Topological Modeling Of Human Anatomy Using Medical Data

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Abstract

Medical imaging can provide data for useful views of the interior details of human anatomy. In addition to visualization, which in general has been the primary reason for obtaining these data, many other uses are possible. These include modeling of different elements and their inter-relationships -- topological modeling, simulation of physical processes, analysis of movements and validation of models. Here, we describe some of the modeling issues from medical imaging. The issues are particularly related to topological modeling of different anatomical elements: bones, muscles, articulations, etc. A 3D topological modeler is presented with which anatomists and other users can build a topological data base containing structural, topological, and mechanical information of anatomical elements.

1. Introduction

The challenge of imaging science is to provide advanced capabilities and techniques for acquisition, processing, visualization and analysis of biomedical images to enable faithful extraction of scientific and clinical information [13]. This is a difficult task. However, there have been considerable efforts in this direction in the last decade [10, 12]. These efforts have been primarily directed toward the display and visualization of the contained information. Now clinicians can have a complete 3D view of the volume of a human organ. It is also possible to reconstruct or extract 3D surface of elements from those images[15]. However, these efforts concentrate on 3D visualization, of volumes or surfaces. There is also a need for modeling and analysis of the relevant information coming from images, which can be used for other purposes.

Computationally, modeling is the representation of a collection of data in a coherent way [2]. The related data items may be associated semantically, physically or in some other useful form. Modeling with medical images and data in our context provides both structural and topological information of different elements. In addition to displaying these elements, our interest is in using them for physically based simulations of deformations, motion generation and analysis, and model validation.

Here, we describe the tasks involved in building a topological modeler, a module for the project CHARM (Comprehensive Human Animation Resource Model) [4]. CHARM is a European (ESPRIT) project involving scientific and medical partners from different European countries including Switzerland. The project consists of modeling a 3D solid human body part with its interior details and having physically based simulation of movements and deformations. Modeling and simulations are validated with actual medical data.

The simulation of body deformations during motion requires taking into account the articulations of the skeletal structure as well as the mechanical properties of soft tissues. Once the components of the model are connected with their mechanical characteristics defined, a dynamical process is used for simulation. The forces estimated for muscles are fitted to the centroid line of action and applied to the skeleton, and the articulated structures deform. The incremental dynamic process of

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simulation accounts for the finite element computation of deformation and interaction of all the soft tissues.

In this module, we are not only concerned with providing the facilities of 3D display and reconstruction of shapes of the anatomical elements but also in integrating useful additional information of elements which will be used in other modules such as simulation of deformation and movements. A comprehensive database consisting of the structural as well as topological description of a body part is built, which can be used for several applications. Such a data base can be treated as a generic description of a canonical specimen, out of which a specific specimen can be derived or matched. This gives a large scope to the use of the topological modeler.

This paper is organized as follows. First, we give in Section 2, the overview of the main tasks involved. Surface modeling of elements with the labeling tool is presented in Section 3. In Section 4 issues related to topological modeling are presented: we define the topology in our context and present the data structure for the topology, features of the library, and the interactive tool for building the data base. The potential uses of the topological data base for different applications are presented in Section 5. Finally, we conclude and outline the related future work.

2. Overview

An overview of main tasks involved in building a topological model based on medical data is illustrated in Figure 1. It demonstrates the pipeline from the acquisition of images to the construction of the topological model. The human specimen images acquired from sources like Magnetic Resonance Imaging (MRI) or Computed Tomography (CT) are first converted to the readable form, which may then be preprocessed and filtered. Next, these images are interpreted and labeled to identify the useful regions of the image. The interpretation involves definition of contours of the elements of interest (bone, muscle) on the image slice. These contours may be refined by a matching tool to obtain finer contours. The 2D contours are then connected to give a 3D representation of the element. The 3D surface model of parts like bone is used in the topological modeler to establish the inter-relationships between different elements for a specific body part. A data structure representing the structural and topological information is provided to build the topological model for the given body part. Supplementary information for mechanical and physical attributes for an element can also be imparted.

3. Surface Modeling

A number of complementary diagnostic tools exist, such as X-ray, Computed Tomography (CT), Magnetic Resonance Imaging (MRI), or Positron Emission Tomography (PET). In general the resulting images are interpreted visually and qualitatively by radiologist or other medical experts. Voxel-display representation, though provides useful sophisticated visualization, offers little capability for treatment of the data in a manner consistent with their physical properties. This is due to the lack of geometry. Surface models are capable of representing the geometric structure of the elements. These structures facilitate the use of models for various tasks such as fabricating prostheses, facsimiles, inspecting occluded joints, pre-operative simulation, post-operative analysis, etc. [13].

