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Application of SOFA Framework for Physics-Based Simulation of Deformable Human Anatomy of Nasal Cavity

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Abstract. Surgical medicine is one of the most radical approaches for the treatment of numerous types of diseases. Recently broad application has taken the direction of computational surgery that aims to improve the quality of treatment through the use of computer tools. The use of computational surgery in rhinoplasty is important due to the fact that the results of the intervention directly affect the geometry of the nasal cavity and, as a consequence, the aerodynamic parameters of the nose. In turn, these parameters determine the functional characteristics of the patient's nasal cavity. In this paper, we have focused on modeling the deformation of anatomical structures using SOFA framework software library considering tetrahedron finite element modeling (FEM), hexahedron FEM, triangle FEM and mesh spring force fields. The simulation results indicate the high functionality of the SOFA framework for modeling the deformation of the airway in rhinosurgical interventions. These results could further be applied for modeling the deformation of the anatomical structure taking into account the change in the topology of a 3D model to simulate such surgical procedures as a cut.

Keywords: Computational surgery · Rhinosurgery · Simulation · Elastic tissue deformation · Finite elements · Respiratory tract · Virtual reality · Volume segmentation

1 Introduction

Application of information technology in medicine has been considered as one of the most demanding fields due to the fact that it makes extensive use of data collection, processing, and analysis technologies [1–3].

The methods of processing and analysis of medical information are of utmost importance in making a clinical diagnosis and thus affect further treatment approaches.

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In turn, the direction has significant prospects for implementation in rhinosurgery. It includes information technology, simulation, robotic medical systems, imaging technologies, and others. The importance of this area lies in the possibility of calculating the results of the surgical intervention and the choice of optimal therapy [4, 5]. This could further improve the patients' life expectancy and quality.

In this regard, rhinosurgery is one of the applications of computational surgery. It relates to the surgical access and the significant influence of the geometric parameters formed as a result of the operation on the aerodynamic indices of the nasal cavity.

Topics on development and visualization of a three-dimensional geometry of the anatomical models of the nasal cavity has been widely covered in the current literature [6–8]. The related methods include computational geometry, image processing and recognition. Here, the ability to perform a functional analysis of a three-dimensional (3D) model is of particular interest since it could provide the information on deformation of anatomical structures. For this purpose, both the virtual model and full-scale can be utilized. Rapid prototyping or 3D printing is the most useful and easy-to-use approach to produce 3D models [9, 10].

The development of visualization tools allows performing the analysis in a virtual space [11, 12], which has additional application in the development of distance learning in education and clinical practice. In online education, virtual training systems could ensure an extensive access of the students to obtaining initial practical skills. In addition, such systems could also make it possible train young surgeons and to simulate the process of surgical intervention, predict the result and possible challenges as well as identify and avoid dangerous situations, which could happen during surgical intervention. At the same time, one of the most challenging tasks is the simulation of interaction with a deformable three-dimensional physical object and simultaneous modeling of the aerodynamic flow. Thus, the purpose of this study was to analyze the possibilities of the SOFA framework [13] to simulation of realistic deformation of the patient's nasal cavity at the stages of preliminary planning and training.

2 Materials and Methods

As input data, 600 $\times$ 600 pixel computer tomography (CT) slices with a pixel spacing of 0.2 mm were used (Fig. 1). The respective CT scans were provided by Ear, Nose, And Throat Unit of Kharkiv Regional Hospital (Ukraine). The CT scans of the patient were obtained according to written informed consent for the purpose of anonymized evaluation and publication of the data. The slices were obtained using a PHT-60CFO device (Vatech Limited). The images covering the complete nasal cavity are stored in a DICOM format.

The open-source 3D Slicer software was used for the manual segmentation of 3D tissues, namely cartilage tissue and muscle tissue [14]. The resulting model was preprocessed using MeshLab, which is one of the most functional open-source software in processing polygonal models [15]. Figure 2 shows the result of the segmentation and pretreatment of the polygonal model of the nasal cavity. Modeling of deformation is a very complex process that involves computational geometry and mechanics, polygonal

