Designing a Brain Phantom Model and Surgical Simulation System for Testing Surgical Robots

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Background

Testing and evaluating surgical robots in a realistic operative scenario is an important process in surgical device development. It provides insight on functional improvements and user feedback from trained surgeons in a simulated surgical test. It is common to use silicone or hydrogel phantom models as surrogates for both animal and cadaver testing, allowing faster and more efficient data collection for medical and surgical devices [1].

Hydrogels are polymer gels synthesized from hydrophilic monomers with a catalyst that promotes cross linking polymer chains [2]. Controlling the formation of these cross-linked networks can alter the physical properties of the hydrogel. As it is formed by hydrophilic monomers, the hydrogels will shrink and dry if not kept in water. Hydrogel phantom models can be used as substitutes for both animal and cadaver testing, allowing faster and more efficient data collection for medical and surgical devices. The pediatric skull and brain phantom was used for testing a neurosurgical device for pediatric hydrocephalus, thus simulating an endoscopic third ventriculostomy (ETV) procedure.

CT Scans to Hydrogel Phantom Model

1.

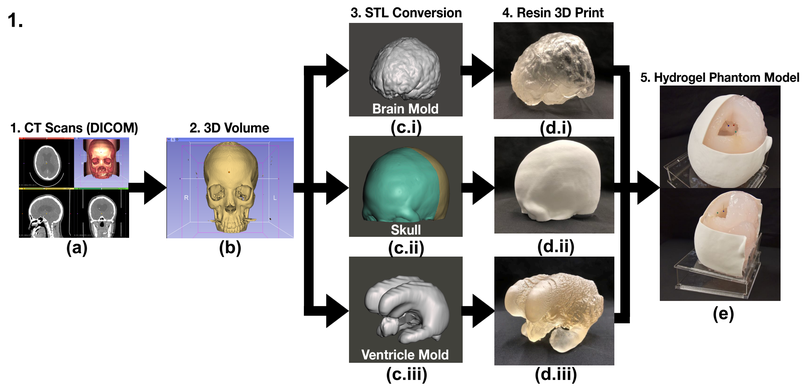

Fig.1: Hydrogel phantom model production flowchart: (a) CT scans of patient with hydrocephalus in 3DSlicer. (b) Rendered 3D volume processed from 2D images. (c) Segmented brain (c.i), skull (c.ii), and hydrocephalic ventricular mold (c.iii) imported into Meshmixer. (d) Resin 3D printed brain mold (d.i) and hydrocephalic ventricular mold (d.iii), as well as SLS-printed skull (d.ii). (e) Complete phantom model with ventricular cavity positioned at similar angle to that of instance of neurosurgical procedure.

The overall process in producing hydrogel phantom models is represented as a flowchart in Figure 1. The first step is to produce reusable molds of the anatomical structure through 3D printing capabilities. Image processing software (3D Slicer [3], http://www.slicer.org) will take in the CT and MRI images and overlay them to create a 3D volume. The main components of the anatomical structure are then segmented individually from the overall 3D volume as separate entities, which could then be exported as stereolithography files (.stl). 3D modeling software such as Meshmixer (Autodesk Inc., CA, United States) can then be used to post-process, modify, and finalize the model in preparation for printing. Fig.1, (d.i) and (d.iii) are two molds that were printed using the Form2 resin 3D printer (FormLabs, MA, United States), using the ”Tough” resin. The skull in Fig.1, (d.ii) was printed using the Formiga P110 SLS printer (EOS GmbH Electro Optical Systems, Munich, Germany). The brain and hydrogel molds were then aligned while hydrogel solution was created and poured into the molds. After hydrogel curing, the ventricular mold was removed to create a true ventricular cavity in the brain.

Hydrogel Casting

Synthesis of hydrogel is done once the molds are ready for use. 6% Polyvinyl alcohol (PVA), the hydrophilic monomer, and 0.85% Phytagel (PHY), the gelling agent catalyst, (Sigma-Aldrich, MO, United States) are prepared [4]. Both solvents must be rigorously stirred and heated in deionized water for 1-2 hours at 90ºC. Once fully dissolved, the two solutions are mixed together with a 1:1 weight ratio, heated at 70ºC and stirred for for 30 minutes [3]. 1 drop of red, water-soluble food coloring was diluted in 100 mL of deionized water, then 5 mL of the diluted colored water was added to the PVA and PHY solution while mixing.

The mixed solution is cooled at room temperature for 30 minutes, then poured into the brain mold. The hydrocephalic ventricle mold was then fixed at the center of the brain mold to create a negative space in the hydrogel phantom. The mold was then kept in a freezer at -10ºC overnight, then thawed out.

2.