Surface modeling first involves identifying the region of a desired tissue in the volume and then constructing a description of this region as a surface. Interpretation or identification of regions is meant for selecting "what is needed" and eliminating "what is not needed". This is important as medical imaging particularly MRI, has enormous information and it is often the case that anatomists or clinicians are interested in only a few elements in those images. For interpretation, the user interactively specifies the contours on the selected slices. These contours correspond approximately to the cross-section profile of the object in that slice. This approximation of the rough contour may be further refined using a segmentation or a matching technique. We have employed the matching tool from the University de las Islas Baleares (UIB), which uses snakes [7] for matching the contours. However, initial experience has revealed that automatic segmentation especially for MRI images, does not correspond to the actual form an anatomist conceives. User intervention becomes necessary to validate and correct the contours.

3D reconstruction to obtain the surface could be accomplished by either using the contours extracted from the images or using directly the 3D volume information of the stack of slices. A technique like Marching Cube [9] does the segmentation of the entire volume for a given threshold to obtain an isosurface. This was developed and employed, but was later rejected because of the artifacts using with MRI images and the large number of the polygons produced. A contour based technique [6] has been used which provides better control on the shape and the resolution of the geometry. The surface modeling tool has in principal two viewers, one for the 2D images, called the slice viewer and the other

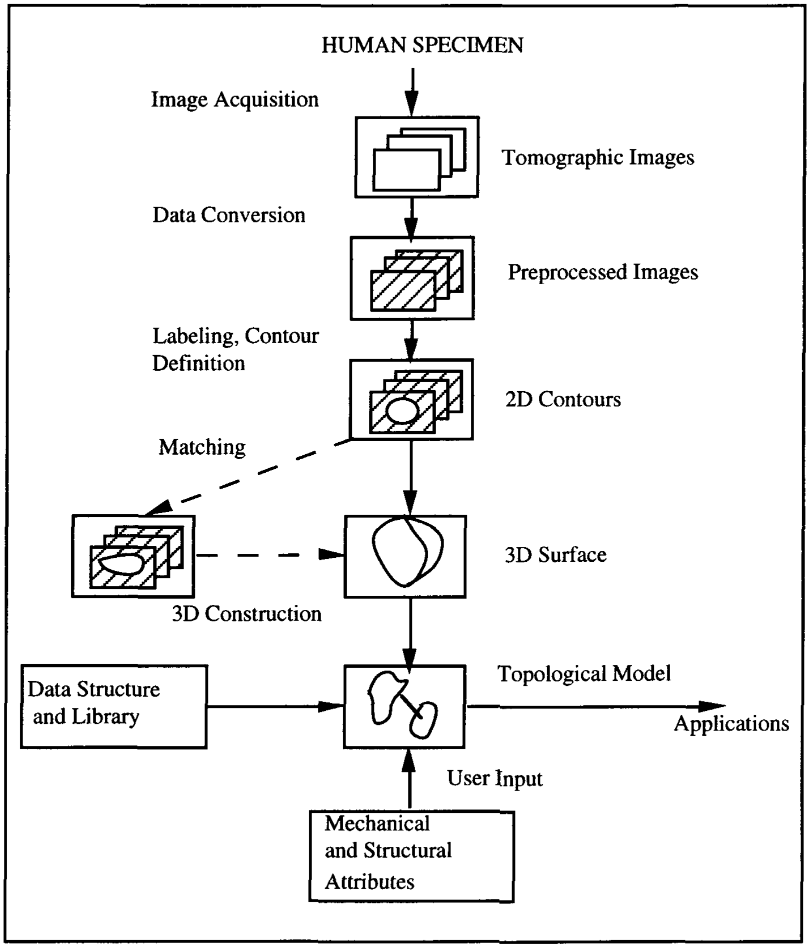


Figure 1: Overview of construction of topological model.

one is the 3D viewer for the stack of images, called the stack viewer. In the stack viewer, user can also view the 3D surfaces and contours. Speed of interaction and drawing are considered vital for the user. For certain hardware, it exploits their facilities like texture mapping and display. However, for others which do not support these facilities the corresponding functionalities have been provided. The 3D shapes with geometrical representations thus extracted are used for topological modeling and mechanical simulation for deformation and motion.

3.1 Examples

Figure 2 (see also in Color Plates) shows construction of the surface model of a bone from CT images. The two viewers (for stack and slice) are shown. The surface reconstructed can be simultaneously visualized with the stack of images. The cross-section contours are also displayed.