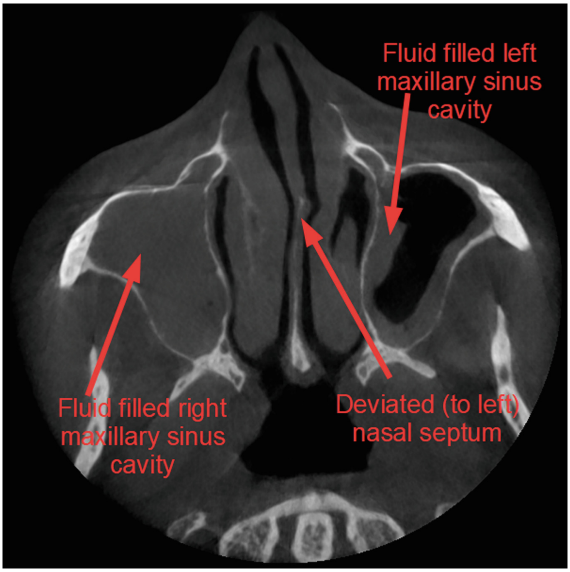

Fig. 1. A CT section of the nasal cavity depicting maxillary sinus cavities filled with liquid as well as deviated nasal septum.

visualization, and others [16–21]. The implementation of all these components becomes almost impossible without the involvement of a large number of specialists.

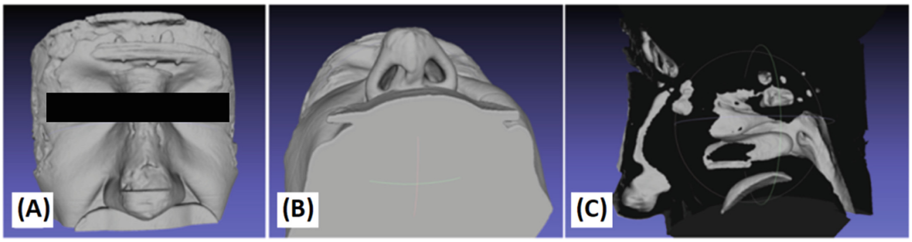

Fig. 2. A three-dimensional polygonal model with segmented nasal cavity: A – anonymized frontal view, B – view from down to the top, C – sagittal.

A specialized SOFA framework library is an open-source framework that allows one to represent the process of simulation (scene) in the form of a set of objects, each being represented in the form of three models, namely models of imaging, collision, and deformation (Fig. 3) [13].

The modeling process consists of describing the simulation scene by developing a corresponding scene file, an XML file as shown on Fig. 4.

As can be seen from Fig. 4, the parent node of a SOFA scene file contains child nodes that describe all the necessary components for modeling. These include force of

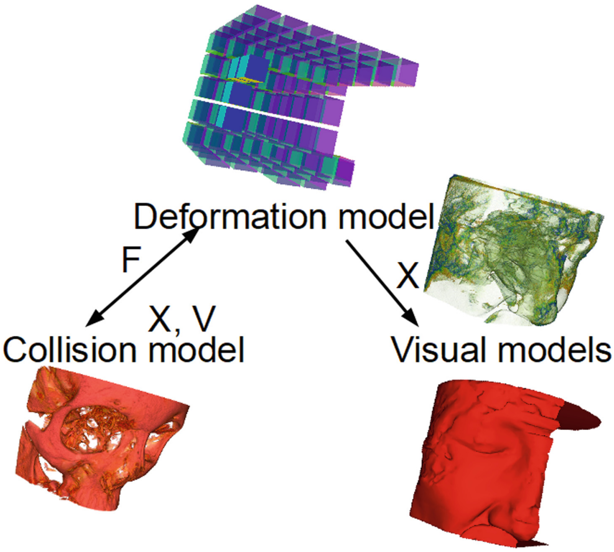

Fig. 3. Models in the SOFA framework.

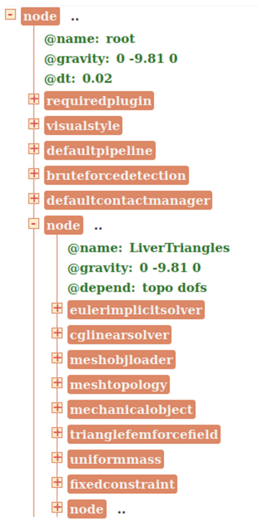

Fig. 4. A graphical representation of a SOFA-scene file.

gravity, time step during the simulation (Δt), topology of 3D meshes, solvers, constraints and used force field.

3 Experimental Results

3.1 Application of Force Field Templates

At first, the force field must be determined to calculate the deformation. This component allows performing summarization of the forces and thus calculates the object deformation. The forces include tetrahedron finite element modeling (FEM), hexahedron FEM, triangle FEM and mesh spring force fields.

Each of these components has its advantages and disadvantages and can be used to model a particular class of an object [13]. As an example, Fig. 5 shows the hexahedron FEM force field initially obtained from input polygonal model.