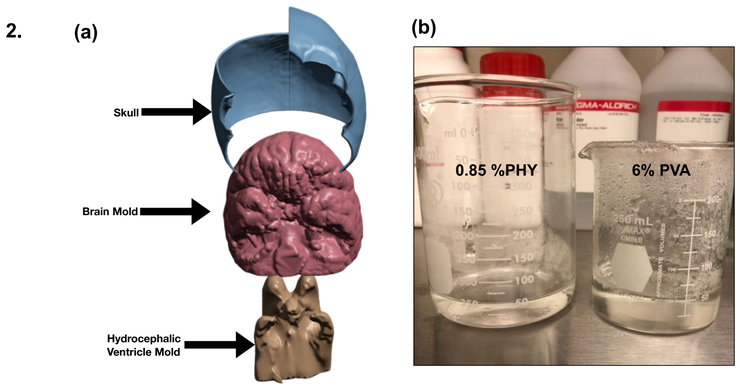

Fig. 2: (a) Exploded view of 3D-printed mold configuration prior to casting hydrogel solution. (b) Two solutions, 0.85% PHY and 6% PVA, prepared to create hydrogel solution.

Hydrogel Hardness Analysis

After discussing with a neurosurgeon collaborator, it was concluded that the 6% PVA / 0.85% PHY composition did not have realistic physical properties to that of a real brain. To observe how the concentration of gelling agent alters the viscosity and hardness of the hydrogel, seven different concentrations of PHY solutions were tested with a 6% PVA solution. The results show that increasing PHY concentration will increase hardness of the hydrogel. The model below can be used to estimate PHY required for a hydrogel of desired hardness.

3.

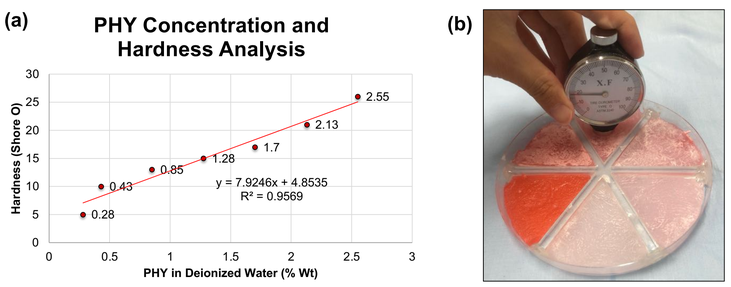

Fig. 3: (a) Graph with linear regression of PHY concentration and hardness data. (b) Testing apparatus for six different hydrogels (excludes 0.85% PHY sample).

Surgical Simulation System

The surgical testing simulation will consist of utilizing the endoscopic tool on the hydrogel phantom model and making contact with three physical targets that are visible through the burr hole that the surgeon creates to insert the robotic tool. Additionally, a fourth target that is not in the endoscope field of vision will be present for the surgeon to attempt to reach. The visualization can be done through a computer model of the hydrogel phantom, in which the robotic tool and target points are mapped onto the 3D computer model in real-time. MATLAB (Mathworks, MA, United States) was incorporated to reproduce a computer visualization of the phantom model, and the kinematic model of a known robotic tool was integrated in the computer model. Three 6-DoF Electromagnetic (EM) trackers and the Aurora Tracking System (Northern Digital Inc., Waterloo, Canada), were used to allow for real-time visualization: two to align the coordinate system of the computer model with that of the physical hydrogel model, and one on the base of the physical robotic tool to track the orientation and position of the robot.

4.

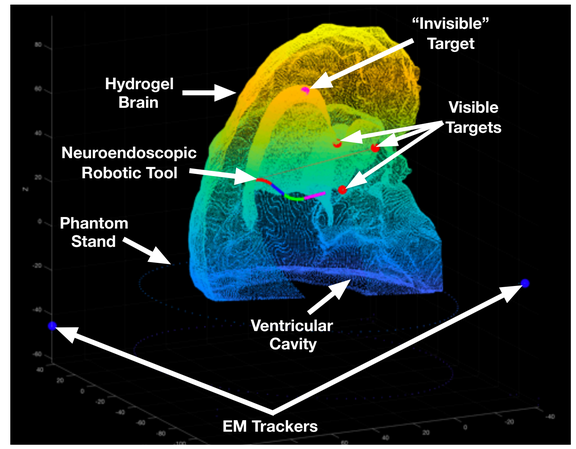

Fig. 4: 3D model and visualization of the physical phantom brain and robotic tool in MATLAB.

Conclusion and Future Work

A pediatric phantom model of the brain and skull was created using medical image-processing techniques and hydrogel. A computer model of the phantom was created for real-time visualization of the phantom for the surgical simulation. Future work includes improving on the physical properties of the hydrogel phantom to mimic that of a real brain, obtaining simulation trial data from neurosurgeons, and developing a augmented-reality (AR) headset that can project the computer model on the headset.

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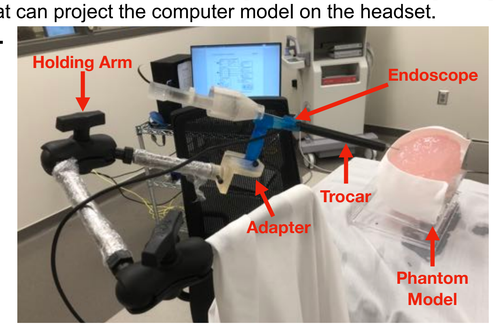

Fig. 5: Surgical testing system with devices and pediatric phantom model.

References

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