly spaced at 6 different knee flexion angles) was acquired (3.5 s per image) on 2 separate occasions while the volunteer flexed their knee under load using an in-house designed MR-compliant exercise rig (Figure 1) using a field of view of 42 x 42 cm and a 512 x 512 acquisition matrix, resulting in an in-plane resolution of 0.82 mm.

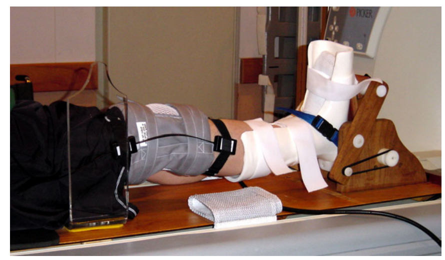

Figure 1: MR-compliant exercise rig

An expert segmented the images manually (SURFdriver 3.5) and the segmented volume was registered onto the sparse dynamic segments using a rigid transformation method developed in-house. The resultant 4x4 matrix was decomposed into its Euler rotation components utilising the Levenberg-Marquardt non-linear least squares minimisation method.

Results

Figure 2 shows the results of the knee rotation angles (tibia relative to femur) for the two independent knee motions, relative to the flexed (15º) static knee. When compared with flexion angles measured directly from the cine MR images (not shown), the first motion plot (--) has an maximal error in knee flexion of 4.6º at position 6 (mean error 0.76º), while the second plot (─) has a maximal error of 2.9º at position 4 (mean error 1.2º). Both motions appear to indicate a coupled internal rotation of the tibia of between 11.8º and 21.2º when flexing from fully extended (the screw-home mechanism) for flexions of 13º and 11.8º respectively, which fit with reported values in the literature[1]. At larger flexion angles, internal rotation remains relatively constant at approximately -9.5º. It is likely that such reported internal rotation is a reflection of the tibia being rotated externally when the static T2* sequence was acquired, resulting in an off-set when axial rotation is calculated relative to the static joint position. Varus / valgus tibial angles between –2.6º to 2.8º (--) and -4.2º to 2.3º (─) are indicated. An initial investigation of segmentation / registration repeatability suggests sub-degree level variations in reported angles are achievable. However, further work is underway to assess segmentation repeatability and its influence on calculated 3-D joint angles.

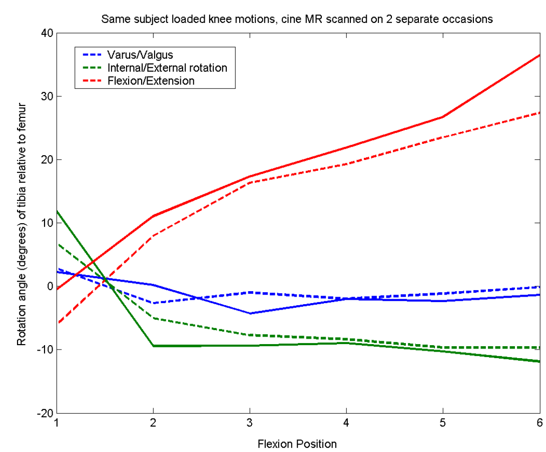

Figure 2: Calculated knee rotation angles from 2 independent loaded knee motions (1-6: fully extended to flexed) using the same subject.

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Discussion

Initial results appear promising, particularly when the process of measuring directly from MR images is itself subject to error. A further cine MR sequence has been acquired incorporating sagittal and transverse slices to strengthen the registration process; it should clarify whether additional image information is required to reduce registration errors to improve the rotation calculations. The authors believe that the method will provide a non-invasive, high-resolution method for assessing 3-D joint motion.

References:

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