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Application of 3D Printing Support Material for Neurosurgical Simulation

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Abstract— **Brain dissection, an intricate neurosurgical skill, is central to life-saving procedures such as intrinsic brain tumor excision and resective epilepsy surgery. The aims of this manuscript are to outline the selection process of a suitable material for the development of a dissectible brain simulator and to present the use of support material, SUP 706, manufactured by Stratasys Ltd. as a non-waste alternative for sustainably engineering solutions for surgical education. A feasibility study was conducted through qualitative function deployment (QFD) followed by a material selection process. End-user requirements and manufacturing product characteristics were incorporated into the workflow. Three materials, silicone, TissueMatrix™ and support material each formed the primary component of the first two prototypes. Expert feedback, manufacturing cost, safety profiling, functional fidelity and post-processing time data were collected and analyzed. The unique break-away feature of moist support material was found to be more suitable than using silicone or TissueMatrix™ for demonstrating brain dissection techniques. In addition, support material displayed higher functional fidelity by mimicking surgical tissues such as pia mater, gray and white matter, and blood vessels. The cost of the support material prototype was 39% less that of TissueMatrix™ and roughly the same as the silicone model. It took twice as long to post-process the support material prototype than it did the TissueMatrix™ design. Support material lost its ideal dissection properties and began to disintegrate after 30 – 45 minutes. In conclusion 3D printer support material is a low-cost material for a dissectible brain simulator.**

Clinical Relevance— **The use of support material as the primary material in developing a dissectible brain simulator is a promising way of advancing neurosurgical education.**

I. Introduction

Neurosurgical simulation for competence-based surgical education utilizes technologies such as virtual reality (VR), robotics or three-dimensional (3D) printing. Surgeon trainees have preference for the hands-on training opportunities that 3D printed simulators present [1]. Dissection of brain lesions is an intricate skill: one that takes years of practice to learn. Yet it must be mastered because there is little to no room for human error in the operating room [2]. Surgical simulation has been demonstrated as a method of shortening the technical skill learning curve [3]. Developing a brain dissection simulator would be an important contribution to neurosurgical education.

Material options have proliferated in the years since a patent for the first 3D printer was filed in 1984 [4], [5]. This variety of printing materials has been used in surgical simulators for surgical training workshops [6], [7], [8]. Although the field of neurosurgery has developed simulators for neuroendoscopy, skull base, vascular and craniosynostosis surgeries, brain dissection simulators have not been developed to the same degree [6], [7], [8], [9], [10]. Simulating brain dissection would require that simulators possess a complement of detailed anatomical accuracy (high physical fidelity) as well as a soft texture mimicking brain tactility (functional fidelity) [11], [12], [13]. Often, the cost of materials, manufacturing and labor is in direct proportion to a simulators level of anatomic complexity [14], [15]. In addition, the cost is further increased as many simulators can only be used once before they are discarded. Current simulators lack the desirable compressibility to demonstrate brain dissection techniques [16]. Methods of measuring the desirable level of material softness include force measurements during deformation and expert surgeon feedback [16], [17], [18]. It is reasonable to utilize palpatory feedback from expert neurosurgeons to select satisfactory materials for brain dissection simulator design because a positive correlation exists between the measured physical properties and the sensory perception of materials [19]. Typically, for 3D printed parts both a desired material and scaffolding support material around the part are manufactured. This paper aims to discuss the use of dissolvable support material as a lower cost alternative material for neurosurgical phantoms.

II. Methods

A. Material Requirements Definition

The study was approved by a University of Toronto committee overseeing the project. To determine a set of material requirements, qualitative data were gathered from a practicing neurosurgeon and senior author. In this feasibility study he represented the end-user's interest and the most important qualities. These requirements form a Quality Function Deployment tool (QFD) which is an approach that

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translates an end-user's needs into technical requirements. The material properties of a previously reported endoscopic third ventriculostomy (ETV) brain model were compared against those of the desired brain dissection simulator [6]. The ETV brain model was developed using Dragon Skin and slacker in a 2:1 mix ratio [6]. In the absence of a feasible resective epilepsy and intrinsic brain tumor resection simulator in literature, the CIGITI ETV model, a validated tool for demonstrating neuroendoscopy was deemed as a reasonable "competiter". Based on the weighted end-user's needs, the manufacturing design requirements and the competitor comparison data were documented in a QFD diagram (Fig. 1) [20].

