SOFT TISSUE MODELING FOR VIRTUAL SURGERY SIMULATION

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Abstract: Nowadays on medical and healthcare areas, training and learning methods for surgeons are based on skills development. In order to improve this learning process, virtual reality simulators have been proposed due its capacity to reproduce surgical procedures without any risk or harm on patient. These devices represent a wide research area that involves multiple fields of knowledge, such as mechatronics, computational mechanics and information technology.

In this work are exposed the improvements for soft tissue modeling on the virtual environment of an open-source laparoscopic surgery simulator.

In this paper, the *Exoskeleton Structure* (ES) method was developed and applied on a 3D mesh in order to create interactive simulations for concave geometries on the simulation core. Moreover, the *Equivalent Strain Energy Density* (ESED) model was implemented, showing good performance in prediction of soft tissue behavior on preliminary results for a one-dimensional element on uniaxial testing.

These results validate the application of both proposals for soft tissue modeling on the development of real-time surgery simulations.

Keywords: Virtual reality, InVesalius, Surgery simulation, Tissue modeling.

Introduction

Currently, medical training on surgical procedures is focused on skills development and practical learning. For this application, several technologies have been proposed to create tools for training, trying to improve the process in which physicians acquire experience and practical knowledge, avoiding any risk on patients.

For instance, virtual reality has been applied to create learning tools and devices for surgical training, due its capacity to generate controlled environments without any risk or harm on patients. Simulation systems created with this technology allow the physician to interact with the device in order to complete several tasks (with failure detection and improvement measurement) over and over until the user achieve the quality level required for the procedure [1].

One of the most important parts on the development of a virtual surgery simulator is the functional integration of multiple concepts in order to create a training system as close as possible to reality. Therefore, virtual simulators intended to support skills development on surgical procedures should involve an appropriated combination of graphical tools, physics and mechatronics, and considering computational performance and visual response.

In this work, the new developments of an open-source laparoscopic surgery simulator are exposed, focusing on improvement for soft tissue modeling on the virtual environment.

Background

This work is based on the integration of three major parts: 1) InVesalius software for 3D reconstruction of medical images, 2) a simulation core of mechanical properties for soft tissue characterization and 3) a mechatronic design for user interaction. The main concept of this framework is presented on Figure 1, showing the interaction between fields.

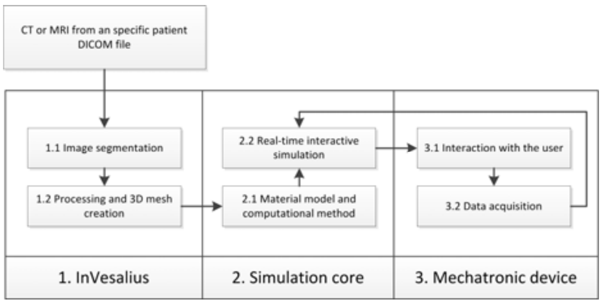

Figure 1: Main concept of this framework

InVesalius is an open-source software used to create 3D reconstructions from medical images, such as CT (*Computed Tomography*) and MRI (*Magnetic Resonance Imaging*) on DICOM (*Digital Imaging and Communication in Medicine*) format [2,3]. It was developed with Python programming language and VTK (Visualization Toolkit) and includes segmentation and measurement tools for geometrical features [4].

Given that InVesalius is open-source software with GNU General Public License, it represents a platform that allows the development of new tools for research purposes on a wide range of medical applications [5-8].

One of the main objectives of this framework is to implement a surgical simulation module for InVesalius, by developing tools to create simulations of specific patients in order to provide support for training and planning that particular surgery.

A first approach for an open-source laparoscopic surgery simulator was achieved by creating a simulation core based on a *Spring-Mass Model* (SMM) with an *Internal Skeleton Structure* (ISS). Using that hybrid model, Euler's method with a central finite difference was applied, and a basic simulation core was implemented with Python and VTK to allow a future integration with InVesalius [6,7].

On the mechatronics part, a device to represent the surgical instruments used on laparoscopy was developed to allow users to interact with the system. This interaction device was developed considering common materials and a simple design, using Arduino™ technology as platform for data acquisition. Further publications will be released focusing on the design and development of the interaction device.

