Application of TPU – Sourced 3D Printed FDM Organs for Improving the Realism in Surgical Planning and Training

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Abstract

Since 3D printing was developed, it became the most promising technique to speed up prototyping in a wide variety of areas across the industry. Rapid prototyping allows the medical industry to customize the surgery procedures, thus predicting its result. Biomedical applications made by medical grade elastic thermoplastic polyurethane (TPU); a non-traditional plastic material which allows to obtain additional benefits in rapid 3D prototyping because of its flexibility and anti-bacteriological capabilities. The aim of this study is to assess the efficacy of TPU polymer, FDM objects sourced from CT scanned 3D surfaces for helping surgeons in preoperative planning and training for increasing environment perception, that is, geometry and feeling of the tissues, whilst performing standard procedures that require complex techniques and equipment. A research was performed to assess the physical and qualitative characteristics of TPU 3D developed objects, by developing a proper SWOT analysis against PLA, a widely used, and cost-effective option in FDM industry. Therefore, giving a proposition opposite to other known modern medical planning techniques and bringing out the benefits of the application of TPU-sourced, FDM parts on professional medical training. As a result, PLA is a reliable, wide-available process whilst TPU's flexible capabilities improves realism in 3D printed parts. Surgical planning and training with rapid prototyping, would improve accurate medical prototyping for customized-procedures, by reducing surgery times, unnecessary tissue perforations and fewer healing complications; providing experience that other FDM materials like PLA cannot be reached.

Keywords
TPU, Surgical Training, QFD, 3D Scanner, 3D Printing.

1. Introduction

Nowadays 3D printing sourced from CT scans is emerging as a powerful tool by helping to improve efficacy at training, planning, and further customize medical procedures. While a growing number of researchers in the biomedical engineering field are employing 3D printing as a transformative tool for biomedical applications like tissue engineering and regenerative medicine, using rapid prototyping to plan complex medical procedures have found to improve the efficacy in operator-dependent interventions, by means of reducing overall surgery times, less tearing and unexpected tissue perforations are performed if a customized model is used for surgery planning, and leading to less healing complications and less dehiscence. Further research is then required in the rapid prototyping area in order to improve the accuracy of procedure planning, by means of new proposals about materials and equipment that would help the medical industry to strengthen their needs.

1.1 State of the Art:

New technological advances have enabled other industrial areas to become part of the problem-solving methodologies for today's requirements. Three-dimensional (3D) printing is a commonly used term that is often considered synonymous with additive manufacturing. 3D printing has drawn a lot of public attention, especially for its use in medical research. There has been a rapid growth in applications of 3D printing in manufacturing customized implants, prostheses, drug delivery devices, and 3D scaffolds for tissue engineering and regenerative medicine.(Tappa & Jammalamadaka, 2018)

Modern improvement in 3D printing technologies made this process as a dynamic tool in biomedical engineering field with several number of researches in tissue engineering and generative medicine (Zhu et al., 2016). Some recent investigations have shown different kinds of implementation of 3D organs and tissues (Osti et al., 2019)(Yakof et al., 2018). Associated with manufacturing of these tissues and organs, 3D medical modelling can be convenient for the surgical robot operations where the doctor does not have firsthand connection with the surgical area. (Osti et al., 2019). The accurate training of medical professionals has turned out progressively more difficult, the traditionally accepted method of direct supervision has become more difficult given the high affluence of professional medical students. (Vicknes Waran & Pancharatnam, 2014). Computed axial tomography (CAT), nowadays simply called CT, is a radiological method that produces cross-sectional images of specific areas of the body. The result of the scan show body layers, based on their density (Frizziero, Liverani, et al., 2019)(Caligiana et al., 2020). For medical applications, images are acquired by CT scans or MRI. The X-ray data set is in the DICOM file format. The first step in the generation of a three-dimensional anatomical model is the extraction of the target geometry from the medical images imported in the DICOM format (Frizziero, Santi, et al., 2019), (Frizziero et al., 2020)(Osti et al., 2019). This image segmentation process divides an area of the radiograph into non-overlapping regions, connected, coherent and homogeneous. The level of image partitioning depends on the complexity of the problem being faced (Auricchio & Marconi, 2016).

