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Foreseeing new multi-material FFF-Additive Manufacturing concepts meeting mimicking requirements with living tissues

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Abstract

The development of additive manufacturing (AM) during the last years has revolutionized not only the industry, but also the medical sector. This alongside the necessity in our society and in medicine to enhance the quality of life of the population has led to the creation of surgical training prototypes. They are used during surgery's planification phase before carrying out an operation. Surgical training is a good method for medical teams to visualize and have an idea of what they can encounter in the interventions.
In order to meet this objective, these prototypes should mimic as much as possible the corresponding living tissues. To achieve that, different parameters are taken into consideration: viscosity, elastic modulus, shore, etc. Nonetheless, it is difficult to achieve that aim, since until now only mono-material prototypes are accessible to hospitals due to the high cost of multi-material prototypes made with industrial proprietary AM equipment.
Therefore, a deep study is done in the different multi-materials concepts within an open – and thus accessible – technology: Fused Filament Fabrication (FFF) 3D printers. Finally, a desktop multi-material AM open concept based on multiple independent extruders for surgical training prototypes is described.

Keywords: Additive manufacturing, 3D printing, multi-material, living tissues, medicine.

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1. Introduction

Additive manufacturing (AM) has existed for over 30 years, but its popularity has mainly grown during the last years. Until nowadays, additive manufacturing has been mainly characterized by mono-material solutions, even though there are some kinds of multi-material AM technologies that can be found (1) . Several different values were achieved for physical parameters (colour, hardness…) from a single basic material printed to obtain a prototype (2). However, most of these machines are expensive industrial-grade equipment (3). Hence, they limit their accessibility to general and new users.

The dawn of a new era based on desktop 3D printers has been the key factor to extend the use of AM to new markets, where benefits can be huge, but costs are a limiting factor. Moreover, new approaches to multi-material AM technologies are in a starting research level and, in fact, research that works on AM are mainly focused on developing new materials to be applied in mono-material AM equipment. Meanwhile, the arrival of FFF (Fused Filament Fabrication) multi-nozzles desktop 3D printers opened a path to make accessible multi-material AM parts.

Therefore, firstly a description and classification of multi-material solutions is presented with concepts related to multi-filament FFF 3D printers. Also, a compilation of the requirements is summarized in order to fulfil a multi-material system addressed to one of the most demanding sectors – surgical planning prototyping – where expensive mono-material or partial multi-material present solutions are a serious limitation to the blooming of AM application. From this starting point, it has been made an exploration of new concepts, by developing and testing experimental machines to obtain prototypes. Then, a report about the limitations and potentials of these concepts has been written, and a final conceptual approach about new multi-material AM equipment has also been detailed, assuming that its materialization should take the AM state of the art one step beyond.

2. Multi-filament FFF 3D printers

FFF uses a filament spool of a thermoplastic material from which the piece is constructed. The printing toolhead heats the material until it fuses and pushes it out by a nozzle which deposits it on the tray to build the piece. In FFF technology there are two different approaches to obtain pieces of various materials and/or colours (see *Fig. 1*):

- Multi-nozzle strategy: to achieve the capacity of deposition of different materials. The 3D printer needs as many extrusion nozzles (extruders) as materials are intended to be used, usually with two or more nozzles that are arranged in a single toolhead, but there are also solutions in which each nozzle is mobilized by a different toolhead. In both cases, it is necessary to associate each filament spool in the specific nozzle/toolhead that is desired to be used. The filaments used to make a piece will not have been mixed prior to their deposition.
- Mixer single-nozzle strategy: it is based on the passage of different filaments, mixed or not, through a single nozzle. In some cases, it is used sequentially passing different filaments through a nozzle, and, in others, different filaments get mixed in a chamber before being extruded through the nozzle instead.

