Proceedings of the 2021 Design of Medical Devices Conference
DMD2021
April 12-15, 2021, Minneapolis, MN, USA

DMD2021-1026

ENHANCING MIMETIC THREE-DIMENSIONAL MODELING AND PRINTING FOR PRESURGICAL PLANNING APPLICATIONS: IMPROVED SOFT TISSUE ASSESMENTS, ANALYSES AND CONSOLIDATION STRATEGIES

Jorge A. Vergen[1], Tinen L. Iles, Paul A. Iaizzo
Department of Surgery, University of Minnesota
Minneapolis, MN, USA

ABSTRACT

Mimetic three-dimensional (3D) printing has been shown to enhance presurgical planning and improve patient outcomes. However, data inconsistencies and non-optimized soft tissue data management strategies have impaired efforts to characterize soft tissues and translate biophysical values to 3D printing media durometers and shore values. As a result, finished models are inconsistent and exhibit reduced mimetic qualities. Improving biophysical characterizations of soft tissues, analysis strategies, and consolidation infrastructures are important factors that will improve 3D modeling in a presurgical planning setting. In our ongoing associated studies, both physiologically viable and formalin fixed large mammalian tissues (including human) were assessed using uniaxial and biaxial testing strategies. Biophysical datasets were analyzed using a gated analysis strategy, tailored to data acquisition methods developed within the University of Minnesota Visible Heart® Labs (VHL). A SQL database was then constructed to consolidate analyzed data for future retrieval. This strong preliminary data is a foundation for further development and refinement of future studies. It is our long-term goal that these strategies be improved and adopted to enhance the mimetic qualities of 3D presurgical planning models.

1. INTRODUCTION

3D printed models improve patient outcomes by increasing the planning capabilities of medical care providers. As previous studies have shown, 3D printing has directly benefitted patients by increasing the use of presurgical planning guides, reducing a patient's operating room time, and reducing procedure related risks[1,2,3,4]. An important factor for 3D presurgical modeling is the mimetic quality of finished models. The more visually and mechanically realistic a model is, the better it can be used to inform medical decision making. However, despite these contributions, a classic "big data" problem exists. Large volumes of biophysical tissue data, and inconsistencies between datasets, have made tissues difficult to characterize and translate into 3D printing media durometers and shore values. The end result is reduced mimetic quality of 3D printed models.

Fused filament fabrication (FDM) and PolyJet printing (PJP) are two prominent 3D fabrication techniques that are currently employed to build presurgical planning models. While FDM and PJP can achieve resolutions of 24μm and 14μm respectively, finished models are often a compromise between visual and mechanical realism. Typically, FDM products are brittle and PJP models are costly, delicate, and exhibit haptic properties similar to rubber. Acknowledging the commercial landscape of 3D printing and soft tissue characterization technologies, we hypothesize that improving data management strategies, to include soft tissue biophysical assessments, data analyses, and data consolidations, will improve mimetic 3D printing.

Assessing the biophysical properties of soft tissues is a critical first step towards establishing acceptable baseline tissue values that can be translated to 3D printing media. Uniaxial and biaxial tissue testing are accepted contact manipulation strategies that use external push and pull forces to measure unique stress-strain profiles, force-displacement relationships, deformation, and tissue recovery following periodic loading[5,6,7].

[1] Contact author: verge020@umn.edu

Uniaxial testing exerts a unidirectional force along a single loading vector while biaxial testing can exert up to four independent push-pull forces along two principle loading vectors[8,9]. Therefore, uniaxial testing is best suited for tissues with a single native loading vector while biaxial testing is preferred when testing tissues with native anisotropy. Despite these inherent differences, uniaxial and biaxial testing are equally capable of assessing the same soft tissue values regardless of tissue type.

In a presurgical modeling setting it is crucial that data be uniform to expedite tissue characterizations and subsequent model fabrication. Uniform data analyses and consolidation practices will improve the ease of data retrieval and model characterization. Recognizing these lapses in data management, this study was approached with the following three aims. First, to create an improved approach for acquiring soft tissue biophysical data using uniaxial and biaxial systems available within the University of Minnesota's VHL. The second aim was to develop standardized analysis protocols using gated data analysis strategies with clearly defined decision points based on unique data characteristics. The third was to create an initial framework for a consolidated soft tissue biomechanics database with built-in query and view functionalities.