An important number of computer-based platforms have been developed in the past few years, like Touch Surgery, a novel online platform geared towards innovating professional training for surgical procedures (Mandler, 2018). Recently, a number of researchers have developed a variety of anatomically accurate physical models based on computed tomography (CT) and (magnetic resonance imaging) MRI data, using 3-dimensional (3D) printing technology (McGurk M, 1997) (Waran V, 2012). Moreover, CAD models based on patients with a certain pathology have been developed, and using FDM printing technology, texturized models that can resemble normal tissue structures have also been created (Waran V M. R., 2012). Therefore, this training procedures imply the use of expensive and complex surgical tools, special physical and cognitive skills for the performance of certain standard neurosurgical procedures using real patient data.

1.2 3D Printout Models vs. 3D-Rendered Images: Which Is Better for Preoperative Planning?

3D volume rendering and 3D printing were performed respectively to create 2 different training ways. Results from this study support our hypothesis that 3D-printed models improve the quality of surgical trainee's preoperative plans. Residents in 3D printing group showed significantly higher quality of the surgical plan scores compared with residents in group of 3D computer models.(Zheng et al., 2016)

1.3 3D Printing for Surgery:

A qualitative evaluation of applying 3D printing in preoperative surgical planning and intraoperative guidance feasibility for all patients was included in the study. The vast majority of surgeons interviewed scored their quality and usefulness as very good. The utility of 3D models was proposed in all facets of surgical practice; from educating patients before the procedure, as a preoperative and intraoperative tool, and using those same models for medical education. This holistic approach of integrating 3D models into patient care will result in this promising new technology becoming adopted by more surgeons in their everyday practice. Although the technology is still in its early stages, presented models are considered useful in preoperative planning and patient and student education.(Witowski et al., 2017). Life-like tactile feedback is particularly difficult to reproduce. Technological innovations may contribute novel solutions to these shortages. 3D technology was used to simulate laparoscopic choledochal surgery for the first time. As a result, 100% stated that they felt they could reproduce this in their own centers, and 100% would recommend this simulation to colleagues.(Burdall et al., 2016). The purpose of this research is to develop a rapid prototiping scenario with a heart model to give the medical field a proposal in order to increase the perception of the problem for a better result in organizing the real surgery. Thus, it is aimed to considerably reduce the risks of surgical procedures and healing complications .

2. Materials:

3D printed model usage simplifies the analysis of the patient anatomy through the study with a real time model and haptic feedback before surgical operation. Recent improvements in the use of 3D-printed models have shown the potential of this technology in health care and may help to enhance the quality of preoperative planning(Zheng et al., 2016).
Therefore, this study has focused on the use of TPU and PLA polymer-based filament for 3D printing technology, in which studies have shown the biocompatibility and tissue response of PLA-based applications(Ren et al., 2015), and consequently that TPU addition in PLA could change its brittleness properties (Hong et al., 2011).

2.1 TPU Usage in 3D printing:

The rigid and soft blocks that are involved by TPUs are subjected to segregation, initiating for nanodomain morphology. Thus, the materials and the system step into a physical crosslinking, subsequently forming thermoplastic elastomers (TPEs). Even if TPEs perform like elastomers, they can be processed like thermoplastic materials which facilitates making filaments from TPU material. (Guelcher, et al., 2005)

Furthermore, when (TPUs) properly designed, they become appropriate material to use in Fused Deposition Modeling (FDM), especially for 3D Printing. In FDM technology, a thin filament that includes thermoplastic polymer matrix is used. FDM printer uses 3D models via the STL format and enable to manufacture 3D structures layer by layer (Agnieszka Harynska, 2019), (Xiao & Gao, 2017). The mechanical (Belter & Dollar, 2015)(Ren et al., 2015)(Zein et al., 2002) and biological properties (Rabionet et al., 2018), (Ariadna et al., 2016) of printed 3D object are mostly rely on design features and 3D printing parameters.