B. *Material Selection Criteria*

Based on the QFD diagram, the materials needed to be dissectible, skin safe, require short post-processing times and have a relatively low cost of manufacturing. Material safety data sheets were also obtained despite the fact that surgeons would ordinarily don gloves during simulation workshops as during live surgery. Adaptability (ability to be customized for anatomic landmarks such as a gray-white matter interface and pathology-specific neurovasculature) for high functional fidelity was the final design requirement criteria.

C. *Material Options*

Silicone (Dragon Skin™) and TissueMatrix™ were the materials initially selected. Open source (Digital Imaging and Communications in Medicine) DICOM brain magnetic resonance imaging (MRI) sequences were obtained from 3D slicer [21]. Software segmentation of brain MRI data were performed and Standard Tessellation Language (STL) files rendered (Fig. 2). A negative mold was manufactured using a Stratasys J750 Digital Anatomy Printer and a layered silicone technique used to cast the first prototype, a left hemisphere of the brain, illustrated in Fig. 3. The silicone mixture comprised of Dragon Skin™ part A, part B and Slacker™ in the ratios 1:1:3. A second prototype, the left temporal lobe of the brain, was directly 3D printed using TissueMatrix™. Printer settings allowed for the accurate anatomic representation of the brain's gray-white matter junction, Fig. 4. Further investigation showed that support material, SUP706, was identified as a potentially suitable material owing to its' mechanical characteristics. Ordinarily, SUP706 acts as a temporary scaffold for overhangs of lattice structures printed using polyjet technology. SUP706 would undergo photopolymerization once extruded and would then be removed in a post-processing step either under a water jet or in a sodium hypochlorite bath [22], [23]. A third prototype, the left cerebral hemisphere, was manufactured using support material as the primary component (Fig. 5). To differentiate the support needed for the material selection process from the traditional uses of SUP706 the terms 'necessary support' and 'scaffolding support' are used in this manuscript. A thin layer of TissueMatrix™ (0.3mm) was used to mimic pia mater, an intimate layer of the meninges that covers the human brain. A separate layer of TissueMatrix™ (0.15mm) wrapped the segmented white matter creating a gray-white matter interface in the final prototype (Fig. 5).

Figure 1. A Quality Function Deployment Diagram Illustrating the Voice of the Customer against the Engineering Characteristics of a Brain Dissection Simulator.

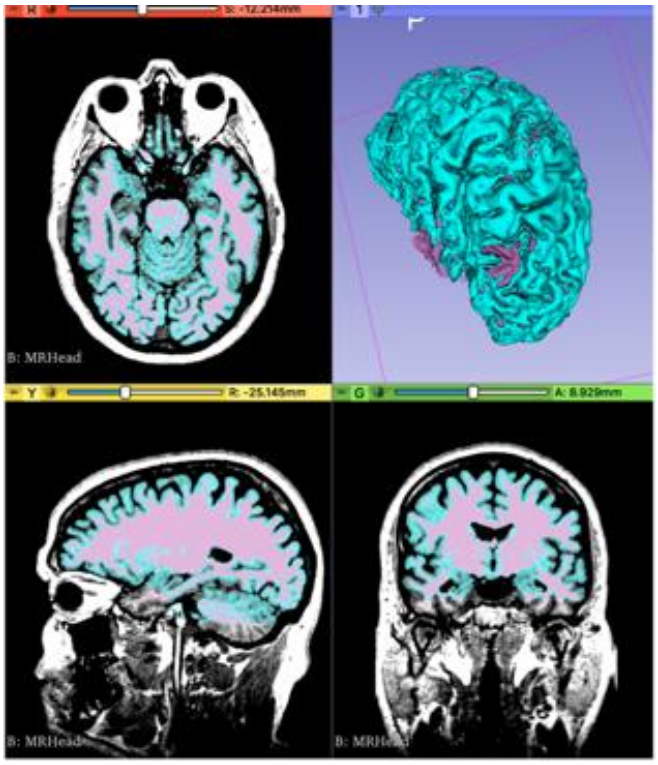

Figure 2. Illustration of the Brain MRI software segmentation process using 3D Slicer as an Assembly of both Gray and White Matter Masks.

