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Short Communication

Towards a Personalized Ligamento Skeletal Model-based Finite Elements Approach to Biomechanically Predictive Scoliosis Surgery Planning

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Abstract

This paper describes a new research project that will establish the foundation of a scoliosis surgery planning and simulation system, emphasizing i) minimally supervised, multi-surface deformable model-based segmentation of ligaments, vertebrae and intervertebral discs, featuring statistical shape priors of bones and ligaments produced with cadaveric tissue mapping studies, ii) the estimation the forces needed for corrective therapies through subject-specific finite elements (FE) studies, in turn iii) validated and fine-tuned by cadaveric loading studies and tool instrumentation studies. The project builds on the team's prior work on Simplex deformable multi-surface models, used successfully to segment vertebrae and intervertebral discs of the spine without overlap. It also builds on expertise in FE-based biomechanical simulations, in positioning and loading devices for the musculoskeletal anatomy, in scoliosis surgery, and in cadaveric tissue identification. The ligaments and bones identified on cadaveric subjects will form the basis of a ligament skeletal template anatomy that can be nonrigidly registered to any subject subsequently, in a manner anchored by bones well contrasted in either MRI or CT. This deformable multi-surface Simplex model approach will mitigate any ambiguity present in the identification of ligaments due to limited contrast in CT or MRI.

ABBREVIATIONS

MRI: Magnetic Resonance Imaging; CT: Computed Tomography

INTRODUCTION

This paper describes a new research project on scoliosis surgery planning that builds on the group's prior work on minimally supervised spine segmentation, cadaveric imaging studies, finite elements, and musculoskeletal loading. The patient-specific computer simulation studies achieved by this project will provide surgeons valuable information on corrective forces that will improve workflow and patient outcome in scoliosis surgery. For some large and rigid scoliosis cases, the rigidity of the deformity cannot be overcome enough to achieve satisfactory correction. In these cases, a release procedure, either anterior or posterior, is used to render the spine more flexible and enable correction, albeit at the cost of a more complex and extensive procedure. In an anterior release, intervertebral disc tissue is removed from the front. The alternate option is posterior removal of ligament and bone, including parts of the spinous process and facets to partially correct scoliosis. If the amplitude of corrective forces were known prior to surgery, surgical workflow would be improved, the patient would spend less time in the OR, while limiting anterior and posterior release procedures to a minimum and facilitating their planning. While finite-element-based biomechanical studies in orthopedic surgery are not new, they emphasize pedicle screw insertion mechanics, while patient-specific anatomical models that account for interaction between vertebrae, bound to each other by ligaments, featuring shared surfaces at tissue interfaces, are not found in the literature or in clinical practice. Thus, no existing work in surgery planning or simulation can provide a surgeon with an estimate of the amplitude of corrective forces involved in scoliosis surgery. Limitations of the state of the art have two main causes. First, spinal ligaments do not show up well in MRI or CT: these tissues exhibit little contrast in relation to other soft tissues nearby. Second, even if one could identify these tissues (segmentation), these tissue blobs would need to be decomposed

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into elements (meshing), where elemental decompositions need to abut perfectly where in contact; currently, volumetric meshing is not done in a manner that produces patient-specific models with shared surfaces.

MATERIALS AND METHODS

This project will establish the foundation of a scoliosis surgery planning and simulation system, emphasizing i) minimally supervised, multi-surface deformable model-based segmentation of ligaments, vertebrae and intervertebral discs, featuring statistical shape priors of bones and ligaments produced with cadaveric tissue mapping studies, ii) the estimation the forces needed for corrective therapies through subject-specific finite elements (FE) studies, in turn iii) validated and fine-tuned by cadaveric loading studies and tool instrumentation studies (Figure 1). The project builds on the team's prior work on Simplex deformable multi-surface models, used successfully to segment vertebrae and intervertebral discs of the spine without overlap. It also builds on expertise in FE-based biomechanical simulations, in positioning and loading devices for the musculoskeletal anatomy, in scoliosis surgery, and in cadaveric tissue identification. The ligaments and bones identified on cadaveric subjects will form the basis of a ligament skeletal template anatomy that can be nonrigidly registered to any subject subsequently, in a manner anchored by bones well contrasted in either MRI or CT. This deformable multi-surface Simplex model approach will mitigate any ambiguity present in the identification of ligaments due to limited contrast in CT or MRI.