Figure 3 (see also in Color Plates) shows surface models of bones constructed with MRI images. MRI images render better details for the soft tissues like

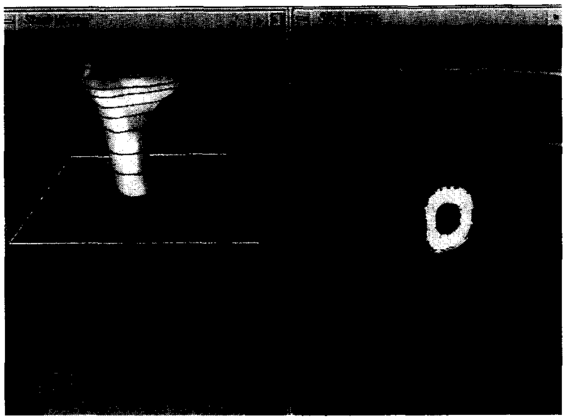


Figure 2: Bone reconstruction using CT images.

Figure 3: Bones reconstruction using MRI images.

muscles, however, for bones these are less effective. In order to extract both bones and soft tissues effectively, multimodal merging for the images obtained is needed [3, 11]. In addition, to enable assembling of images for a specific part taken in different orientations, multisection matching is required [1, 5]. By incorporating these aspects we intend to make our tool more general and versatile.

4. Topological Modeling

Topology in our context is defined as a 3D connectivity graph of anatomical elements for a given body part (e.g., arm). The topological relation in terms of connectivity of the elements can be drawn as shown in Figure 4. The number shown on the arc connecting two different elements indicates the cardinality of the relationship i.e. the manner in which the two elements are related. For example, between bone and attachment, there are several (n) possible references for the bone whereas for an attachment there is a single reference for the bone.

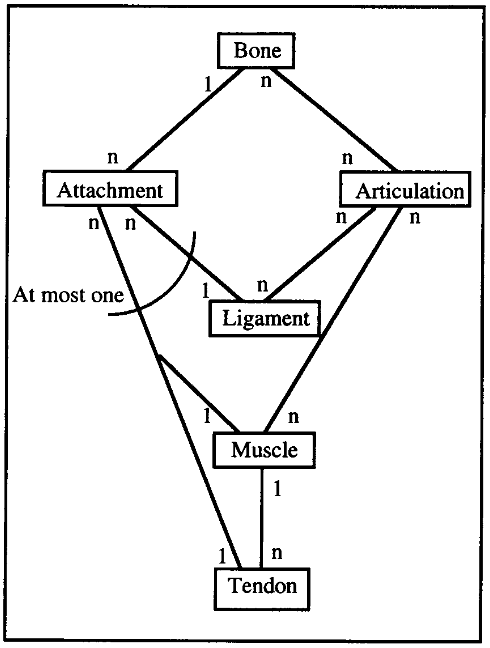


Figure 4: Connectivity graph.

For the data structure, object oriented methodology is used where each element is considered like a class, encapsulating the necessary information about its geometry and physical attributes. A library is built for manipulation and access of different elements, and thus provides means for creating, editing and saving the database for the topology of different elements. There is a base class Biology which includes general functions for accessing and manipulating the element of the class type. All the specific elements like bone, muscle etc., are the derived classes of the class Biology. Figure 5 shows the inheritance of the class Biology.

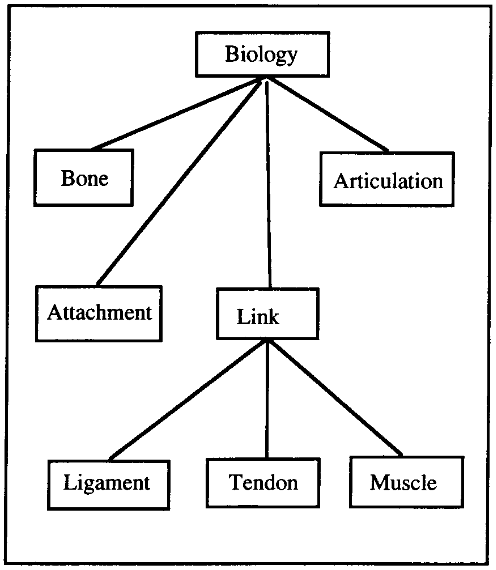


Figure 5: Class inheritance.