D. *Evaluation of Materials*

Expert feedback on material compressibility was documented using verbal feedback. The end-user determined the neurosurgical dissectibility potential of each of the three designs. Safety data sheets of the materials were reviewed and the cost of production recorded (Table 1). Finally, a material selection flow chart was created to summarize the material selection process (Fig. 6).

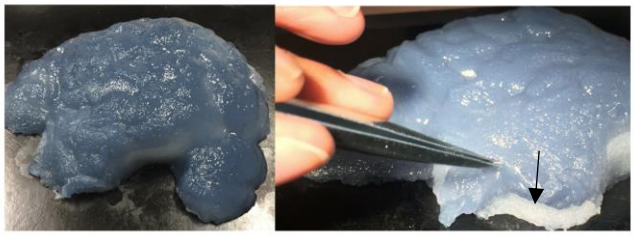

Figure 3. Photographs of the Silicone Phantom Prototype. The two layers representing the brain's gray and white matter are illustrated (arrow).

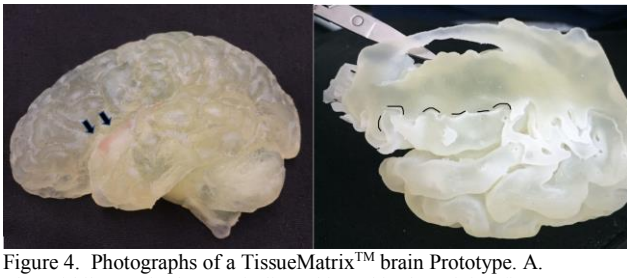

Figure 4. Photographs of a TissueMatrix™ brain Prototype. A. The Middle Cerebral artery indicated in red in the sylvian fissure (arrows). B. Gray-white differentiation (dashed line) in a cross-section of a TissueMatrix™ model.

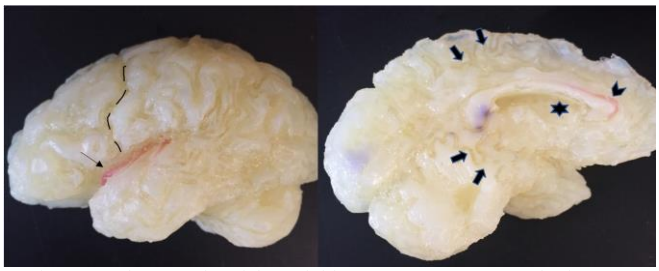

Figure 5. Photographs of the Soluble Support Prototype. A brain phantom of the left cerebral hemisphere, with visible sulci and gyri as well as the middle cerebral artery in red (arrow). The central sulcus (dashed line) demarcates the pre- and post-central gyri. The medial aspect of the brain model demonstrates key anatomical structures - the ventricle(asterisk), the pericallosal artery (arrow-head) and gray-white matter differentiation (bold arrows).

III. Results

A. Material Requirements

The end-user identified softness (the ability of a material to break-away in a controlled fashion thereby mimicking surgical dissection), anatomic versatility, skin safety and affordability as the most important factors for an ideal dissectible brain simulator. The engineering process identified post-processing time, production cost, functional fidelity and a material's biocompatibility as the product requirements. According to the end-user, the competitor model rated poorly for compressibility, however, the skin safety profile and affordability were found to be reasonable. The end-users needs, the engineering design requirements and the competitor research findings are summarized in a QFD diagram (Fig. 1).