Table 1. TPU Filament for 3D printing Chemical Details (ChemIDplus, 2021)

Denomination
CAS number: RN: 9078-71-1
Formula
1,4-Benzenedicarboxylic acid, 1,4-dimethyl ester, polymer with 1,4-butanediol and alpha-hydro-omega-hydroxypoly(oxy-1,4-butanediyl)
Classification Code
TSCA Flag XU (Exempt from Reporting under Chemical Data Reporting Rule)
Molecular Formula
(C10-H10-O4.C4-H10-O2.(C4-H8-O)mult-H2-O)x-
Molecular Weight
446.5317

2.2 PLA as FDM Most Effective Solution.

Adjustable mechanical properties, degradation into natural substances, biocompatibility, and low cost makes PLA one of the most common material for clinical applications (Lopes et al., 2012), (Ulery et al., 2011)[16-14ref, 16-15]. Filaments that have bioactive substances such as drugs can be used in FDM to impede biofilm formation on the scaffold and assist to adjust the cell behavior (Farto-Vaamonde et al., 2019).

As a manufacturing method of the thermoplastic polymers, Fused deposition modeling (FDM) has been broadly used in several field. FDM method has its advantages by means of operation simplicity and high quality of printed products. Besides that, this method gives opportunity for proper tuning and structure regulation. Additionally, manufacturing of layer by layer affects the mechanical properties of printing products relating to printing direction (Lyu et al., 2020).

2.3 Mechanical properties of TPU and PLA

Among the reasons for choosing thermoplastic polyurethane (TPU) are its high strength, high elongation at break and high elasticity (Yakof et al., 2018). The mechanical properties of polyurethanes depend among others on: degree of crystallinity, concentration and structure of rigid segments, or ability of soft segments to crystallize (Lee & Tsai, 2000). By changing the weight ratio of hard and soft segments, the mechanical properties of polyurethanes can be modified.

Table 2. Used TPU and PLA FDM Filament Properties

General Properties	**TPU**	**PLA**
Filament diameter	1.75 mm	1.75 mm
Specific Gravity	1.22 (g/cc)	1.24 (g/cc)
Moisture Absorption - 24 hours	0.18%	
Mechanical Properties		
Tensile Strength, Ultimate	39 Mpa	47.8 Mpa
Tensile Modulus	26 Mpa	2467 Mpa
Elongation at Yield	55%	2.8%
Elongation at Break	580%	4.59%
Toughness	117.2 m*N/m^{3}x10^6	
Hardness	95 Shore A	83 Shore D
Impact Strength (notched Izod, 23C)	19.1 kJ/m^2	17.91 kJ/m^2
Thermal Properties		
Melting Point	220° C	145-160 °C
Glass Transition (Tg)	-24° C	60 °C

3. Methods

The flowchart in operating 3D printer is shown in Fig. 1. Information from the TAC image of the leftmost part of the human thorax was analyzed by means of InVesalius 3 Software, in which a preliminary 3D mesh of the heart is obtained (Figure 2); this mesh is then exported to Stereolithography (STL) format. Afterwards the Mesh was optimized with Blender V2.9 for better printing quality (Figure 3), thus being able to reach accurate manufacturing times. The Optimized 3D heart model in STL format was processed for FDM printing with use of Simplify 3D software (Figure 4), in which the mesh was divided in layers according to the printer and nozzle parameters for each tested material (Table 4), creating the tool path on the build platform. This process allowed the support structure to be formed and the model scale to be changed accordingly. The final G-code file could be obtained after a number of print simulations in the software in which the printing parameters could be monitored for ensuring the best overall printed part quality and detail. After the specifications were properly set (Table 4) and the filament was inserted into the extruder, the machine was run automatically. Each layer was laid successively until the heart model including the support structure was completed. For better results in TPU printing quality in AnyCubic 3D printer device, a Direct Drive, extrusion material feeder had to be fitted into the printing head for proper TPU printing quality. In both cases, each layer printed was about 0.2 mm in thickness (the thickness is adjustable) for both heart models. The machine in progress was monitored from time to time to ensure no errors were made (Figure 5). The printed object was removed from the platform after the printing was complete and was allowed to properly set before removing the support structure.

