Musculo-Skeletal Simulation: Finite Element Meshes Derived From Magnetic Resonance Volumes

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Abstract

The purpose of the study was to enable high-quality patient-specific finite element (F.E.) meshes of knee joints to be generated rapidly from 3-D MR volumes. High resolution T2* and T1-weighted images were acquired, segmented, 3-D surface reconstructed and a F.E. mesh generated using hexahedral elements. The mesh will act as a template that can be transformed into a new mesh using the mapping function produced from the registration of a reference image to a patient image. A F.E. flexion simulation of the tibia about the femur was performed using an explicit F.E. solver and validation of the results is discussed.

Introduction

The SimBio project aims to develop a generic simulation environment; its utility is being evaluated by testing for clinical applications relating to the brain and the knee joint. The menisci perform an important role in load bearing in the knee; current treatments to replace damaged menisci, such as transplanting human meniscal tissue (van Arkel and de Boer, 1995) or encouraging meniscal regeneration using a collagen scaffold (Stone *et al*., 1997) have been problematic due to ethical considerations and failures. It is intended to evaluate the SimBio environment in virtual prototyping of test designs for a meniscal knee joint implant to improve the potential for a successful implant post-project. The first step is to validate the quality and behaviour of one F.E. knee mesh before progressing to creating patient-specific knee meshes to assess meniscal injuries pre-and post operatively.

Methods

Imaging: MR imaging was performed at 1.5T (Eclipse, Marconi Medical Systems). Two sets of MR images of volunteer knees were acquired using a general purpose flexible receive-only RF coil. High resolution images were acquired using a T2*-weighted sequence (TE=47ms, TR=15ms, Flip angle=30º) and a T1-weighted sequence (TR=12ms, TE=4ms, Flip angle=20º) with an initial acquisition matrix of 256 x 256, resulting in an in-plane pixel resolution of 0.7mm. For validation purposes, pseudo-dynamic MR images were acquired using a T2*-weighted (TR=29ms, TE=13.0ms, Flip angle=20º) cine sequence while the volunteer extended their knee using an in-house designed MR-compliant test rig (see Figures 1 and 2). The in-plane resolution was 1.56mm due to the larger field of view required to image the joint during knee extension.

Figure 1 Flexed knee in MR compliant test rig

Figure 2 Extending knee in MR compliant test rig

Image segmentation: Each structure of the knee was hand-segmented using the software SURFDriver™, which utilises a boundary detection approach. The T1-weighted sequence was particularly useful for imaging the cruciate ligaments. The reference MR image volume from which segments have been derived is registered to patient image volumes using the non-linear registration tool (*vreglocal3d*). The resultant mapping from this registration will be used to map the reference image segments to the patient image A sample image resulting from the registration-based segmentation is shown in Figure 3. The mapping can be used also to transform a template mesh.

Figure 3 Automatic segmentation of the bones from a volunteer MR image of a knee using the registration-based approach

Mesh template approach: The manual segmentation process is labour-intensive, but it need only be done once. The purpose is to produce one high-quality segmented image template that will be registered subsequently to individual patient images and the resultant mapping used to transform the template F.E. mesh into a patient-specific mesh using the function *vtransform3d*.

Figure 4 Template 3-D image

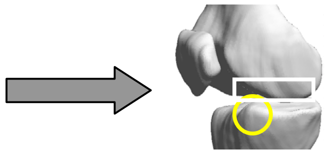

Figure 5 Volunteer "A" 3-D image

Figures 4 and 5 above show the results of registering the template segments to a volunteer image to generate a volunteer 3-D image. Differences can be seen in the shape of the tibial plateau and femoral condyle as indicated in Figure 4.

Mesh generation: A binary volume was created from the contour set and iso-surfaced using in-house Matlab™ code. Matlab™ smoothing routines were used to adjust the iso-surface, aided by a concurrent visual inspection of the raw data to ensure that it had been represented adequately. The knee structures were meshed into hexahedral finite elements using the pre-processor of ANSYS® 5.6. Patient-specific meshes will be created by morphing the template mesh using the registration and transform tools. Mesh quality checks will be applied to ensure that that the mesh-transform process does not result in poor quality (e.g. distorted) elements.

Results

A template F. E. mesh has been generated from the volumetric MR dataset. A simulation has been performed for flexion of the tibia about the femoral condyles (Figures 6-8) using the explicit finite element solver PAM-SAFE™ (ESI, Paris). It was run on a SGI Origin 2000 with four 250 MHz R10K processors and 2560 Mb of RAM, and took 17 hours to complete.

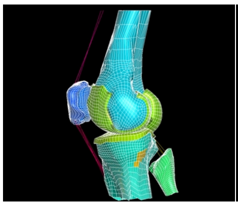

Figure 6 F.E .Knee mesh in extension

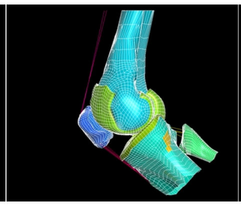

Figure 7Mid flexion cycle of knee mesh

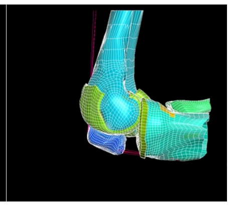

Figure 8 Knee mesh at 78º flexion

Discussion

Work is progressing for calculating the three Euler angles and three rotations of the behaviour of the tibia with respect to the femur from the cine MR images acquired while using the exercise test rig. This will permit the simulation results to be validated formally, although initial rotations of the tibia about the fixed femur appear in reasonable agreement with the literature (e.g. Bull and Amis, 1998).

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