2. MATERIALS AND METHODS

The following tissue preparation and testing protocols have been successfully conducted using fresh and formalin fixed esophagus, pericardium, and aorta from porcine, sheep, and fresh human samples.

2.1 Large mammalian tissue collection and preparation

Fresh human cadaveric tissues were collected according to approved University of Minnesota Anatomy Bequest Program, and Life Source research protocols. All animal tissues were collected on protocols that were approved by the University of Minnesota's Institutional Animal Care and Use Committee. Tissues were initially dissected and transferred to a carbogen (95% O_2, 5% CO_2) perfused Krebs-Ringer solution to maintain physiologic viabilities. Samples were obtained and prepared approximately 5-10 minutes post-mortem for animal tissues and three to five hours post-flush with preservation solutions for human tissues. Connective tissues and mucosal layers, if present, were removed. Tissues with a single loading vector were cut into strips measuring approximately 2 cm in width by 3-4 cm in length using an Epilog Helix Laser Cutting System (Epilog USA). Tissues allocated for biaxial testing were sectioned into squares measuring approximately 3 cm long by 3 cm wide. Following initial and secondary preparations tissues were mounted to the ElectroForce Planar Biaxial Testbench using Wintest7 software (TA Instruments/Bose USA) using clamps coupled to 225 N load cells.

2.2 Uniaxial and biaxial tissue assessments

Tissues were mounted to the ElectroForce system and mechanically stretched to zero passive tension (Fig. 1). Uniaxial studies were conducted using two independent axial Bmotors while biaxial testing was conducted using four independent motors. For the latter, force-controlled testing protocols using a sinusoidal wave were programmed for each axial motor. Prior to starting an experiment and when changing tissue types, each motor was calibrated for a specific tissue sample using the TuneIQ function built into the ElectroForce system. Following successful motor calibration, five regions of interest (ROIs) for the digital video extensometer system (DVE) were painted to the superior surface of the given tissue and marked in Wintest7. Pull related forces, displacements, and deformation measurements were collected in ten second scan intervals. Tissues were assessed between 15- 90 minutes.

2.3 Gated data analytic strategy development

Recognizing the value of previously collected data, a gated analytic strategy was developed that could rapidly analyze soft tissue datasets while incorporating clear decision points and pathways based on the acquisition methods employed. Gated data analysis strategies for uniaxial and biaxial protocols were developed such that the majority of the downstream analyses were performed using looped R based scripts. At the present time our analysis strategy is organized into two branches based on the number of files generated by the system used to assess soft tissues. Data generated using the ElectroForce system are consolidated within a single file and were organized into a common pathway. The VHL tissue bath system, that operates using LabView, generates up to 16 tissue contractility output files that require distinct user inputs. As a result, contractility datasets are analyzed using the second pathway.

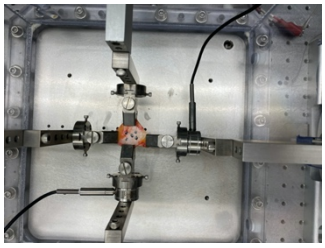

Figure 1: HUMAN PEROCARDIUM WITH DVE ROIS MOUNTED TO THE ELECTROFORCE PLANAR BIAXIAL TESTBENCH (TA INSTRUMENTS/BOSE USA) IN A FOUR MOTOR BIAXIAL CONFIGURATION.

2.4 R based analytic scripts

Since R was developed for statistical data analyses and has multiple graphing libraries that can be added it was selected as the base language for ElectroForce and tissue bath analyses scripts. Each script was task

organized into three sections: package loading, data importing, and output generation.

2.5 Consolidation of soft tissue biomechanical and biophysical data using a SQL database management system

Developing an Entity Relationship (ER) Diagram was an important first step to establishing a usable and efficient database schema, since this process will serve as an early error detection and reduction mechanism. The current ER Diagram uses a B+ tree index structure and consists of four entities (Fig. 2). The "Treatment" entity consists of an identifier for the specific tissue type (tisid) and experimental treatment (tid) that is stored in the "Tissue" table as a foreign key. The tissue source entity (Tissue_source), along with the "group_id" entity denote the tissue host and anatomic location. The type of tissue (Tissue_type) is an attribute, also stored as a foreign key in the tissue table, that identifies the unique tid and tissue type. Initial query and view functionality were tested by classifying available measurements and transferring table to a single entity using a SQL multi-inner join operation across the four primary tables. Small scale data migration and DBMS functionality was tested using MySQL workbench. Initial queries and views proved successful. However, as will be discussed in the following section a B+ tree index was determined to be a poor choice for this application.