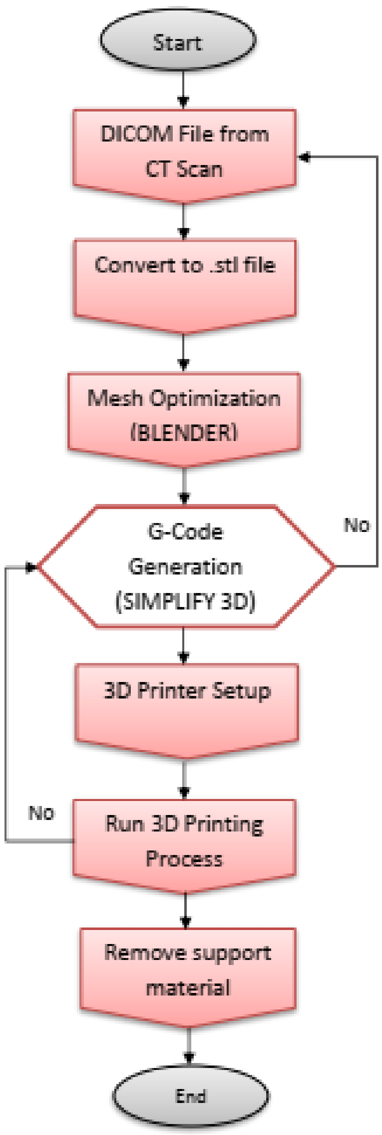

Figure 1. 3D FDM Part obtained from a CT scanned

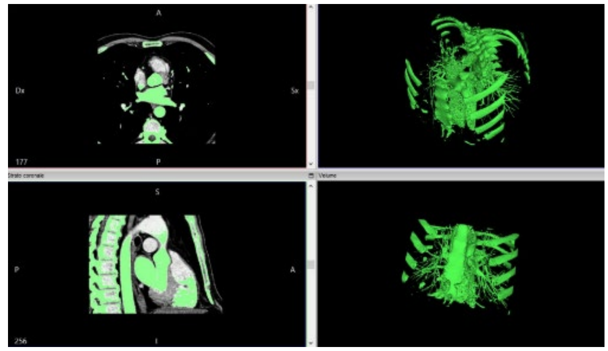

Figure 2. DICOM Image (left)
CT scan Procedure and 3D mesh gathering (Right)

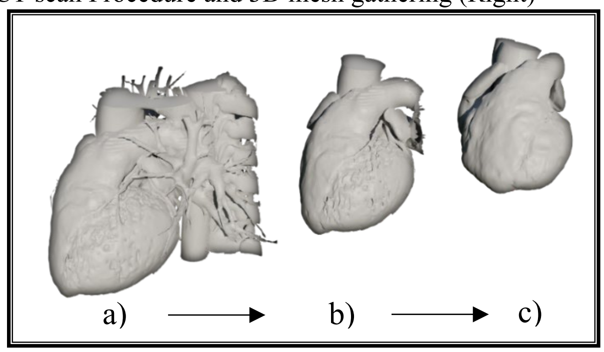

Figure 3. Gradual Optimization of the 3D heart model

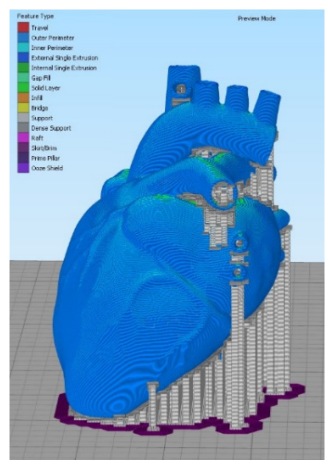

Figure 4. STL Tool-path processing for G-code Generation

Table 3. Technical Specifications of AnyCubic Predator 3D Printer

Printing Technology	FDM (Fused Deposition Modeling)
Printing volume	370×370×455 mm
Layer Resolution	0.05-0.3 mm
Positioning Accuracy	X/Y/Z 0.0125 mm
Extruder Quantity	Single
Print Speed	20~150 mm/s (suggested 60 mm/s)
Supported Materials	PLA, ABS, TPU, HIPS, Wood
Ambient Operating Temperature	8°C - 40°C
Operational Extruder Temperature	max 250°C
Software Input Formats	STL, OBJ, JPG, PNG
Connectivity	Memory card; Data cable
Weight	19.2kg