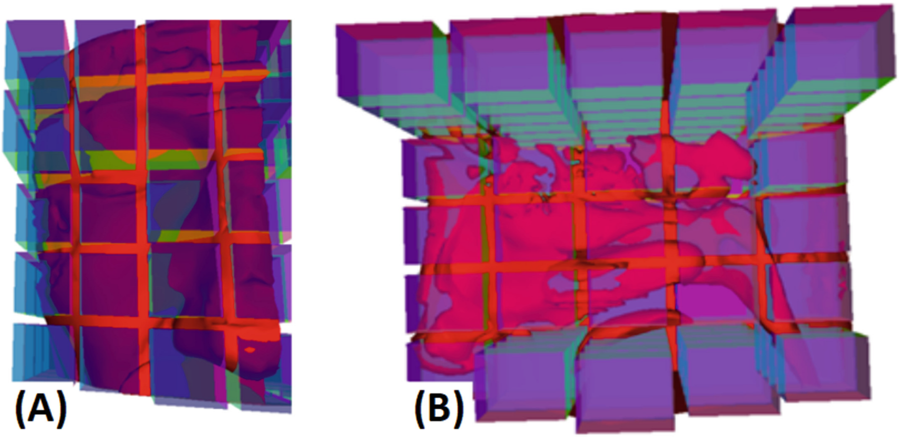

Fig. 5. Visualization of hexahedron finite element method force field: A – frontal view; B – sagittal view of nasal cavity. Cubes represent units of deformation in the deformation model.

Although the model describes the hexahedron force field as a rough approximation, such a model might be sufficient in many cases. To change the force field to the hexahedron FEM force field, the following description was be added:

<HexahedronFEMForceField template=“Vec3d” name=“FEM” method=“polar” poissonRatio=“0.3” youngModulus=“250”/>

In turn, visualization of the triangle FEM force field is shown on Fig. 6 by frontal (Fig. 6A) and sagittal (Fig. 6B) views. The respective color gradients describe the triangles of the mesh that are used for calculations. Similarly, a force field is implemented based on a polygonal model as follows:

<TriangleFEMForceField template=“Vec3d”/>

The corresponding description for visualization of mesh spring force field was the following:

<MeshSpringForceField template=“Vec3d” name=“Springs” stiffness=“4500”/>

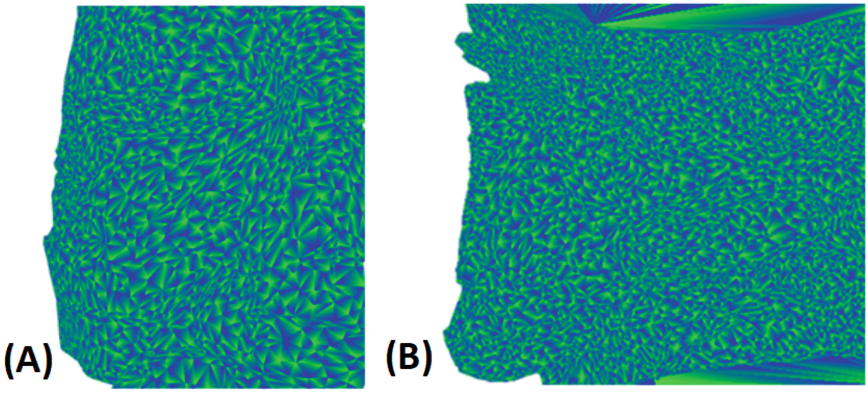

Fig. 6. Visualization of triangle FEM force field: A – frontal view; B – sagittal view of nasal cavity. A color gradient describes the triangles of the mesh that are used for calculations.

The result of visualization of mesh spring force field is shown on Fig. 7, which represent frontal (A) and sagittal views of the nasal cavity. The blue color represents the edges of the mesh, which were used to calculate the spring force field.

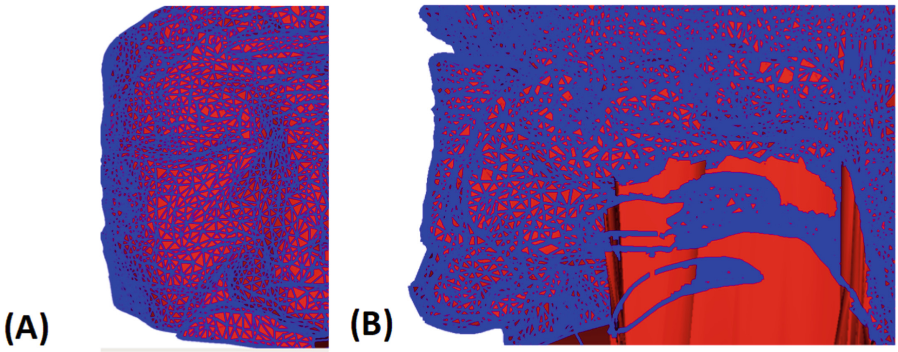

Fig. 7. Visualization of mesh spring force field: A – frontal view; B – sagittal view of nasal cavity. The edges of the mesh spring, which were used to calculate the spring force field, are marked in blue.