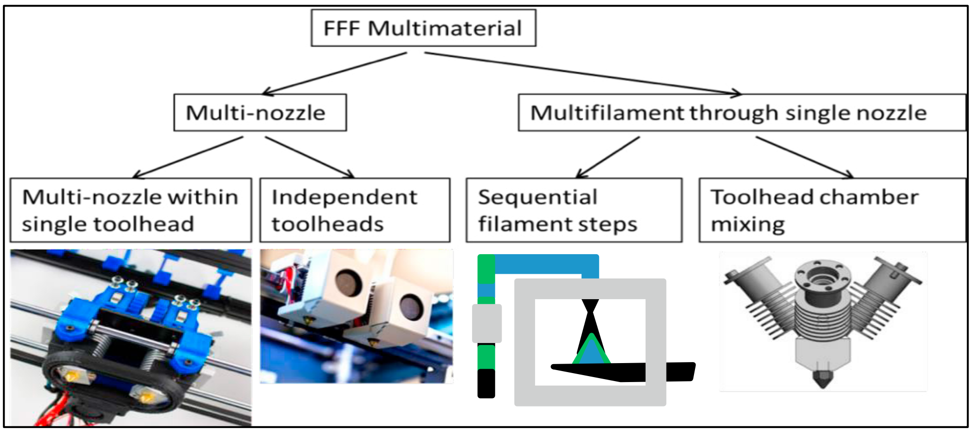

Fig. 1. Classification of multimaterial FFF technologies according to the way of work.

3. Surgical planning prototyping

3.1. Background

Surgical planning is performed using all the information at hand, as for example DICOM images from MRI (Magnetic Resonance Imaging) and CT (Computed Tomography), and this is a common practice amongst the surgeons, since they need to perform complex technical tasks during the operation. Nonetheless, their dedicated training hours are not enough as they should be, having direct consequences into the outcome of the surgeries: more surgery time, complications, etc. On the other hand, execution skills would be more developed if surgeons could spend more time training. Therefore, two types of surgical prototypes are needed: models for general training to be used at Medical Schools, and prototypes reproducing the real case that is going to be operated in the next hours or days. So, these last "real prototypes" must be done digitally (from DICOM to a CAD 3D model, and then to a 3D printer) in order to perform a rehearsal of the operation: that would revolute surgical planning, and that is what some of the authors have experienced and related (4, 5). But the path to progress is limited by two main difficulties: getting access to multi-material AM technologies – real surgery implies different tissues (organs, bones, vessels…) –, and obtaining prototypes made from industrial materials mimicking the different living tissues in order to get the best practicing experience. Thus, defining mimicking requirements and finding available materials to be 3D printed meeting these requirements are two key points to solve, prior to studying how to get multi-material AM technology.

3.2. Requirements for mimicking living tissues

As stated above, mimicking living tissue using different materials is challenging as each human tissue has its own properties. Overall, it has been seen that there are several basic parameters for mimicking living tissues: colour, density, sound speed, hardness, elasticity and shear (and, in soft tissues, viscoelasticity parameters). The fact is that surgeons use different instruments to interact with the body. The surgeons' perception of how these tools interact with living tissue is what is needed to know in order to identify what "mimicking" means. And that can be difficult since engineers need to convert their perceptions into measurable parameters.

High level research related to mechanical characterisation of living tissues can be found (6). But in this research, a great simplification has been made in order to unlock the progress to find first solutions for 3D-printable industrial materials, accepting that further and expanded research is compulsory. So, due to surgeon advice, mechanical parameters are being focused on those related to consistency perception. The most evident parameter is then hardness, and Shore durometers have been used to measure hardness of different tissues/materials. There are different scales, and the relationship among them is not direct. The most relevant scales are D, A, O, OO, and OOO, ranging from more rigid to softer. Within these scales, the range of values goes from 0 to 100, being the highest values of the hardest materials. Soft tissues are commonly identified into Shore OO scale, but also Shore A (more rigid) and Shore OOO (extra soft).