Table 4. Application Parameters of 3D Printing Machine (The name of the machine)

Parameters	**PLA**	**TPU**
Printing (Nozzle) Temperature	200°C	220°C
Heated Bed Temperature	60°C	65°C
Nozzle Diameter	0.4 mm	0.4 mm
Layer Thickness	0.2 mm	0.2 mm
Printing Speed	60 mm/s	20 (mm/s)
Infill Density	15 (%)	25 (%)
Flow	100 (%)	110 (%)
Max overhang angle	50°	35°

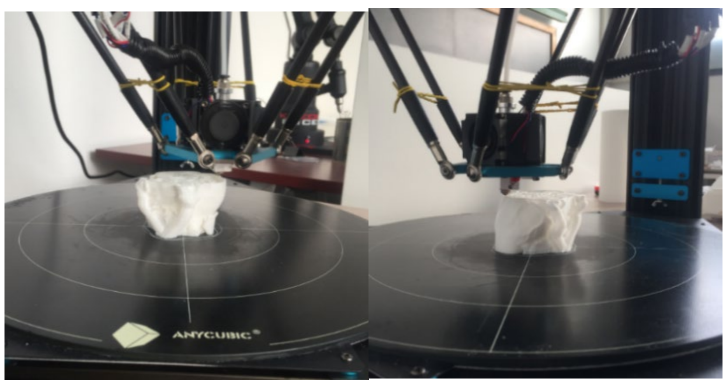

Figure 5. FDM Process on Anycubic Predator – Modified 3D Printer

4. Results and Discussion


Figure 6. View A of PLA Heart (lh), and TPU Heart (rh)


Figure 7. View B of PLA Heart (lh), and TPU Heart (rh)

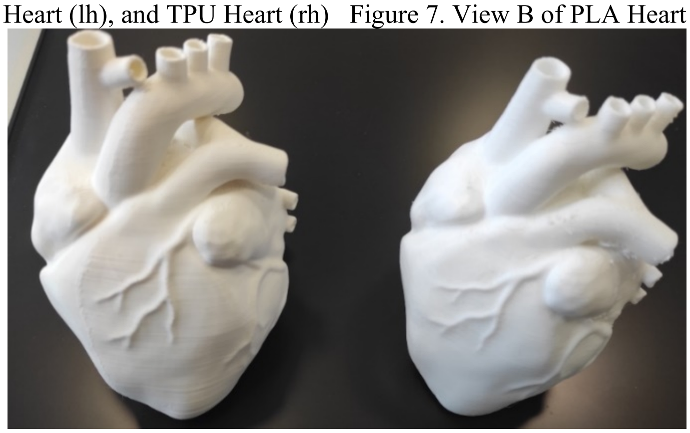
Figure 8. View C of PLA Heart (left), and TPU Heart (right)

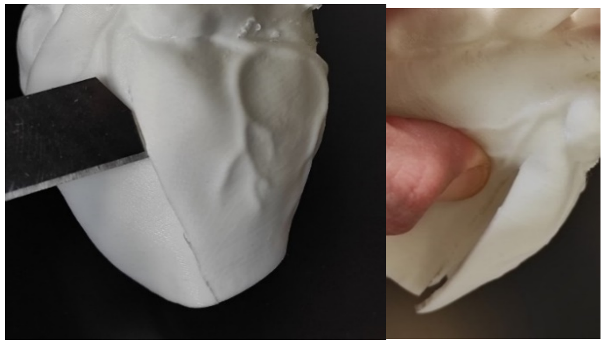

Figure 9. Detail View TPU Material Cut With a Regular Knife (left), and Flexibility Properties (right)

The 3D printing process was then compared according to a number of specific requirements fulfilled both heart models. The potential benefits of having flexibility and elasticity are discussed in this study, which allows the heart structure to simulate beats in the same way as the real organ does. The inside chambers for coronary arteries have been elaborated just like the real heart is, to be hollowed to allow air flow, fluid flow and catheter insertion practices. This study was conducted in two stages. The first stage used traditional polymer for FDM PLA, which is a non- flexible filament as the printing material. The second trial was the improved version of the first trial using a more flexible material TPU with characteristics as shown in Table 4.

