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Physical patient simulators for surgical training: a review

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Abstract

The purpose of this article is to review the fabrication process of physical patient simulators for surgical training and describes current research areas.

Medical image acquisition and analysis are tools to reproduce human anatomy in 3D models. Data acquisition techniques include CT scans, MRI, and ultrasound. Post-processing of this data is necessary to obtain a file for 3D printing.

Two available fabrication methods are direct 3D printing of an organ model and 3D printing a mould to cast an organ replica. Direct 3D printing presents several limitations. Therefore, casting techniques with silicones and hydrogels are better suited for the fabrication of softer tissue models.

Surgeons qualitatively evaluate the simulators and their ability to train students. It is also possible to make a quantitative evaluation to compare the properties of the simulators to the physical properties of organs. Different methods exist to measure the physical properties of soft tissues, mainly to find the Young modulus of the soft tissue. The tests can be in vivo*,* in situ *or* in vitro*. Researchers perform tests on human tissues or animal tissues.*

The use of surgical simulators has shown satisfactory results in surgical training. Nonetheless, limitations remain, simulators lack realism and are not available for some pathologies. Future work in this area could be of benefit to surgical training.

Keywords

Soft tissues – Biomechanics – Surgical simulation – Patient specificity

Introduction

Medical students learn new surgical skills by performing surgeries on cadavers or animals. [1] Specific pathologies such as tumours or rare diseases are unavailable during these training sessions, and studies show that medical students are only able to practice a limited number of surgical skills [2] Previous research investigated physical patient simulators for their potential for training medical students and surgical planning. [3] [4] [5]

With the evolution of 3D printing technologies, there is an exploration of the applications in medicine. Tissue engineering and patient-specific implant design are examples of the broad scope of applications. [6] With 3D printing, it is also possible to create complex models which mimic the anatomy of the patient. When combined with medical imaging, 3D printing can generate patient-specific models useful for surgical planning and teaching. [7]

This article presents a state-of-the-art review of surgical simulators and their limitations.

Data acquisition

Data acquisition of patients' anatomy is a method to build 3D models of organs. Those 3D models are the base of the creation of physical simulators. Furthermore, the fabrication of a patient-specific simulator requires medical images of the patient. Patient-specificity allows better surgical training, surgical planning and patient understanding. [4] [5] [8]

Magnetic resonance images (MRI) provide 3D models of patient anatomy. [4] [9] Other options include multi-detector computerized tomography [3] [4] [8] [9] or ultrasounds [10].

It is necessary to post-process the image to convert the DICOM file into a 3D model. Literature reports the use of commercially available software such as Mimics (Mimics, Materialise, Ann Arbor, MI) [4] for the image segmentation, and the differentiation of the tissues into subsets. It is also possible to use image recognition algorithms (Synapse 3D, Fujifilm, Tokyo, Japan) or software available in the public domain such as InVesalius [11]. The data are imported into engineering software such as Geomagic (3DSystems, Rock Hill, South Carolina, USA) [4], Catia (Dassault Systèmes) [11] or SolidWorks software (Dassault properties Systèmes). [12] to generate a printable STL file

Physical simulators fabrication methods

Different techniques are available for the fabrication of a patient simulator. The choice of the technique depends on the anatomy and the desired properties of the specific organ. Medical scanning, combined with 3D printing technologies provide a solution to the reproduction of models that display the complex geometries, textures and tactile feel of human organs.

Fabrications methods

There are two main digital fabrication techniques used to build surgical simulation models, direct 3D printing of materials able to mimic the human tissues and 3D printing of moulds, used to cast flexible materials to replicate organs.

3D printing of soft materials

3D printed models of organs can be used to create patient simulators. This method reproduces the hardest tissues such as bones (osseous tissue) [3], blood vessels [5] [11] and some organs [13].

The evolution of 3D printers in the last decade makes softer materials printable. A 3D printer by Stratasys (Eden Prairie, Minn. & Rehovot, Israel) can print soft tissues replicas with the same properties as the cardiac tissues [14].

3D printing of moulds

3D printing of moulds allows the use of a broader range of soft materials.. The moulds are created by digitally subtracting the organ model volume from a larger rectangular volume using CAD software. [15] This method can reproduce a wide variety of tissue, such as arteries [9], abdominal organs [8] [15], and brains [1] [4].

For hollow structures, the moulds are more complicated in order to be able to remove the model after casting. It is possible to create heat-sensitive moulds and to remove them by melting them. [9] Another option for hollow organ fabrication is to design a mould consisting of two outer shells and an inner core. [8] [16] The parts of the mould are assembled, then the casting material is poured inside. The mould is disassembled when the casting is finished to release the organ replica.