A class BodyPart is considered to define a generic part of the body, such as a limb (leg, arm), which would be modeled. For a body part there are two components: the topology of the biological elements and the hierarchy. The topology contains the reference for all the topological elements and their relations between each other, and the hierarchy helps define hierarchical information of biological elements. Hierarchical relation for elements like bones may provide the necessary constraints for the movements of the elements in a body part. For example, in the case of an arm, when the shoulder moves the other bones lower in the hierarchy (humerus, radio-ulna) follow the movement.

The following description presents brief information about the various elements considered.

4.1 Bone

Bones are represented as 3D geometry acquired from image-slices. The 3D geometry consists of a triangular mesh to represent the shape (see Figure 6). Bones are considered as rigid and "undeformable" parts. These are used in many instances as the "referential" elements to associate the other elements.

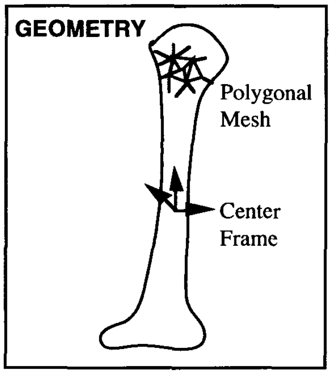


Figure 6: Bone with its geometry

4.2 Articulation

An articulation contains information about its connectivity with one or more bones, one or more muscles, one or more ligaments. Implicitly it is represented as an "axis frame" with three orthogonal axes and a center. Articulation plays an extremely important role for the motion of the skeleton. The reference bone used for the articulation is called the "master". Figure 7 shows the articulation between bones.

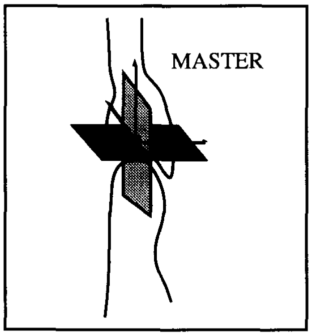


Figure 7: Articulation Frame

4.3 Attachment

Attachment provides the information of "what" link is connected to the bone and "where". Thus, it contains the information about the bone, the muscle, the tendon or/and the ligament. The attachment is defined as a collection of triangles/polygons of the bone where the link is attached. It also contains the point of attachment and its type (ORIGIN, INSERT, GUIDE, NONE). ORIGIN pertains to where the link initiates and INSERT to where it terminates. The option of GUIDE is meant for the constraints imposed by the intermediate bone attachment(s). Figure 8 shows attachment for the two bones. The geometrical reference for the attachment is the bone of which the attachment is constituted.

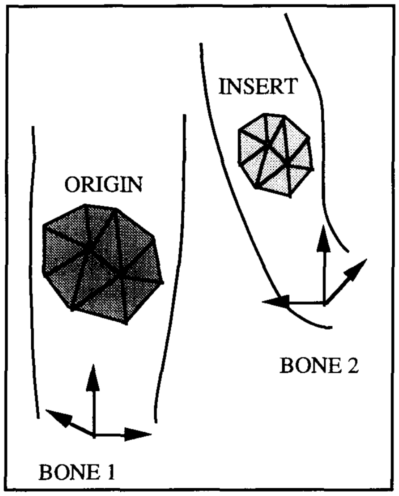


Figure 8: Attachments

4.4 Link

A link is defined as the generic element which is connected to the bones through the "attachment." A link can be a muscle, ligament or tendon. A muscle in fact, gives the power and control for the motion, a ligament provides a control for the limit of the joint movement (articulation); and a tendon is the transmission network of the muscle and the bone. Each link type may have its own characteristics. For example, a muscle is defined as a set of arcs consisting of a set of points and a direction defined on the attachment point indicating the force direction (see Figure 9). The true geometry of shape can also be obtained with surface modeling like of bones.

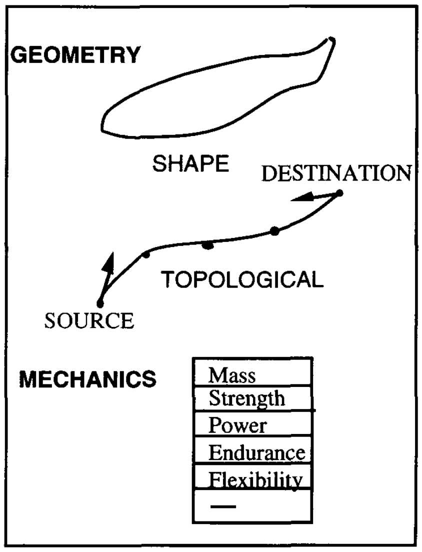


Figure 9: Muscle with its geometrical and mechanical attributes

4.5 Interactive Manipulation

Obtaining a static model is generally considered a major task of modeling. However, refining, modifying, and supplementing it with other information is also a critical aspect. A model with no notion of constraints, no perception of dynamics, and no knowledge of muscle attachments would restrict its utility to only visualization. In our topological model database, we provide these properties and the functional relationships of different elements. The intention is to build the working models with capabilities for medically acquired and bio-medically valid musculo-skeletal system [8].