4.1 TPU vs. PLA Materials: SWOT Analysis:

Research activity about using TPU as a standalone, or in combination of PLA in order to develop materials for reaching new applications and further improve its usage in medical-oriented solutions have been gathered out in a SWOT analysis performed for both FDM printing techniques that can be useful to summarize the objectivity of usage of TPU material for FDM opposite to PLA.

The results of this study were obtained in function of areas like Biocompatibility, Mechanical Properties, Manufacturability, Medical Training and other Medical Applications as summarized in Table 5. The summary chart exhibits the main advantages and disadvantages of the application of TPU-sourced materials in FDM processing, as well as looking into their probable use for Medical intervention simulations and other found medical applications in literature.

Overall, literature analysis was used to support the proposed application of TPU; findings about the opportunity of 3D printed-sourced procedure simulations and need of a Life-like tactile feedback during surgery planning and training, its balanced mechanical properties and manufacturability stress the suitableness for the application; its squishiness, flexible behavior were useful for increasing touch-feeling experience, as operators can feel the inside structure of the printed part. Lower tensile strength modules able the printed objects to be cut with a scalpel for increasing the simulation experience. The overall as additional findings about PLA brittleness and low recovery shape ratio, as well as higher glass transition temperature than human body temperature was found. TPU is a current matter of study for numerous medical applications thanks to its biocompatibility characteristics by means of tissue scaffolds (Mi et al., 2013) and with other biomaterials for wound healing applications(Mistry et al., 2021). Other characteristics worth noting about these types of polymers are its degradation capabilities, which might be deliberately used to design biodegradable polyurethanes as needed. PLA offers an overall cost and time effective solution, which also offers integrity for clinical usage, by the latter it could be said that PLA based FDM for medical solutions is a proven alternative for applications in which its lack of elasticity and low shape memory ratio do not present an issue.

5 Conclusion

This research work demonstrated the feasibility of application of 3D modelling and printing technology for applications in the context of a heart model. Other investigations among the same field have shown that a proper methodology of 3D model set-up for FDM printing can be obtained by means of a user-friendly process which allows to use CT scans to create physical objects. The need of applying realistic models for professional surgery planning was assessed, the application of a methodology and materials have paved the

Table 5. SWOT Analysis of TPU and PLA Materials FDM 3D Printed Parts According to Different Points of View

<table>
<tr><th colspan="2"></th><th>Biocompatibility</th><th>Mehanical Properties</th><th>Manufacturability</th><th>Medical Training Capabilities</th><th>Other Medical Applications (Prosthesis etc.)</th></tr>
<tr><td rowspan="4">TPU</td><td>Strengths</td><td>Not intended to degrade (Dogan et al., 2017)(Tatai et al., 2007).</td><td>High elongation at break; high elasticity, moderate tensile strength and young's modulus, excellent abrasion and tear resistance (Mi et al., 2013)(Yakof et al., 2018).</td><td>Easily melted and shaped by FDM process (Yakof et al., 2018).</td><td colspan="2">Lower Glass Transition Temperature; capable of be cut with medical instruments, able to modify its shape without degrading its properties.</td></tr>
<tr><td>Weaknesses</td><td>Susceptible to hydrolytic, oxidative and enzymatic degradation in vivo (Dogan et al., 2017)(Tatai et al., 2007).</td><td>Much lower stiffness opposite to PLA (Table 2).</td><td>Printing Issues - parts can be easily tangled into the extruder (Yakof et al., 2018).</td><td>Higher printing cost than PLA</td><td>Lack of cellular affinity by standard polymer blend techniques (Mistry et al., 2021)</td></tr>
<tr><td>Opportunities</td><td>Degradation might be deliberately used to design biodegradable polyurethanes (Tatai et al., 2007).</td><td>Combination of PLA and TPU: suitable for tissue engineering scaffold applications (Mi et al., 2013).</td><td>Behave like an elastomer, but it can be processed like thermoplastic material. (Guelcher et al., 2005)</td><td colspan="2">Commonly used polymers with their good mechanical properties, biocompatibility (Tatai et al., 2007) and shape memory behavior (Dogan et al., 2017). Innovative element (density grading, energy absorption, damping behavior) on flexible structures (Toth et al., 2020), exhibited potential for further clinical evaluations to enable their commercialization. (Mistry et al., 2021)</td></tr>
<tr><td>Threats</td><td>degradation for some application long lasting biomedical implants (Tatai et al., 2007).</td><td colspan="3">Would require additional supports and requires Direct Drive material feeder; Lower detail-3D print quality, Higher Production Costs, Higher Time for Manufacture</td><td>No evidence about thermal insulation and flex resistance characteristics (Toth et al., 2020)</td></tr>
</table>