Regarding the elasticity and shear of viscoelastic soft tissues, Dynamic Mechanical Analysis (DMA) is one of the selected measurement tools so as to obtain values (storage modulus and loss modulus) related to tension-compression (Young's modulus E', E") and shear (shear modulus G', G"). On the one hand, regarding viscoelastic behaviour, simplified elastic Young modulus can be obtained by carrying out a tension-compression test. Shear modulus is obtained by a shear test. But commonly the use of ultrasound or MRI is a better source for obtaining these data, with the use of 3D maps of E and G of a body. Similarly to DMA laboratory tests, but directly scanning the body, microdeformations are induced from longitudinal or transversal frequency waves, therefore obtaining values of the sound longitudinal wave velocity (c_L) when crossing a tissue, or the sound shear wave velocity (c_S).

After a wide analysis of previous research, a compilation of estimated values related to some of these parameters is offered. To finally get both values of E and G, a direct relationship must be considered between them as long as Ʋ for soft tissues can be considered with a constant value of 0.5. This has been verified thanks to information obtained from sources and then using *Eq. 1* to introduce both velocities and obtaining Ʋ.

$$\frac{c^2{}_S}{c^2{}_L} = \frac{(1-2\upsilon)}{2(1-\upsilon)} \qquad (Eq.\ 1)$$

Therefore, with only one velocity – and knowing the tissue's density ρ –, it can be obtained E, G or even the bulk modulus K, since it measures how resistant is a non-contained tissue to a compression, similarly to the way a doctor proceeds to palpate a patient, trying to find hard consistent areas and then identifying a tumour. See *Eq. 2*.

$$K = \rho {c^2}_L \quad (Eq.\ 2)$$

Useful relationships between Ʋ (Poisson's ratio), E (Young's modulus), G (shear modulus) and K (bulk modulus) are easily obtained from equations of Mechanics of Materials, so knowing one sound velocity and the density of a tissue, the information of a value to get an idea of its consistency is obtained. See *Eq. 3*, *Eq. 4 and Eq. 5*.

$$G = \rho {c^2}_S \quad (Eq.\ 3)$$

$$E = 2G(1 + Ʋ) \quad (Eq.\ 4)$$

$$K = \frac{E}{3(1-2Ʋ)} \quad (Eq.\ 5)$$

In the end, it is useful data to guide the search of industrial materials that would mimic living tissue in a 3D printed surgical planning prototype. *Table 1* shows some of these values – not including DMA viscoelastic values – for several soft tissues.

Table 1. Characteristics of the different living tissues.

Organ	Density (kg/m^3)	Hardness	Elastic modulus (kPa)	Shear modulus (kPa)	Bulk modulus (MPa)
Lung	394	40 Shore OOO – 10 Shore OO	2.85	0.95	355
Liver	1079	52 Shore OOO – 25 Shore OO	6.55	2.185	2713
Breast adipose tissue	911	54 Shore OOO – 35 Shore OO	9.90	3.3	1890
Kidney	1066	56 Shore OOO – 40 Shore OO	12.66	4.22	2608
Pancreas	1087	58 Shore OOO – 45 Shore OO	14.40	4.8	2752
Breast fiberglandular tissue	1041	56 Shore OO – 10 Shore A	22.50	7.5	2358
Parotid gland	1048	60 Shore OO – 13 Shore A	31.14	10.38	2549
White matter brain	1041	70 Shore OO – 20 Shore A	40.80	13.6	2509
Breast tumor	1050	30 Shore O – 22 Shore A	45	25	2678
Muscle	1090	35 Shore O – 25 Shore A	49.80	16.6	2750

3.3. Materials

Producing the surgical training prototypes that could mimic, i.e. meet the values characterising living tissues, requires the use of different materials: plastic filaments (from rigid to elastomeric, and ultraflexible) and liquid catalyzable materials (silicones, hydrogels and photopolymeric resins).