The key to achieving highly predictive surgery simulation lies in combining patient-specific anatomical models of high fidelity with highly accurate biomechanical therapy models. While there is competing work underway on scoliosis surgery planning [1], the anatomical models used by these research groups are of limited fidelity, failing to account for the effect of spinal ligaments, which are difficult to personalize without exhaustive user input. These limitations degrade both the usability and accuracy of any surgery planning downstream. The inability of competing methods to account for subtle connective tissues, difficult to visualize due to low contrast in MRI, and the prohibitive workload involved in their segmentation and meshing approaches, have limited their clinical impact to a small patient studies. In contrast, as a result of its emphasis on descriptive, minimally supervised anatomical modeling as well as accurate biomechanical testing and simulation of the ligament skeletal system, this project will not only estimate corrective forces in scoliosis surgery but serve as foundational infrastructure for broadly usable predictive therapy simulation that achieves optimal solutions, based on competing what-if scenarios, for scoliosis surgery treatment planning while also enabling the reproduction of potential pitfalls [2].

The anatomical modeling, comprised of segmentation and meshing, will be based on the work of the first author [3,4]. Segmentation maps image intensities to tissues and falls under three categories: voxel-based classification methods, boundary methods based on deformable surface models and atlas-based methods that warp a digital label map to MRI or CT. Meshing decomposes segmented tissue blobs into simple elemental shapes needed for biomechanical simulation. Our segmentation work combines boundary and atlas methods: a Simplex deformable surface model, which is a mesh featuring 3-connected vertices (Figure 2), and a digital atlas of the anatomy. The anatomical

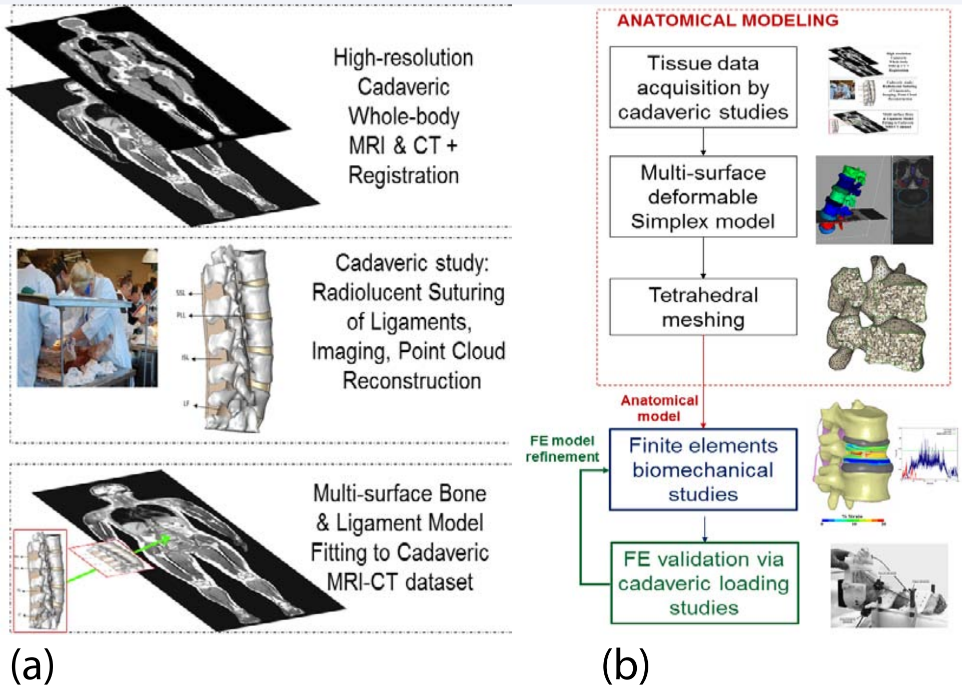

Figure 1 Overview of proposed Approach. (a) Multimodal cadaveric image and point cloud acquisition; the imaging and radiolucent suturing will be an iterative process that may strip away occluding tissues. (b) Project overview, featuring anatomical modeling, spine loading device and surgical tool instrumentation development, as well as finite elements studies.