This paper is mainly focused on new improvements applied on the simulation core. On the next sections, the development of a new meshing method for specific geometries is exposed, as well as the implementation of a material model for soft tissue that was not applied on real-time surgery simulations before.

Simulation core improvement – Although SMM is commonly used for deformation applications, is a fact that real behavior of soft tissues cannot be described by one-dimensional elements with only elastic and damping parameters, not even with the implementation of an ISS. Also, the creation of the internal structure is a method with problems for concave geometries, having difficulties with some organs and anatomical shapes.

The mechanical properties of soft tissue are related to their cellular composition, which in most cases is non-uniform, and should be considered as a composite material of a matrix with an isotropic behavior and a bundle of collagen fibers with an anisotropic behavior [9,10]. Therefore, a material model that includes properties of transverse isotropy, anisotropy and hyperelasticity should be considered for this application.

For this problem, it was found that Elías-Zuniga et al developed a mathematical model able to characterize soft tissue and biological materials, based on the rule of mixtures of strain energy. In this constitutive model, it was considered finite deformations of hyperelastic materials by applying the rule of mixtures to create an *Equivalent Strain Energy Density* (ESED) model, which includes energy contributions from isotropic and anisotropic volumetric fractions of the material [10].

Although this model has not been used for real-time surgery simulation, has proven to predict the behavior of biological materials in an accurate way, through comparison with experimental data and estimation from other material models [10]. In this article, a first approach for the implementation of the ESED model on the simulation core will be exposed.

One of the biggest advantages of this model is that can closely predict the behavior of a wide range of materials, such as mice skin, polypropylene suture, and human tissues (tracheal, vaginal and brain), by calibration of a set of parameters. This property of the ESED model could allow the simulation core to represent different soft tissue behaviors using a data base of parameters experimentally found.

This lead to two main objectives for improvement of the simulation core in this work: 1) the internal structure meshing method, by developing a new method for concave geometries and 2) the mechanical properties of soft tissue, by implementing the ESED model on the simulation core.

Materials and methods

In order to achieve the objectives previously exposed, there was applied software like InVesalius, Python, VTK, MeshLab, and other open-source software. The internal structure meshing method of the simulation core was improved by developing a new method based on an exoskeleton structure (ES). Also, the simulation of mechanical properties of soft tissue was improved by implementing the ESED model, which was not applied for real-time simulation before.

Exoskeleton structure (ES) – One problem with the ISS method is that the process to create the internal mesh of control points is not easily applicable to concave geometries of specific organs, like the uterus, intestine, kidney and other anatomical structure. Also, there are problems with geometries based on curved tubes or small spheres as part of a bigger volume.

For those cases, a method based on an external mesh of control points is proposed as an *Exoskeleton Structure* (ES). The main function of the ES is to calculate the response of the simulated organ, just like the ISS, but can be applied to a wide range of geometries. The ES proposal is based on the creation of an external mesh of control points based on the original geometry, and then an assembly process to create the volumetric structure is applied.

To create an external mesh of control points, a Uniform Mesh Resampling (UMR) algorithm was applied to the original mesh with an offset parameter, and then a Quadric Edge Collapse Decimation (QECD) for simplification. Based on this new method, a representation mesh of the uterus geometry (Figure 2a) was processed and the external mesh of control points was created (Figure 2b) with a 70% offset.

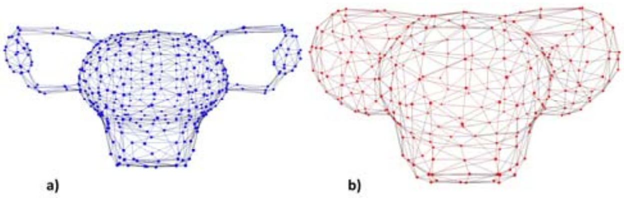

Figure 2: Uterus geometry a) processed mesh, b) external mesh of control points.

Then, an assembly algorithm for the ES was developed on the simulation core. In this assembly process, a volumetric mesh based on the ES was composed by creating an element between each vertex of the original mesh with the three closer external control points. After this process, the simulation mesh with ES was achieved, as shown on Figure 3.