As one can see from the XML descriptions, they contain specialized attributes that describe the material parameters for the material, such as Young modulus (in the HexahedronFEMForceField XML template you can see it), stiffness (in MeshSpringForceField XML template), etc.

3.2 Simulation of Deformation of the Nasal Anatomic Structures

Simulation of the deformation of the nasal septum during rhinosurgery was conducted in the SOFA framework (Fig. 8). The developed 3D model contains 110,000 vertices forming 21,000 triangles. Visualization is provided at 60 frames per second.

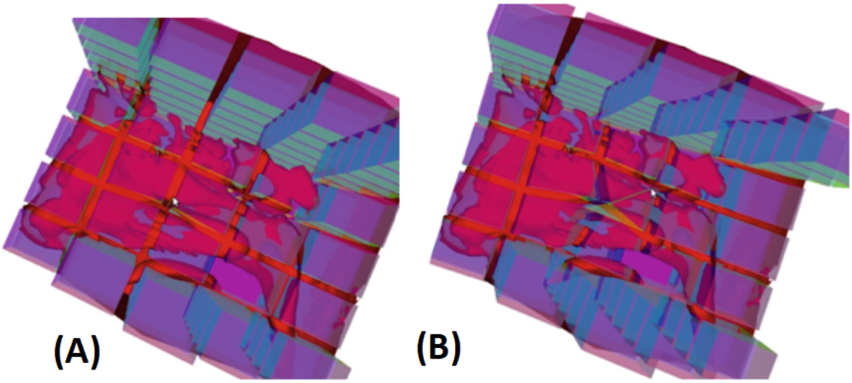

Fig. 8. FEM simulation of deformation of the nasal septum during rhinosurgery in SOFA software at different times: A – at time t = 0 s; B – at time t = 10 s.

The deformation process is more clearly visible on the outer surface of the nose, as represented in Fig. 9. The results show excellent capabilities of the SOFA framework for modeling object engagement. This is especially important for modeling the process of deformation of the most prominent interest in biomedical engineering because it allows performing simulation of anatomical tissues and organs.

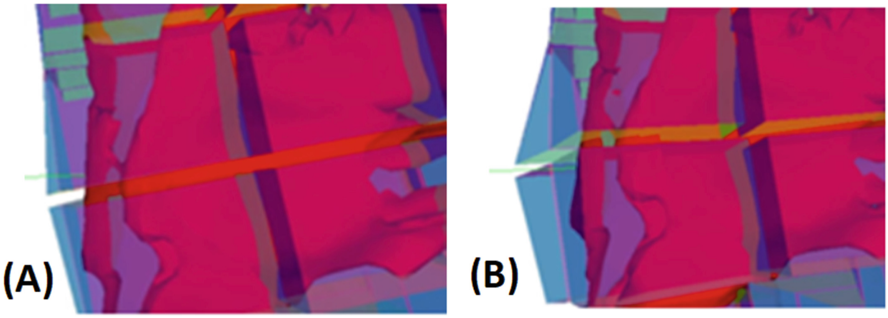

Fig. 9. FEM simulation of deformation of the outer shape of the nose in SOFA software at different times: A – at time t = 0 s; B – at time t = 8 s.

4 Conclusions

In this work, we used the SOFA framework to obtain a topological description of the nasal cavity, which was used for subsequent modeling, for the application in rhinology. The results show that the deformation module can operate in real-time (at 60 frames per second) using simplified deformation models. Available computational models allow carrying out the deformation procedure taking into account various external influences in real-time.

The main prospect of applying the results of the current work is the application of the developed models in development of a specialized otolaryngological simulator for medical purposes. In addition, further studies in the field of modeling the simultaneous deformation of the nasal passages and modeling the aerodynamics of the nose should allow real-time assessment of the result of functional surgical interventions.

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Conflict of Interest. The authors declare that they have no competing interests associated with the current manuscript. This study included neither animal experiments nor clinical studies. All reported investigations were conducted in accordance with the International Code of Medical Ethics and national regulations.

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