In order to create such a database we provide a convivial interface for user interaction and manipulation. The tool developed for this purpose is called *tm* (topological modeler). It provides extensive 3D visualization and direct interaction and manipulation. The main task of *tm* is to create and modify the information contained in a topological database. *OpenInventor* [16] toolkit is used to realize the interface of *tm*. The *OpenInventor* (or *Inventor 2.0*) toolkit provides a library of objects for describing 3D scenes and methods for interacting with them. A scene built with such objects (called *nodes*) may be saved and loaded from a file and may also be easily rendered, with no low-level graphics programming. Furthermore, *OpenInventor* includes many other features such as triangulated meshes, NURBS, light sources of different types, draggers and manipulators for direct 3D interaction, engines for animation, automatic update of object dependencies and more. It also provides a simple event model for 3D interaction, efficient picking and rendering, defines a standard file format for 3D data interchange and is independent of platform and window system. Tasks such as scene traversal, interactivity, picking, bounding box calculations, and other object space tasks, are relatively easy to handle. The usage and layout of *tm* conform mainly to the mainstream look and feel.

Each class of the database may correspond to a new class of Inventor nodes encapsulating all the features and behavior needed for user interaction and for database interfacing. These new nodes are more precisely node kits [17] encapsulating different nodes together. The 2D user interface is realized through the use of the Motif widget library.

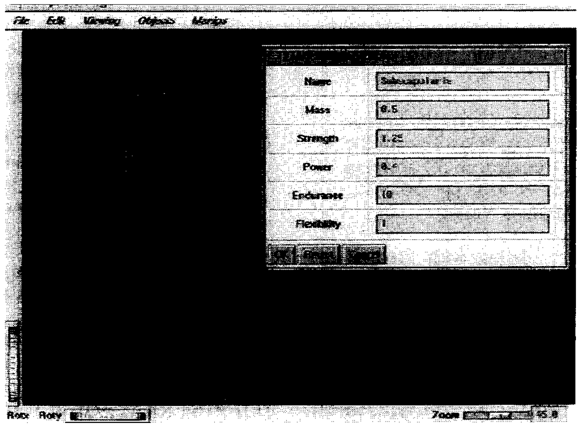
4.6 Example

Figure 10 (see also in Color Plates) shows topological modeling of some elements in the shoulder part of an arm using *tm*. The muscular links are shown as straight-line arcs between bones. The surface of attachments (origins and inserts) for links are defined on the reference surface of the bones. The articulations are shown as frames at the joints.

5. Uses

The utility required for interactive model manipulation can serve a variety of purposes. In our context, 3D tools can be used to specify tissue composition and relationships: muscles and attachments could be created and connected to specific bone sides and given properties that will characterize their behavior.

Most of the applications using medical imaging can use these tools to facilitate investigations and experimentation with the data. These may be diagnosis of abnormality (structural or movement), interactive surgical investigation, examination for orthopedic



Name: Subscapularis
Mass: 0.5
Strength: 1.25
Power: [illegible]
Endurance: 10
Flexibility: 1

Figure 10: Topological Modeling in *tm*.

therapy, prostheses design and simulation, etc. In addition, the topological database can be used for other potential applications of CHARM such as sports, education and entertainment.

6. Conclusion

Volume display of medical images provides good information for clinical evaluation, however, more advanced capabilities such as structural manipulation of the data, and simulation and analysis of dynamic function and behavior, require different formalisms of modeling and design of tools. We have employed surface based models comprising 2D and 3D representation of the data and developed interactive 3D tools for their investigation, analysis and manipulation. These tools may help medical experts in their investigation and analysis. In addition to the medical applications topological modeling of human anatomy has a wide scope in other applications like sports, education and entertainment.

The topological modeler is linked to many other future work modules for the project CHARM. The contents of the modeler may evolve in many ways. Improvement of tools will be done both for their interface and their functionalities from the feedback of the users. The tools are currently being used by other partners including medical people. With the development of other work modules (e.g. mechanical simulation, validation) it may become necessary to add or extend the features of the present tools. For certain functionalities like segmentation and 3D matching it may be necessary to seek more generality and offer better automation. A class "skin" is to be added to the database allowing for simulation of biological process such as aging and wrinkle formation [18].

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