B. Model Results and Evaluation

The prototypes are illustrated in Fig. 3 (silicone), Fig. 4 (TissueMatrix™) and Fig. 5 (necessary support material). Expert compressibility testing identified support material as having the most reasonable softness for the purpose of demonstrating brain dissection techniques. To simulate the model in an anatomical environment, the model was placed in a water bath where mechanical manipulation of the materials showed similar characteristics to actual tissue. This would facilitate surgeons using standard tools such as suction and forceps on the model. When placed in a water bath, necessary support material softened indicating that it would be easy for the surgeon to use suction and bipolar tips, two of the standard neurosurgery dissection tools, to excise intrinsic tumors or resect epileptogenic lesions. The biocompatibility of all three materials was found to be similar. Silicone, TissueMatrix™ and photopolymerized SUP706 are all classified as 'not hazardous' and lacking in skin antigenicity when used in the prescribed setting [24], [25].

The post-processing duration estimate was shortest for the TissueMatrix™ prototype (15 minutes) and longest for the silicone prototype (45 minutes) as timed using a stopwatch. It took 30 minutes to post-process the support material prototype. The unit cost of production was highest for the TissueMatrix™ prototype (CAD$3,800) and not extremely dissimilar for both the silicone (CAD$ 1,450) and SUP706 (CAD$ 1,475) prototypes. Mass production might decrease costs substantively.

Both necessary support and TissueMatrix™ modelled the high functional fidelity features (neuro-vasculature and gray-white interface visualization). The silicone prototype failed to achieve anatomical accuracy of the separate gray and white segmented entities, instead, a multi-layer process meant that the overlying gray matter took the shape of the white matter. A tabulated summary of the product characteristics is provided in Table 1. Fig. 6 is a flowchart summary of the material selection process.

TABLE I. A Summary of the Product Characteristics

Product Characteristic	Simulator Material		
	Silicone	***TissueMatrix™***	***SUP706***
Post-processing time (min)	45	15	30
Production cost (CAD$)	1,450	3,800	1,475
Compressibility	average	low	high
Fidelity (high/low)	average	high	high

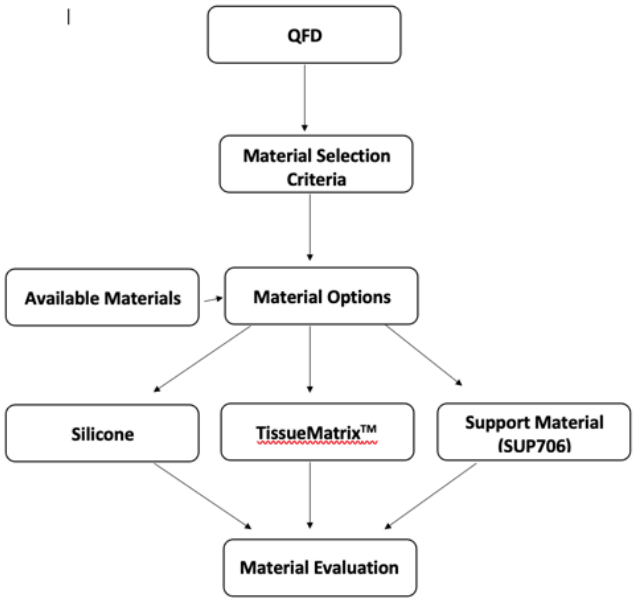

Figure 6. A Flowchart Summary the Material Selection Process.

IV. Discussion

Support material acts as the primary component in one of three prototypes we developed to simulate brain dissection. It was superior to TissueMatrix™, a material marketed as "the softest commercially available 3D printing material" [26].

In this feasibility study, we describe the selection process of a material suitable for brain dissection procedures such as intrinsic tumors or resective epilepsy surgery, using a materials engineering workflow [27]. Our methodology utilized end-user feedback from a practicing neurosurgeon. The end-user identified softness of a material as the most important factor needed to develop a useful dissectible brain model. The other requirements listed included surgical versatility, skin safety and affordability.

Support material, SUP706, was recruited in the selection process following the observation of how it softened during the post-processing step of the TissueMatrix™ model. Usually, support material would play the singular role of being a temporary scaffold for primary structures [22], [23], [28]. Following its recruitment into our material selection process we used the terms 'necessary support' and 'scaffolding support'. Necessary support constituted the primary material of our third prototype, whereas scaffolding support was the material we brushed off from the overhangs of the manufactured design. The necessary support prototype achieved optimal softness after soaking in a water bath for about three to five minutes prior to the end-user's compressibility assessment. The ability to soften in water is an important factor in the end-user's selection of support material as being non-biologic yet suitable-enough to demonstrate important neurosurgical skills, an advantage over the traditional silicone models we have used in other simulator applications [6]. Silicone models were found to be harder in consistency and had less functional fidelity compared to the moist support material prototype.