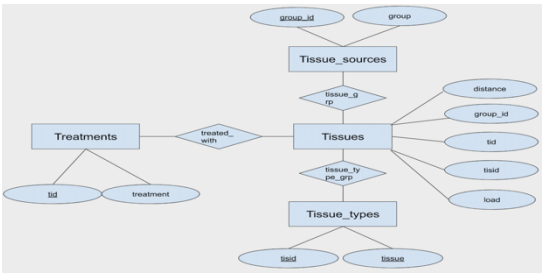

Figure 2: CURRENT ER DIAGRAM OF THE SOFT TISSUE BIOMECHANICS DATABASE.

3. Fresh and Formalin Fixed Human Esophagus Comparative Studies

Our preliminary comparative studies on fresh and formalin fixed human esophageal tissues show measurable changes in load (N) versus displacement (mm) (Fig. 2), strain along the horizontal axis of the tissue (%E11) (Fig. 3), and strain along the vertical axis of the tissue (%E22) (Fig. 4). At the present time this data is considered qualitative and requires further development. However, these preliminary studies validate our tissue assessment protocol. It is our goal that, with further development, these data can be translated to print media shore values and a fresh to formalin fixed transfer function can be developed.

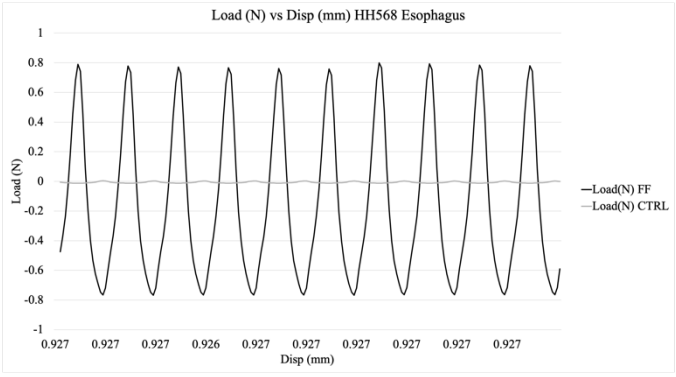

Figure 3: LOAD (N) VERSUS DISPLACEMENT (MM) OF FRESH AND FORMALIN FIXED HUMAN ESOPHAGEAL TISSUE USING A FORCE CONTROLLED BIAXIAL TESTING PROTOCOL.

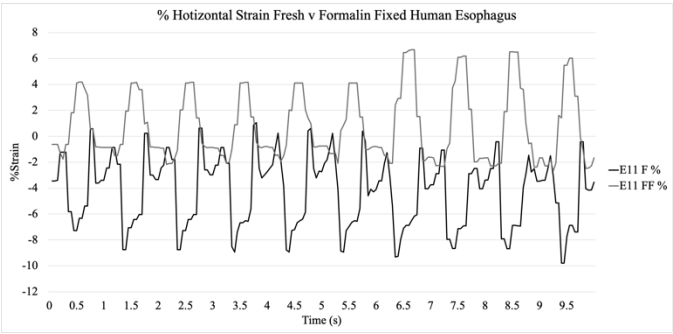

Figure 4: COMPARATIVE % HORIZONTAL STRAIN OF FRESH AND FORMALIN FIXED HUMAN ESOPHAGEAL TISSUE USING A FORCE CONTROLLED BIAXIAL TESTING PROTOCOL.