Influence of the 3D printer technology

The 3D printing technologies used in the field of surgical simulators are material extrusion with polymeric filament, powder bed fusion, material jetting, and vat photopolymerization. [17]

Material extrusion consists of extruding a fused thermoplastic filament onto a heated bed. The melted filament cools and solidifies during the extrusion. This technique is simple and can use with a wide range of materials. The accuracy is not as good as with other techniques, and there is a need for support material for some geometries. It is necessary to remove the support materials after the end of the printing and to post-processing the part to enable a good finish. [18]

SLS (Selective Laser Sintering) consists of the fusion of polymer powder to create a solid object. At first, a laser selectively heats a thin layer of powder to solidify the first cross-section of the solid, then the bed is slightly lower, and the machine adds another layer of powder on the top of the last layer. The process repeats itself until the completion of the printing. This technique is more expensive to use than the material extrusion technique, and the surface of the object is porous. This technique does not require support, and the material can be more flexible.

Another technique with a bed of polymer powder is to disperse a binder on the powder. The name of this technique is colour jet printing. Alternatively, material jetting deposits drops of liquid onto the bed. Then UV light solidifies the drops. Finally, with the vat photopolymerisation technique SLA (Stereolithography), a laser beam selectively solidifies a liquid resin by photopolymerisation. These last two techniques have the highest resolution.

A study compares the three following 3D printing technologies: a material extrusion technique (FDM), a colour jet printing, and a PolyJet technique (material jetting). The relative difference between the 3D printed model and the STL file were respectively 4.00%, 2.36% and 1.51% for the FDM, the colour jet printing, and the material jetting. The cost was high for the PolyJet middle for the colour jet printing and low for the FDM. The printing time for the FDM was 65 hours, against 7 hours for the colour jet printing and 18.5 hours for the PolyJet. [19]

Materials

The choice of the material depends on the selected fabrication technique and the targeted organ. The hardness of the tissue differs from bone to brain tissues.

Previous research has used silicone because its physical properties can reproduce those of human tissues. [9] Silicone is a versatile material for casting surgical simulation models, the transparent types can be useful for enhancing the usability of the models by allowing observation of internal components, for instance, for aneurysm reproduction. [16] It is possible to add colourant into silicone mixture to reproduce the appearance of real organs. [8]

Another casting material widely used is hydrogel because of its softness. Brain and lung tissues are the softest tissues in the human body [20], and the reproduction of their properties can be challenging; therefore, researchers use hydrogel to make brain and lung tissues simulators. [1] [4]

For direct 3D printing, other materials include Makerbot flexible filament [5] and photopolymers [13] can be utilised.

The properties of all these materials can be adjusted, when using silicone, mixing the silicone with another agent modifies the stiffness of the outcome. [15] Similarly, the properties of a hydrogel can be adjusted by varying the agarose concentration to give the correct feel of an organ such as a liver. [8] The modification of the properties of other polymers is feasible using this method. [17]

When the organ simulation model is directly 3D printed, the PolyJet 3D printer can blend hard and soft materials during the build process to simulate the tactile feel of a human organ [21].

Evaluation of the simulator

Surgical simulator evaluation uses both qualitative and quantitative methods. Quantitative tests include measures of the materials' properties, measures of the gain in the training of the students, and analysis of the geometry of the material. Qualitative tests are evaluations of the prototypes by surgeons or other medical specialists on their resemblance to the human anatomy and on their usefulness as a teaching tool or during pre-operative planning.

Soft tissues characterization

The evaluation of the simulator consists of the estimation of its usefulness during surgical training. [3] [4] [8] [13] it is possible to make a physical characterisation of soft tissue properties and to compare them to the simulators' properties. [1] [20]

In vivo non-invasive test on soft tissues

The stress-strain response defines the elastic properties of materials. Bouten uses this method to identify the elastic properties of the tibia. His method presents the benefits of being non-invasive and non-traumatic. The tibia undergoes a gradually increasing pressure, and MRI images record the deformation of the soft tissues. A finite element model calculates the elastic properties. [22] Frauziols uses a similar approach to analyse the deep tissue properties of the tibia. [23]

This method can study the properties of superficial tissues. Elahi uses a suction device to apply negative pressure on a soft tissue surface. A finite element inverse identification provides the Young modulus of the tested samples. [24] Similarly, Zahouani studies the visco-elastic response of the skin with an airflow system. The analysis of propagation waves on the surface of the skin is used to calculate the Young Modulus. [25]

Using the internal stress within the body to study the properties of the tissues is another option. Franquet used this method to study pathological arteries. Phase-contrast MRI images generate a displacement map of the arteries with a finite element method. From the measured variation of blood pressure, it is possible to calculate the Young Modulus of the arteries. [26]

In vivo invasive tests on soft tissues

In vivo biomechanical tests can also identify the properties of the internal organs. However, these tests are invasive. Rosen describes the use of a motorized endoscopic grasper. It reproduces the stress applied to organs during surgery and measures the displacement of the tissues. He tested his method on animals by inserting the device into their abdomens. The procedure is similar to laparoscopy. [27] Tay used a similar method to measure the static and dynamic mechanical behaviour of pig liver and lower oesophagus. [28]

Schwenninger used a trocar system to flush a fluid against the internal organs during an endoscopy. Suction is applied to the soft tissue, and the displacement of the tissue is measured. Then an inverse finite element analysis is used to determine the elastic properties of the tissue. [29] Hollenstein used a similar technique to test the human liver, the vaginal wall and uterine cervix properties. [30] This method was used to determine the organ's properties and has proven to be reliable and safe. It could be used in laparoscopy to measure the organ's properties.