On the one hand, within the plastic filaments a huge range of materials can be used, being PLA the most commonly used in desktop FFF 3D printers. Known as poly (lactic) acid, it is a thermoplastic made from sugars of vegetable origin. It has an excellent biocompatibility and good behaviour for additive manufacturing purposes. Also, ABS (Acrylonitrile Butadiene Styrene) has a great resistance and rigidity, yet cannot be used for soft tissues due to its properties. Then, looking for softer materials, elastomeric thermoplastic (TPE (thermoplastic elastomer) and TPU (thermoplastic polyurethane)) filaments are a mixture of thermoplastic and elastomeric materials. The first gives them the ability to be used for making filaments for 3D printing, extruded at temperatures above 180ºC. The other provides a soft consistency which is useful so as to approach the low hardness of living tissues. For example, blood vessels and nerves. None of these materials allows climbing down on the Shore hardness scale from the Shore D or A range to the Shore OO or OOO where soft tissues are located. Finally, PCL and PGA are most common to be used in bioprinting in order to support cell proliferation.

On the other hand, within liquid materials, silicones, hydrogels and photopolymeric resins are highlighted. Although photopolymeric resins have been widely used, even the softest silicones do not reach the requirement to mimic the cut of the surgeons in soft living tissues. Regarding the hydrogels, a lot of research has been carried out so as to mimic the living tissues. Hydrogels are hydrophilic polymers chains that form a three-dimensional network by joining together with interlocking points. They have two phases, one solid which is giving support and structure to the materials and then a liquid phase which is normally water. In *Tan et al.* (2018) (7), both poly (vinyl) alcohol (PVA) and Phytagel (PHY) with different concentrations were used to mimic brain, lungs and liver. Although it hasn't being cited, polyurethane (PU) can be also used, at least for rigid transparent prototypes. But its use on AM technologies is considered difficult, and also unhealthy for desktop applications due to toxic VOC.

4. Initial exploration of multi-material 3D printing concepts

With respect to the FFF classification explained in section 2, eight different concepts have been found which are presented for the initial exploration of multi-material 3D printing.

First of all, within the strategy of multi-nozzle with one toolhead there are two concepts: revolver toolhead – on a unique rotating structure, different toolheads are available, and only the one located in the extrusion point will work – and convergent nozzles – means of a single toolhead with individual nozzles simulating a mixture of deposition, making a convergent deposition at a point–.

Secondly, in terms of the mixer single-nozzle strategy, there are three concepts: cross-shaped materials – filaments entering into a single toolhead where they are subdivided and crossed so as to end up coming out by the same nozzle, making the filaments deposit together–, toolhead chamber mixing – means of a toolhead with passive or active mixture of materials by depositing a single filament of one or more materials previously mixed in a mixing chamber– and deposition of catalytic liquids (silicone, polyurethane…) – they come in a toolhead with an active mixture that allows to start the catalysis, solidifying the liquid once it is deposited –.

And last but not least, regarding the independent toolheads strategy, the final concept is to have more than two independent toolheads in order to get some of them with catalytic liquids. There are three different concepts: deposition of silicones – using the silicone directly as a material to be deposited from a silicone that is catalysed by a mixture of components–, deposition of UV liquids (silicones, hydrogels…) – they can be solidified in the same way as the photopolymerizable resins used in 3D printing – and prototypes of low consistency by means of FFF 3D printed moulds – this concept closes the exploration of the use of FFF multi-material technology to obtain low-hardness prototypes suitable for hospital use, and great advances have been made using this indirect AM technology (8).

As it can be seen in *Table 2*, each concept has its own advantages as well as drawbacks. These concepts were developed one by one, and part of them were constructed and tested. *Fig 2* shows a picture related to each of them.

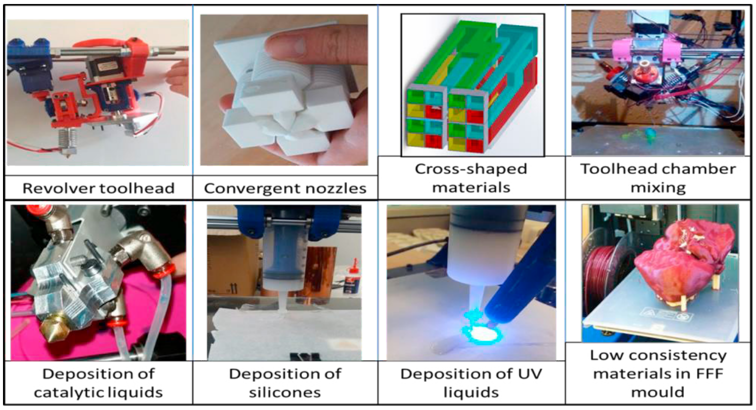

Fig 2. Multi-material 3D printing concepts.