modeling approach uses a multi-surface Simplex model to identify complex tissue boundaries, leading to a triangulated surface by geometric duality, which in turn is applied to constrain the subsequent tetrahedralization. The Simplex model features a computer discretization of a Newtonian expression for vertex position:

$$m\frac{d^2P_i}{dt^2} = -\gamma\frac{dP_i}{dt} + \alpha F_{\text{int}} + \beta F_{ext} \tag{1}$$

Where *m* and *y* represent vertex mass and damping, and the latter two terms are sums of internal and external forces. The external force F_{ext} includes an image force that binds the surface mesh to a tissue boundary coinciding with an image gradient in the direction normal to each vertex. The internal force can impose smoothness on the surface; in addition, it is possible to enforce consistency of the surface with a statistical shape model. This SSM encodes common variations in a set of training shapes, through Principal Component Analysis (PCA) [5]. Figure (2) depicts the top three modes of deformation of SSMs of 10 L1 vertebrae. Next, following Gilles [6], the Simplex model can also exploit collision detection to prevent spatial overlap between neighboring surfaces. Last, our two-stage approach to tetrahedral meshing [3] produces a high-fidelity, controlled-resolution triangulated tissue boundary, which is complemented by variational tetrahedralization of the tissue [7,8].

The finite elements method (FEM) numerically solves for unknown displacements, deformations, stresses, forces and possibly other variables of a solid body. An exact solution would require force and momentum equilibrium at all times everywhere in the body. The finite element method replaces this requirement with the weaker one that equilibrium must be maintained in an average sense over a finite number of divisions of the volume of the body. These divisions, or elements, are simple shapes such as tetrahedra and hexahedra for 3D volumes; the method relies on estimating the displacement at their vertices, or nodes. Discretizing these mechanical equilibrium equations is based on restating them as a single integral, called the Principle of Virtual Work (PVW), and expressing this integral in a weak form, which leads to a linear system featuring a sparse matrix. Foregoing the details of the derivation of FEM formulation from PVW, the equilibrium expression within each element is given by:

$$\mathbf{q}^e = \mathbf{K}^e\mathbf{a}^e + \mathbf{f}^e \tag{2}$$

where we designate nodal forces $\mathbf{q}^e$ and displacements $\mathbf{a}^e$ $\mathbf{K}^e$ and $\mathbf{f}^e$ are the elemental stiffness matrix and force vector. Summing expressions (2) over the whole volume leads to the FEM formulation:

$$\mathbf{Ka} = \mathbf{f}, \tag{3}$$

Where **K**, **a** and **f** represent the system stiffness matrix as well as the nodal displacement and force vectors. This matrix system can be solved to estimate forces, specifically the forces needed to implement the corrective displacements in a scoliosis procedure.

The last foundational component of this project will build on our expertise in positioning and loading devices as well as force transducers for surgical tools, which has resulted in positioning and loading devices for the ankle and knee [9,10]. We have also developed a methodology based on 3D-printing scaled-down versions of these loading devices, which have been the object of senior-year projects.

The anatomical modeling developed in this project will emphasize cadaveric studies described in the flow chart of Figure (1a), and refinements to the statistical shape-based Simplex multi-surface model. The cadaveric imaging studies will take place at Eastern Virginia Medical School (EVMS) Department of Pathology and Anatomy. These studies will be iterative exercises in scanning the subject in a MRI and CT scanner, exposing the ligament surfaces of interest, and suturing these surfaces with radiolucent thread, followed by further high-resolution scanning to produce a cloud of points coinciding with boundary of the structure of interest. Subsequently, we will register the various datasets together and refine the deformable surface model to fit a surface to these point clouds. The challenge will be to account for