In vitro tests on soft tissues

In vitro tests determine the physical properties of tissue samples outside of the body. Great attention to the test conditions is necessary because the response depends on the temperature and humidity conditions. The variety of tests is wider than for *in vivo* tests. For instance, it is possible to perform rheology tests, elongation tests and compression-relaxation tests. [31] The tests can be made on human tissues or animal tissues. [27] [32]

Evaluation of the usefulness of the simulators

Medical specialists can evaluate the simulators. The evaluations focus on how useful the simulator is in teaching student sand its resemblance to real tissues.

Students can test the simulators. [4] For instance, it is possible to evaluate the learning outcome of the student after training on the simulator. Criteria to evaluate the student performance can be the time needed to perform a procedure and the number of tries before success. [3]

Another possibility is to compare the surgical scores before and after training on a simulator. Scores can include the complication rate, the length of the surgery, the recovery time, and the quantity of blood loss during surgery. [13]

It is also possible to make a qualitative evaluation of the simulator; surgeons can give their opinion on the utility of the simulator. [8]

Qualitative evaluation of the simulator

Qualitative evaluations of the simulators are also necessary to assess the ability of the simulator to reproduce the sensations of the surgery. The simulator must "feel" like real tissues. For instance, the reproduction of the tactile response with the simulator is essential to teach students. [4], it must look like real tissue and have similar handling properties. [15]

Discussion

Diverse methods of fabrication of physical patient simulators have emerged during the last years, simulators are proving to be a promising tool for surgical training of the future generations of surgeons, although it is quite a recent technology, several studies describe the potential of physical simulators. [15] [33]

Despite the potential of surgical simulators, they are not in regular use for residential training, a study in Japan showed that only 12.5% of the university hospitals integrate surgical simulators in their surgical training regularly; however, a survey made in 2013 shows that 77% of surgical residency programs in the US use surgical simulators during their program. [34]

Pre-operative planning in the field of orthopaedic is another use for surgical simulators. A study on their utility for surgical planning shows that they can offer a reduction in operation time of 19.85% and a diminution of intra-operative blood loss of 25.73%. [35], they can have an impact on the medical decision of the surgeon. A study demonstrates that the surgeons change the location of the implantation site in 74% of the cases after pre-operative planning. Surgical planning also had a significant influence on the choice of the instruments in half of the cases. [36] Even though they are less common in other specialities, many surgeons acknowledge their potential and are interested in using them in the future. A study reports that the use of 3D printed cardiac models for surgical planning has an impact on surgical approach in 47.5% of the cases. [37] A survey among cardiothoracic specialists illustrates that 85% of the participants would like to integrate 3D printed models for surgical planning in their future practice. [38]

Several studies report the lack of realism of surgical simulators. Human tissues are complex, and it is difficult to reproduce their properties. For instance, when testing a commercially available laparoscopy simulator, the combined realism score of the simulation is 64.7% [33].

The characterisation of soft tissue is derived from tests on *in vivo* animal tissues, or *ex vivo* or *in vitro* animal or human tissues. Animal tissues do not have the same properties; in a study on lung tissues, Andrikakou shows that rats' and rabbits' lungs do not have the same properties. For that reason, the precise properties of human tissues cannot be determined from tests on animals. [31] Moreover, studies show that *in vivo*, *in situ* and *in vitro* responses of soft tissues differ. [27] [28]

Commercially available simulators mainly focus on some broadly used surgical skills. Nonetheless, there is a lack of dispositive for less common pathologies. For instance, most simulators represent adults, and there is a lack of simulators for paediatric training. [15]

Conclusion

With the improvements of the 3D printing technologies, it is becoming possible to 3D print simulators replicating the properties of soft tissues. Nonetheless, the 3D printed models are not soft enough to mimic all tissues, and the price of the printers makes the generalization of their use in hospitals unlikely. The project will investigate further moulding techniques in future work.

Physical patient simulators are a useful tool for surgical training and pre-operative planning. They are already used for the training of medical students and the surgical planning of some procedures. However, despite their proven utility, there are still limitations to their use. The project will focus on a more realistic reproduction of the soft tissues.

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