Table 2. Potentials and limitations of the different concepts mentioned in FFF technology.

Concepts	Advantages	Disadvantages
Revolver toolhead	The materialization is simple since the components do not need any previous mixture. Different materials can be used. No transition states are expected between materials.	Big volume of the toolhead can affect the productivity of the 3D printing process. The manufacturing speed of the prototypes will be reduced. The limitation in the number of toolheads, which means limiting the multi-materiality.
Convergent nozzles	There is no complexity in the machinery. There is no mixture of materials at the toolhead, so it is not necessary to purge when changing a combination. Each extruder has its own control.	The quality of the deposition can be compromised since it is not done in a vertical direction. It is conceptually impossible to achieve the deposition in the same geometric point.
Cross-shaped materials	No generation of unwanted material of transition. It is expected a good deposition quality.	There is only one temperature for the whole chamber of the toolhead containing the channels, therefore the range of printable materials is tightened to this temperature: it is not a real multi-material solution.
Toolhead chamber mixing	The toolhead is simpler in comparison with the three above. Assuming that the active mixing option is better than the passive one, the latter could be enough, avoiding the mixture of filaments in the chamber.	It is not a novel technology, yet there is a lot sufficient field of research to carry out. The materials that will pass through a single toolhead must have the same thermal characteristics, thus limiting the expected multi-material prototype.
Deposition of catalytic liquids	There is a lot of technology for the deposition of solidifying liquids from other industrial sectors. It is a chance to create materials that are able to form soft parts for surgical planning prototypes.	The availability and treatment of materials is more complex in comparison with the filaments. Needed fast catalyzation is hardly found. If the liquid is PU, it generates toxic fumes and application times are not fast.
Deposition of silicones	The *pot-life* of silicone is less than of polyurethane, and the possibility of lower values of hardness. There is a lot of research and development to accomplish.	The times of *pot-life* seem to be still too high so as to guarantee the quality expected in the overlay of layers. The 3D printing of liquids has the device's block as a natural enemy.
Deposition of UV liquids	The light application makes the technology to be simple, as reduced catalyzation times should be achieved thus making possible a 3D printing process. Transparency and ability to overcome hospital sterilization processes.	Reduced availability of UV silicones and hydrogels for 3D printing. Liquids should be deposited with other compatible materials which are more rigid or have different filament-based colours.
Low consistency materials in FFF mould	Complex modelling of organs by means of low consistency materials like hydrogels. For example, tumour nodules with surrounding arteries inside a liver. Obtaining prototypes for visualization and testing.	In case of very complex geometries, it is difficult to apply this methodology. Implies more use of labour, and hence, raises the cost. The materials have no choice but to be rigid in order not to be deformed.

5. New multi-material AM equipment

As a result of the previous research about new multi-material FFF concepts shown in section 4, a materialisation of a final experimental concept with four independent toolheads was performed. Classified into the multi-nozzle / independent headtools strategy, it can be defined as an IMEX (Independent Multiple Extruders), as long as there are four independent toolheads. The key of this concept is its ability to allow the integration of both filaments and catalyzable liquids in order to achieve the high degree of multi-materiality that mimicking requirements demand. The main tasks to follow in the process of experimental development were: (1) exploitation of experimental IDEX printer; (2) mechanical solution of the IMEX system; (3) solution for the control of the IMEX system; (4) calibration and testing of the IMEX system and its toolheads.

5.1. Exploitation of experimental IDEX 3D printer

The first step was the transformation of an existing prototype of a 3D printer with two independent toolheads (IDEX system) mounted in a Cartesian structure into an IMEX system. The equipment had remarkable dimensions, so it was useful to do not suffer when it came to having more space to duplicate the toolheads. The base was fixed, so that is the axis of movement XY which rises in Z direction when the piece is being built.