<table>
<tr><td colspan="7"></td></tr>
<tr><td rowspan="4">PLA</td><td>Strengths</td><td>Proven biocompatibility and tissue response (Ren et al., 2015),</td><td colspan="2">Availability, Faster printing times, better mechanical strength and integrity (Haroosh et al., 2012), modifications with other Polymers (Hong et al., 2011)</td><td colspan="2">Polymer which provides better integrity for clinical uses (Haroosh et al., 2012), the acidic environment helps to reduce the bacteria growth and promote epithelization.</td></tr>
<tr><td>Weaknesses</td><td colspan="2">Brittleness, degradation during processing but also their impossibility of material recycling with commonly used synthetic plastics (Plavec et al., 2020)</td><td>Higher printing temperatures can modify its inner structure</td><td>Life-like tactile feedback is particularly difficult to reproduce. (Burdall et al., 2016)</td><td>brittleness, degradation (Plavec et al., 2020)</td></tr>
<tr><td>Opportunities</td><td>Possibility of re-using such materials through material recycling (Plavec et al., 2020)</td><td>Mechanical properties modifications with other Polymers (Hong et al., 2011)</td><td>Can be made of renewable feedstocks such as corn-starch, potato, wheat and sugarcane (Avinc et al., 2010)</td><td>Used in 3D printed-sourced surgery simulations studies. (Burdall et al., 2016)</td><td>Blending PLA with Poly(e-caprolactone) (PCL) and Halloysite nanotubes (HNT) can deliver a new drug delivery system in tissue engineering and drug delivery (Haroosh et al., 2012)</td></tr>
<tr><td>Threats</td><td>Limited scientific work on material recycling of biodegradable polymer materials (Plavec et al., 2020)</td><td colspan="4">Some studies found that PLA exhibited relatively low shape recovery ratio and showed higher glass transition temperature than human body temperature (Yang et al., 2010)(X. Zheng et al., 2006)(Lu et al., 2006)</td></tr>
</table>

way for the need to develop FDM processed objects using proper materials that can be used for improving the simulation experience and therefore, the overall efficacy in operator-dependent interventions. This achievement would impact on reducing surgery times, less tearing and tissue perforations (less dehiscence) and lower healing complications.

The quality of the printed part depends on the accurate combination of several factors, a proper methodology for DICOM imaging and 3D model processing, passing through the correct combination of printing parameters, until the proper selection of the FDM equipment. All these parameters need to be carefully considered when printing complex medical objects. Besides this, there is a particular caution to be put especially in the materials selection for printing for both model and overhang structure, as well as the 3D mesh optimization, specifications and settings for 3D printer and its accessories used.

The study focused on the numerous benefits of rapid prototyping for creating artificial, flexible heart by means of TPU-based filament, in which a SWOT analysis was performed in order to demonstrate the consistency of this proposal in function of its mechanical properties, manufacturability, biocompatibility and medical feasibility for preoperative planning and further research in the medical field. The study found that TPU – based FDM objects offer a series of strengths and opportunities that, together with relevant literature, verifies our hypothesis of using this polymer to improve the user feedback in obtaining a better perception of geometry of the heart and increasing overall planning value.

6. Future Developments and Work

-Further studies on materials characterization are needed for a proper FDM parameter assessment and medical compatibility.
-Studies on transparent materials would be important for observing fluid flow structure formed inside the heart chamber and also for catheter insertion practice.
-Further studies on proper combination on PLA and TPU with a similar process can be implemented for offering solutions to other tissues for using in medical planning or training.

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