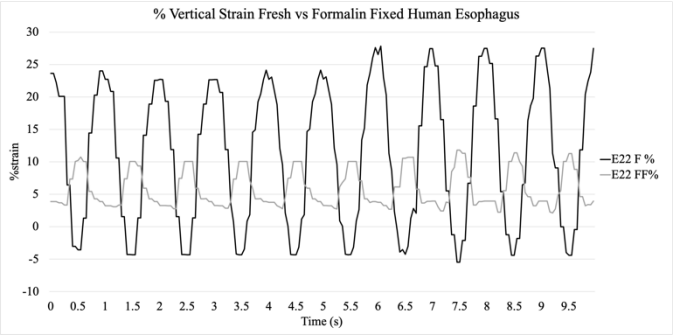

Figure 5: COMPARATIVE % VERTICAL STRAIN OF FRESH AND FORMALIN FIXED HUMAN ESOPHAGEAL TISSUE USING A FORCE CONTROLLED BIAXIAL TESTING PROTOCOL.

4. CONCLUSIONS AND FUTURE RECOMMENDATIONS

To date uniaxial and biaxial studies have been successfully conducted on porcine, human, and sheep tissues in fresh and formalin fixed states. While we

recognize the need for further procedural refinements, we do think this study presents a strong foundation to develop improved strategies for soft tissue assessments, data analyses, and data consolidation. It is our plan to further develop uniaxial and biaxial testing protocols to include strain-rate, creep, and stress-relaxation testing in addition to refined analysis procedures. Tissues studied will be in relaxed, pharmacologically modified (further relaxed or contracting), electrically stimulated or formalin fixed states. Since the long-term goal of this project is to continue populating our database with a large variety of soft tissue metrics a B+ tree index schema is not suitable due to inherent limitations. Once larger datasets become available and the priority shifts to data migration, it would be preferred to adopt a hash index schema with built in triggers to better facilitate views and large-scale updates.

ACKNOWLEDGEMENTS

We would like to acknowledge the support of the University of Minnesota VHL, University of Minnesota Department of Surgery, the Institute for Engineering in Medicine and the University of Central Florida Prototype Development and 3D Print Lab.

REFERENCES

[1] Tack, Philip, et al. “3D-Printing Techniques in a Medical Setting: a Systematic Literature Review.” BioMedical Engineering OnLine, vol. 15, no. 1, 2016, doi:10.1186/s12938-016-0236-4.

[2] Giannopoulos, A. A., Mitsouras, D., Yoo, S. J., Liu, P. P., Chatzizisis, Y. S., & Rybicki, F. J. (2016). Applications of 3D printing in cardiovascular diseases. Nature Reviews Cardiology, 13(12), 701.

[3] Tack, Philip, et al. “3D-Printing Techniques in a Medical Setting: a Systematic Literature Review.” BioMedical Engineering OnLine, vol. 15, no. 1, 2016, doi:10.1186/s12938-016-0236-4.

[4] Gil, R. Sieira, et al. “Surgical Planning and Microvascular Reconstruction of the Mandible with a Fibular Flap Using Computer-Aided Design, Rapid Prototype Modelling, and Precontoured Titanium Reconstruction Plates: a Prospective Study.” British Journal of Oral and Maxillofacial Surgery, vol. 53, no. 1, 2015, pp. 49–53., doi:10.1016/j.bjoms.2014.09.015

[5] Jiang, Mingliang, et al. "Clamping soft biologic tissues for uniaxial tensile testing: A brief survey of current methods and development of a novel clamping mechanism." Journal of the Mechanical Behavior of Biomedical Materials 103 (2020): 103503.

[6] Walsh, M.t., et al. “Uniaxial Tensile Testing Approaches for Characterisation of Atherosclerotic Plaques.” Journal of Biomechanics, vol. 47, no. 4, 2014, pp. 793–804., doi:10.1016/j.jbiomech.2014.01.017

[7] Fung, Y. C., and Richard Skalak. “Biomechanics. Mechanical Properties of Living Tissues.” Journal of Applied Mechanics, vol. 49, no. 2, 1982, pp. 464–465., doi:10.1115/1.3162171.

[8] Jett, S., Laurence, D., Kunkel, R., Babu, A. R., Kramer, K., Baumwart, R., ... & Lee, C. H. (2018). Biaxial mechanical data of porcine atrioventricular valve leaflets. Data in brief, 21, 358-363.

[9] Chanda, Arnab, and Christian Callaway. “Tissue Anisotropy Modeling Using Soft Composite Materials.” Applied Bionics and Biomechanics, vol. 2018, May 2018, pp. 1–9., doi:10.1155/2018/4838157.