5.2. Mechanical solution of the IMEX system

The idea was not to modify the profile structure, but to incorporate a new X bar, which would move along with the existing one. Enough space was free so that each bar could bear two independent toolheads. This freedom between the two X-bars would allow, for instance, printing two pieces simultaneously in order to make the 3D printer more productive. But finally, for the sake of simplicity, the new X bar was attached to the existing one. Nevertheless, it was necessary to put two new stepper motors in the new X bar so as to have the four motors needed to move each toolhead independently in the X direction.

5.3. Solution for the control of the IMEX system

The main challenge was to scale the control of a growing number of drives. The solution finally applied needs the following: four extruders are controlled, they have in common the movement in Z and Y, but each extruder needs a separate control for the X axis. For that, and assuming that Z axis was performed through another 4 motors, 14 stepper motors were required with their respective controls: 4 for Z control (same signal), 2 for Y control (same signal) , 4 for X control (independent signal) and 4 for extrusion control. So, a total of 10 degrees of freedom from drivers were required. Next, the configuration of the control software was done with the aim of controlling over all degrees of freedom, and especially on the independent movement in the X direction of the four toolheads. Relevant instructions were introduced to assign drivers to each engine, limit temperatures, safety distance, etc. In addition, it was necessary to assign controllers to the four extruders that would send material to the toolheads, as well as a series of parameters that will define the movements of the 3D printers with the 4 independent toolheads. Once the experimental development of this IMEX platform had been completed, the next stage was calibration and testing.

5.4. Calibration and testing of the IMEX system and its toolheads

The first step was to set up an IMEX system and to verify that all toolheads moved and reached positions under the same coordinate system. Then, the verification of the correct work of deposition of the toolheads was done. One important point that needed attention was the LED system of the liquid toolhead, which was responsible for providing light energy in the form of UV light for the curing of liquid to be deposited. For a correct work, it was necessary to protect from the light the whole circuit system. And finally, some tests were carried out so as to validate its good outcome. More testing activities, including the construction of new machinery, focused on obtaining complex surgical planning prototypes from this desktop FFF-based 3D printer, are going to be performed within the next months, due to the activities planned into the QuirofAM project. See *Fig.3*.

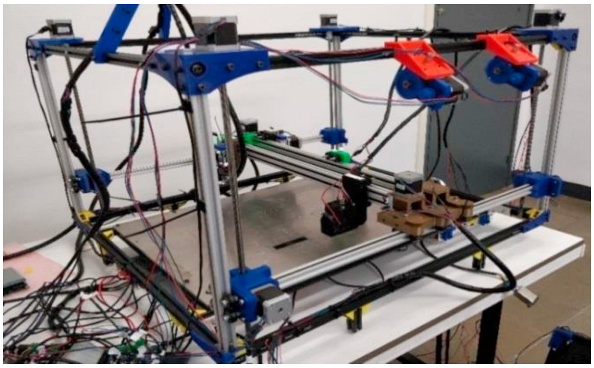

Fig. 3. Experimental IMEX Desktop 3Dprinter prototype.

6. Conclusion and future work

In light of the above, it has been seen that additive manufacturing could solve some problems within the medicine field by 3D printing surgical training prototypes. For example, the surgeon has the opportunity to see and practice beforehand a critical surgery, for example, a resection of the tumour next to relevant anatomical references. Also, it is a good method to be introduced into the practical training in the Medical School for future doctors' education. However, there is still a lot of work to do, especially in terms of achieving a multi-material prototype mimicking the mechanical characteristics of living soft tissues, since until now most of them were done with just one material. Amongst the different concepts mentioned in FFF technology, each one offers both advantages and disadvantages. Finally, new multi-material AM equipment based on IMEX concept was created with four independent toolheads that could meet the main requirement mentioned above: mimicking multi-material living tissues. One of the four toolheads could work with liquids instead of filaments. By this way, it would be possible to integrate softer materials. In future work, the characterization of soft materials to meet the viscoelastic behaviour and interaction with instrumentation should be tested along with identifying different liquids (hydrogels, silicones…).

7. Acknowledgments

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