Converting support material, predominantly considered waste, into a primary design component supports sustainable engineering. In addition, the cost of manufacturing is nearly 40% lower when support material is used over TissueMatrix™ for a similar design.

There are a number of demanding neurosurgical procedures where the dissectibility afforded by support material's softness would allow high fidelity simulation including hemispherotomy for epilepsy, and resection of intrinsic brain tumors [29]. Hemispherotomy is sequence of several procedures that include, temporal lobectomy, corpus callosotomy and cortical disconnections of the frontal and occipital lobes [30].

The support material prototype is not without its shortcomings. One includes the necessity of differentiating the necessary support from scaffolding material. We fashioned a 0.3mm layer of TissueMatrix™ to demarcate the surface of the replicated brain, simulating a thin pial layer an important feature of normal brain anatomy. Support material loses its softness and becomes increasingly friable if left under water for too long prior to using for dissection. Thirty minutes and above was identified as the approximate time beyond which one prototype (one half of a cerebral hemisphere) disintegrated irreversibly.

The next research steps would be to further quantify the material properties as well as developing a patient-specific 3D printed prototype using the SUP706 support material. Incorporating multi-user input and feedback as well as force deformation testing of materials could improve the model's usability.

References

[1] Hochman, J. B., Rhodes, C., Kraut, J., Pisa, J. & Unger, B. End User Comparison of Anatomically Matched 3-Dimensional Printed and Virtual Haptic Temporal Bone Simulation: A Pilot Study. *Otolaryngol. - Head Neck Surg. (United States)* (2015) doi:10.1177/0194599815586756.

[2] Malone, H. R. *et al.* Simulation in neurosurgery: A review of computer-based simulation environments and their surgical applications. *Neurosurgery* (2010) doi:10.1227/NEU.0b013e3181ee46d0.

[3] Milburn, J. A., Khera, G., Hornby, S. T., Malone, P. S. & Fitzgerald, J. E. Introduction, availability and role of simulation in surgical education and training: review of current evidence and recommendations from the Association of Surgeons in Training. *International journal of surgery (London, England)* (2012) doi:10.1016/j.ijsu.2012.05.005.

[4] Hull, C. W. Apparatus for Production of Three-Dimensional Objects By Stereo Thography. *Patent* (1984).

[5] Whitaker, M. The history of 3D printing in healthcare. *Bull. R. Coll. Surg. Engl.* (2014) doi:10.1308/147363514x13990346756481.

[6] Breimer, G. E., Bodani, V., Looi, T. & Drake, J. M. Design and evaluation of a new synthetic brain simulator for endoscopic third ventriculostomy. *J. Neurosurg. Pediatr.* (2015) doi:10.3171/2014.9.PEDS1447.

[7] Bodani, V. P., Breimer, G. E., Haji, F. A., Looi, T. & Drake, J. M. Development and evaluation of a patient-specific surgical simulator for endoscopic colloid cyst resection. *J. Neurosurg.* (2019) doi:10.3171/2019.4.jns183184.

[8] Eastwood, K. W. *et al.* Development of synthetic simulators for endoscope-assisted repair of metopic and sagittal craniosynostosis. *J. Neurosurg. Pediatr.* (2018) doi:10.3171/2018.2.peds18121.

[9] Hsieh, T. Y., Cervenka, B., Dedhia, R., Strong, E. B. & Steele, T. Assessment of a patient-specific, 3-dimensionally printed endoscopic sinus and skull base surgical model. *JAMA Otolaryngol. - Head Neck Surg.* (2018) doi:10.1001/jamaoto.2018.0473.

[10] Lin, J. *et al.* Using Three-Dimensional Printing to Create Individualized Cranial Nerve Models for Skull Base Tumor Surgery. *World Neurosurg.* (2018) doi:10.1016/j.wneu.2018.07.236.

