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Development of subject-specific and statistical shape models of the knee using an efficient segmentation and mesh-morphing approach

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ABSTRACT

Subject-specific finite element models developed from imaging data provide functional representation of anatomical structures and have been used to evaluate healthy and pathologic knee mechanics. The creation of subject-specific models is a time-consuming process when considering manual segmentation and hexahedral (hex) meshing of the articular surfaces to ensure accurate contact assessment. Previous studies have emphasized automated mesh mapping to bone geometry from computed tomography (CT) scans, but have not considered cartilage and soft tissue structures. Statistical shape modeling has been proposed as an alternative approach to develop a population of subject models, but still requires manual segmentation and registration of a training set. Accordingly, the aim of the current study was to develop an efficient, integrated mesh-morphing-based segmentation approach to create hex meshes of subject-specific geometries from scan data, to apply the approach to natural femoral, tibial, and patellar cartilage from magnetic resonance (MR) images, and to demonstrate the creation of a statistical shape model of the knee characterizing the modes of variation using principal component analysis. The platform was demonstrated on MR scans from 10 knees and enabled hex mesh generation of the knee articular structures in approximately 1.5 h per subject. In a subset of geometries, average root mean square geometric differences were 0.54 mm for all structures and in quasi-static analyses over a range of flexion angles, differences in predicted peak contact pressures were less than 5.3% between the semi-automated and manually generated models. The integrated segmentation, mesh-morphing approach was employed in the efficient development of subject-specific models and a statistical shape model, where populations of subject-specific models have application to implant design evaluation or surgical planning.

1. Introduction

Subject-specific finite element (FE) models incorporating anatomical articular cartilage surfaces and soft tissue geometric representations can provide insight into knee mechanics for healthy normal and pathologic conditions [1–3]. Accurate prediction of knee joint mechanics in FE models depends on multiple factors including appropriate representations of the

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geometry, properties of anatomic structures and the application of boundary conditions (i.e. kinematics and muscle forces) [4]. Segmentation of computed tomography (CT) and magnetic resonance (MR) scan data has become the accepted standard for subject-specific model development [4–6]. However, the processing is typically manual and time-consuming; extracting the articular surfaces of a knee joint was reported as requiring approximately 2 days of work [6]. In addition, model development time is increased with the meshing of segmented surfaces into 3D hexahedral solids, which are recommended for accurate FE representations for bone strain [7] and contact [8]. The hexahedral meshing process is also manual, requiring user interaction and advanced knowledge of mesh generation techniques [9].

Recently, statistical shape models have been demonstrated for bony geometries [10–13] with the potential to efficiently generate a patient-specific model from anatomical measurements for use in computer-assisted surgery or to create a simulated population of subjects for assessment of implant design. Statistical shape modeling involves a principal component analysis (PCA) performed on a training set of extracted subject geometries to determine the modes of spatial variation [10–13]. In addition to manually segmenting the geometries to form the training set, a traditional challenge in statistical shape modeling is that registration, a correspondence of the landmark locations (mesh nodes) for each instance in the training set, requires implementation of custom algorithms and can be computationally expensive [10–13].

To address these issues of model development efficiency, recent studies have investigated various aspects of automating the model development process. Automated threshold-based algorithms have been employed to extract bones from CT scans [14,15], however, these techniques have rarely been applied to soft tissue structures (e.g. cartilage, ligaments, muscles) from MR scans [16]. Another common approach is to use traditional segmentation of CT images to generate a 'target' surface and to automate the mapping of a template mesh to fit the subject-specific segmented surfaces [17–22]. Additionally, deformable image registration techniques have been applied to noninvasively measure strain in knee ligaments [23].

The current study enhanced model development efficiency by proposing an integrated segmentation and hex meshing approach that is applicable to structures in both CT and MR scans, has accuracy similar to manual segmentation techniques, and can facilitate statistical shape modeling. As each of the subject models will have the same underlying mesh, the control points can be used directly in the formulation of a statistical shape model. Accordingly, the objectives of the current study were: (1) to develop an efficient, integrated mesh-morphing-based segmentation approach to create hexahedral meshes of subject-specific geometries from scan data and to apply the approach to natural femoral, tibial, and patellar cartilage (and the patella) from MR images, (2) to compare geometries and predicted contact results from a quasi-static FE analyses between meshed surfaces using the semi-automated approach and traditional segmentation, and (3) to demonstrate the direct application of the subject-specific models to create a statistical shape model of the knee characterizing the modes of variation using PCA.

2. Methods

2.1. *Integrated segmentation and mesh-morphing platform*

The integrated platform utilized a custom graphical user interface (GUI) and required a template mesh for each structure. The template mesh, developed using the traditional approach of manually segmenting (ScanIP, Simpleware, Exeter, UK) and meshing the structures of interest for a single subject, was used for morphing the geometries of subsequent subjects. Mesh morphing of the template was conducted using built-in Hypermesh (Altair, Inc., Troy, MI) features that maintained internal element quality (i.e. size and skewness) after mesh manipulation. To prepare for morphing a structure, the template mesh was subdivided into sets of contiguous elements to create groups (domains) bounded by control points (handles) on the group corners (Fig. 1a). Displacing control handles linearly redistributed internal nodes between the final handle positions within each domain (Fig. 1b). Each meshed structure was subdivided into domains and attempted to minimize the number of control handles required to identify anatomic borders while maintaining enough resolution to capture geometric changes.

The GUI was developed in Matlab (Mathworks, Natick, MA) to display a series of sagittal MR images and overlay sets of moveable points corresponding to the coordinates of the template mesh control handles. The GUI was subdivided into five sections to guide user operations: (1) general image and scan information input fields, (2) contour identification for patellar, tibial, and femoral structures, (3) a preview panel to show existing points located on previous images, (4) a mesh preview panel to orient the user to the location of the displayed sagittal slice on the template mesh, and (5) the current sagittal image (Fig. 2). Mesh morphing with the GUI was initiated by specifying image details (e.g. field-of-view dimensions, image resolution, leg side, scanned flexion angle) to convert control handle coordinates from "mesh" space to image "scan" space (i.e. 512×512 pixels). The medial- and lateral-most images associated with visible borders of each structure are then used to scale the template meshes and redistribute control handles along the medial–lateral direction. Points corresponding to template mesh control handles are overlaid on the displayed sagittal images and manually manipulated to identify the perimeter of the desired anatomic structure (Fig. 3). Once a structure was completely outlined, point coordinates were smoothed by fitting piecewise polynomials (2nd–4th order) in the sagittal, coronal and frontal planes minimizing the root mean square error between smoothed and identified handle coordinates. Differences between the initial template and final smoothed point coordinates were exported as morphing commands automatically executed on the template mesh within Hypermesh.

2.2. *Application to structures of the knee*

To evaluate the capabilities of the semi-automated platform, models of the femoral cartilage, medial and lateral tibial cartilage, and patellar bone and cartilage were developed from