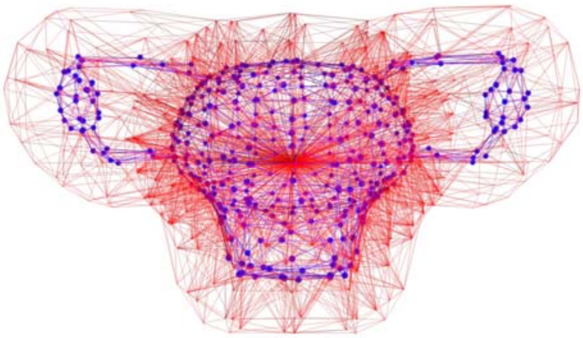

Figure 3: Simulation mesh with exoskeleton structure, created with the uterus geometry and the external control points.

Mechanical properties of soft tissue – To improve the simulation core, the ESED model was implemented in order to include mechanical properties of soft tissue. For this stage, the ESED model was applied on a one-dimensional element for a basic uniaxial test.

In this work, an algorithm based on the ESED model was developed, implemented on the simulation core and applied to a one-dimensional element on uniaxial test. Then, the parameters of the ESED model were calculated to represent the behavior of human tracheal tissue from axial adventitial and submucosa membranes (AAM, ASM), in order to reproduce experimental results found in the literature.

The predictions results (solid lines) were compared with the literature data (spots) obtained from [10,11], and they represent soft tissue behavior as shown on Figure 4. These results are considered a validation of the implementation for the ESED model on this application.

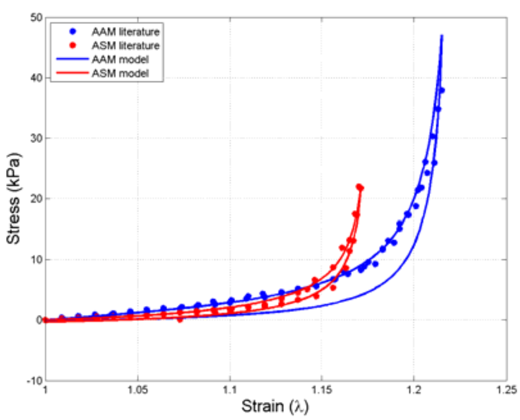

Figure 4: Strain-stress curve from the ESED model implemented in the Python simulation core to reproduce literature data of human tracheal tissue (AAM, ASM).

Results

The ES method developed on this work was applied to the uterus geometry on the simulation core with SMM model. Results were satisfactory for the application compared with the ISS, as shown on Figure 5. On this virtual environment, the simulation mesh with ES was deformed by gravity and instruments interaction, having a good graphical response.

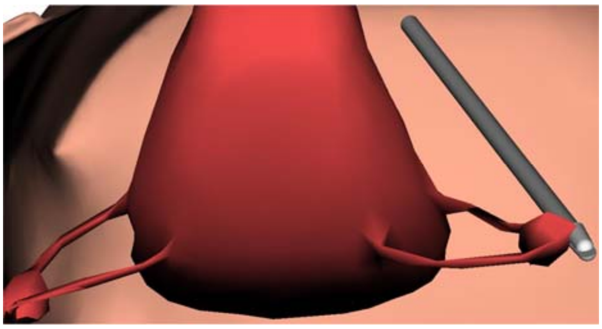

Figure 5: Simulation mesh with exoskeleton structure, deformed with a grasper on virtual environment.

The ISS method improvement was achieved by applying the ES on the simulation core for specific geometries, and results shown that ES was able to solve the initial problem with concave geometries.

Although the ESED model was still not implemented for a complete 3D mesh and therefore was not applied to both ISS and ES methods, the calculation results from the simulation core of the uniaxial test are promising and predict the real behavior of the tissue. In future works it will be applied to a complete 3D simulation mesh and results will be published.

With these results, the improvements on the simulation core's capacity to represent the mechanical properties of soft tissue were achieved.

Discussion

Even when ESED model was implemented on Python simulation core, the current stage was only possible to run with one-dimensional elements with uniaxial tests. For future works, ESED model should be implemented for a complete 3D simulation mesh and then run virtual testing to analyze the behavior and validate the results with other methods (like commercial FEM software). Also, mechanical tests with animal tissue samples should be performed in order to get a database of the ESED model parameters that represent the behavior of different tissues.

Moreover, when the exoskeleton structure was applied to the uterus mesh, it was detected that the simulation core's performance was slightly affected. It is possible that this issue was caused by an increment on the amount of vertex and elements created on the assembly process to generate the simulation mesh. The optimization of the assembly process and computational method is required.