[11] Maran, N. J. & Glavin, R. J. Low- to high-fidelity simulation - A continuum of medical education? *Medical Education, Supplement* (2003) doi:10.1046/j.1365-2923.37.s1.9.x.

[12] Munshi, F., Lababidi, H. & Alyousef, S. Low- versus high-fidelity simulations in teaching and assessing clinical skills. *Journal of Taibah University Medical Sciences* (2015) doi:10.1016/j.jtumed.2015.01.008.

[13] Miller, R. B. Psychological Considerations In The Design Of Training Equipment. *Distribution* (1954).

[14] Bova, F. J. *et al.* Mixed-reality simulation for neurosurgical procedures. *Neurosurgery* (2013) doi:10.1227/NEU.0000000000000113.

[15] Ryan, J. R., Chen, T., Nakaji, P., Frakes, D. H. & Gonzalez, L. F. Ventriculostomy Simulation Using Patient-Specific Ventricular Anatomy, 3D Printing, and Hydrogel Casting. *World Neurosurg.* (2015) doi:10.1016/j.wneu.2015.06.016.

[16] Sase, K., Fukuhara, A., Tsujita, T. & Konno, A. GPU-accelerated surgery simulation for opening a brain fissure. *ROBOMECH J.* (2015) doi:10.1186/s40648-015-0040-0.

[17] Bernardo, A. Virtual Reality and Simulation in Neurosurgical Training. *World Neurosurg.* (2017) doi:10.1016/j.wneu.2017.06.140.

[18] Porte, M. C., Xeroulis, G., Reznick, R. K. & Dubrowski, A. Verbal feedback from an expert is more effective than self-accessed feedback about motion efficiency in learning new surgical skills. *Am. J. Surg.* (2007) doi:10.1016/j.amjsurg.2006.03.016.

[19] Wongsriruksa, S., Howes, P., Conreen, M. & Miodownik, M. The use of physical property data to predict the touch perception of materials. *Mater. Des.* (2012) doi:10.1016/j.matdes.2012.05.054.

[20] Zairi, M. & Youssef, M. A. Quality function deployment: A main pillar for successful total quality management and product development. *Int. J. Qual. Reliab. Manag.* (1995) doi:10.1108/02656719510089894.

[21] Pieper, S., Halle, M. & Kikinis, R. 3D Slicer. in *2004 2nd IEEE International Symposium on Biomedical Imaging: Macro to Nano* (2004). doi:10.1109/isbi.2004.1398617.

[22] Stratasys. Stratasys Objet SUP706 Soluble Support Material. https://www.stratasys.com/explore/video/stratasys-objet-sup706-soluble-support-material.

[23] Grabcad. How to Remove SUP706 Soluble Support on a 3D Printed Part. https://grabcad.com/tutorials/how-to-remove-sup706-soluble-support-on-a-3d-printed-part (2017).

[24] smooth-on. SAFETY DATA SHEET SDS No. 823A. http://www.dick-blick.com/msds/DBH_SDS_619341001.pdf (2020).

[25] Stratasys. Innovation starts here. https://www.stratasys.com/.

[26] Stratasys. Anatomical 3D printer materials. https://www.stratasys.com/materials/search/digital-anatomy.

[27] Pfeifer, M. *Materials Enabled Designs*. *Materials Enabled Designs* (2009). doi:10.1016/B978-0-7506-8287-9.X0001-8.

[28] Mueller, J. & Shea, K. Buckling, build orientation, and scaling effects in 3D printed lattices. *Mater. Today Commun.* (2018) doi:10.1016/j.mtcomm.2018.08.013.

[29] Zhu, F. *et al.* Identifying the properties of ultra-soft materials using a new methodology of combined specimen-specific finite element model and optimization techniques. *Mater. Des.* (2010) doi:10.1016/j.matdes.2010.05.023.

[30] Villemure, J. G. & Mascott, C. R. Peri-insular hemispherotomy: Surgical principles and anatomy. *Neurosurgery* (1995) doi:10.1097/00006123-199511000-00018.