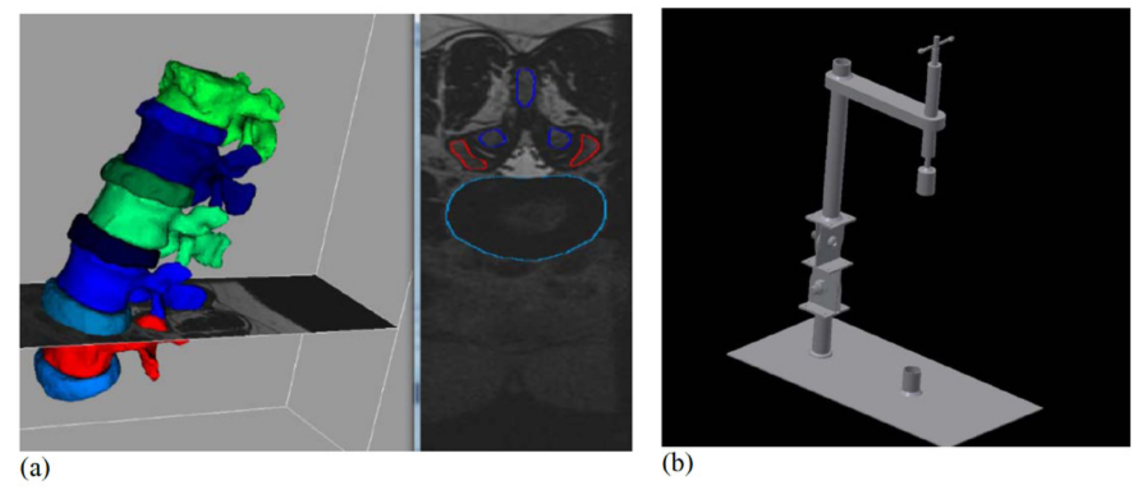

Figure 2 Preliminary results. (a) SSM-aware multi-surface Simplex deformable model-based segmentation of lumbar spine [12]. Inset: 3-connected topology of Simplex mesh, illustrating duality with triangulated surface. (b) First design of spine loading device, produced in conjunction with senior mechanical engineering capstone project at ODU.

multiple modalities while producing a tight-fitting multi-surface model: bones from CT, ligaments from radiolucent point clouds, and so on.

The project will exploit tetrahedral-element support on LS-DYNA, while considering both linear and nonlinear constitutive models for soft-tissue biomechanics. For tissue properties, we will exploit rheological values published in the literature, such as those ascertained by tensile tests as in the work of Chazal [11,12]. It is worth noting that the loading devices developed here can be used to estimate these elastic properties.

The project will develop a positioning and loading device of the spine. In addition, we will develop small force transducers for scoliosis instruments that can measure typical forces imparted during surgery. We will collaborate with Alphatec Spine, which produces scoliosis surgery instruments, to develop force transducers for two instruments involved in scoliosis correction: the reduction tower and the pliers used to rotate the corrective rod. The two main stages of scoliosis surgery that involve the greatest forces are: i) the reduction of the curved rod that positions it to fit within the mouth of the top-loading pedicle screws (inserted in the pedicle and vertebral body of each vertebra), and ii) the rotation of this curved rod that results in the proper alignment of the assembly of pedicle screws and the vertebrae to which they are attached, thereby correcting the scoliosis.

RESULTS AND DISCUSSION

Our results are still in their infancy and are depicted in Figure (2). The Simplex model currently combines the ability to identify multiple surfaces coinciding with vertebrae and intervertebral disc (IVD) boundaries, and ii) shape statistics obtained from CT and MRI respectively for vertebrae and IVDs, with the result that a highly accurate minimally supervised segmentation is feasible from a single MRI dataset, as shown in Figure (2). The supervision provided by the user includes a one-time training of the statistical shape model of the vertebrae and IVDs, a lightweight procedure based on simple manual corrections to a surface mesh segmentation result, and the identification of a few anatomical landmarks on each such structure. The repulsion force by the static collision detection of the multi-surface Simplex effectively eliminates spatial overlap between any two surfaces. However, this anatomical modeling is suboptimal in that space can still occur between two surfaces, whereby the ideal model is one with perfectly shared surfaces, a refinement that will build our ongoing work on multi-material contouring.

Meanwhile, we can also point to a preliminary design of a spine loading device, which is one of the projects under development by a capstone senior design group at ODU. This group is also developing an instrumentation strategy based on strain gauges that will be mounted on Alphatec surgical tools.

CONCLUSION

This short communication described a new research project whose overarching objective will be predictive scoliosis surgery simulation studies based on personalized models of the scoliotic spine that include spinal nerves. The anatomical modeling will exploit a combination of cadaveric imaging studies and multi-surface deformable models. The latter models will serve as the first stage of the tetrahedral meshing process.

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