Conclusion

ESED model demonstrated potential impact on the development and improvement of the simulation core, allowing the prediction of mechanical behavior of soft tissues. The implementation for a complete simulation mesh will be presented on future publications.

Even when ES method was a solution for the current issue with specific geometries, other kinds of methods are being studied to improve the simulation core in a future, like Meshfree and pre-computed Finite Element Methods, taking care of the computational performance.

In conclusion, in this paper the improvements objectives for both proposed areas were achieved on a parallel scheme. Through this work, the steps for development of tools for real-time simulations of soft tissue on InVesalius are defined.

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References

[1] Seymour, N.E. VR to OR: A Review of the Evidence that Virtual Reality Simulation Improves Operating Room Performance. World Journal of Surgery 2008, v.32, p. 182-188.

[2] Amorim, P. H. J. ; Moraes, T. F. ; Azevedo, F. S. ; Silva, J. V. L . InVesalius: Software Livre de Imagens Médicas. In: XXXI Congresso da Sociedade Brasileira de Computação, XI WIM Workshop de Informática Médica, 2011, Natal - RN. CSBC 2011. p. 1735-1740.

[3] Camilo, A. A. ; Amorim, P. H. J. ; T. F. Moraes ; Azevedo, F. S. ; Silva, J. V. L . InVesalius: Medical image edition. In: 1st International Conference on Design and Processes for Medical Devices, 2012, Brescia - Italy. PROMED, 2012. v. 1. p. 279-282.

[4] Moraes, T. F. ; Rospendowski, T. A. M. ; Amorim, P. H. J. . Medições em Imagens Médicas Tridimensionais utilizando VTK. In: X Worshop sobre Software Livre - FISL 10, 2009, Porto Alegre - RS.

[5] Moraes, T. F. ; Amorim, P. H. J. ; Silva, J. V. L ; Pedrini, H. . Visualização Interativa em Tempo Real de Dados Médicos na Web. In: Workshop de Realidade Virtual e Aumentada, 2012, Paranavaí-PR. v. 1. p. 1-6.

[6] Moreno, M. R. ; Marban, A. ; Rojas, J. ; Bosque, G. ; Escamilla, D. ; Silva, J. V. L. ; Diaz, J. . Simulator for laparoscopic surgery with open source approach. In: Proceedings of the 1st International Conference on Design and Processes for Medical Devices, 2012, Brescia. PROMED, 2012. v. 1. p. 207-210.

[7] Moreno, M. R. ; Moraes, T. F. ; Amorim, P. H. J. ; Silva, J. V. L ; Rodriguez, C. A. . Virtual open source environment for training and simulation of Laparoscopic Surgery. In: XII Workshop de Informática Médica (WIM'2012) - XXXII Congresso da Sociedade Brasileira de Computação, 2012, Curitiba-PR.v.1. p.1-4.

[8] Amorim, P. H. J. ; Moraes, T. F. ; Azevedo, F. S. ; Silva, J. V. L ; Pedrini, H. . Reconstrução Panorâmica Automática de Imagens Odontológicas de Tomografia Computadorizada. In: XII Workshop de Informática Médica (WIM'2012) - XXXII Congresso da Sociedade Brasileira de Computação, 2012, Curitiba-PR.v.1. p.1-8.

[9] Holzapfel, G.A. Biomecanics of Soft Tissue, Handbook of Material Behavior: Nonlinear Models and Properties, 2001, v.3, ch.10, p. 1057-1071.

[10] Elías-Zúñiga, A.; Baylón, K.; Ferrer, I.; Serenó, L.; Garcia-Romeu, M.L.; Bagudanch, I.; Grabalosa, J.; Pérez-Recio, T.; Martínez-Romero, O.; Ortega-Lara, W.; Elizalde, L.E. On the Rule of Mixtures for Predicting Stress-Softening and Residual Strain Effects in Biological Tissues and Biocompatible Materials. J. Materials 2014, v.7, p. 441-456.

[11] Teng, Z.; Trabelsi, O.; Ochoa, I.; He, J.; Gillard, J.H.; Doblaré, M. Anisotropic material behaviors of soft tissues in human trachea: An experimental study. J. Biomec. 2012, v.45, p. 1717–1723.