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PARAMETER OPTIMISATION FOR EFFICIENT 3D PRINTING OF BIOMODELS

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Abstract: *Additive manufacturing, particularly in the medical field, has witnessed remarkable advancements, with 3D printing enabling precise patient-specific biomodels and prosthetic implants. To address the pressing need for parameter optimization in 3D printing, this study investigates the influence of support structure density, support pattern, and material choice on critical factors including printing time, material consumption, and cost. Utilizing three distinct skull biomodels representing diverse anatomies, our research highlights the pivotal role of these parameters in achieving cost-effective and high-quality results. Notably, ABS emerges as the most cost-efficient material, and support pattern selection significantly impacts costs. These findings provide essential insights for informed parameter optimization in medical 3D printing, ensuring efficient and economically viable production of patient-specific biomodels.*

Key words: *biomodels, anatomical accuracy, parameter optimization, material efficiency, cost analysis.*

1. INTRODUCTION

Additive manufacturing (AM) technologies have revolutionized various industries, including healthcare, by providing innovative solutions for manufacturing medical products, such as patient-specific biomodels [1], prosthetic implants [2], surgical tools and even complex medical devices [3]. These technologies enable meticulous studies and planning of medical procedures, thereby increasing the success rates of these interventions.

AM, often referred to as 3D printing, has been instrumental in revolutionizing various industries over the past few decades. In medicine, its impact has been particularly profound, as it has provided a means to create highly accurate, patient-specific biomodels and prosthetic implants [3]. These technological advancements have opened up new horizons for the medical field, allowing surgeons to thoroughly study and simulate complex surgical procedures before they are performed. Such preoperative planning enhances surgical precision and minimizes risks, ultimately leading to improved patient outcomes [4].

In the field of medical 3D printing, the utilization of Material Extrusion (MEX) process, as an umbrella for the technology commonly known as Fused Deposition Modeling, has become increasingly prevalent. MEX process, characterized by its ease of use and cost-effectiveness, has found widespread application in the creation of bone tissue models within the human body and beyond, making it particularly suitable for the fabrication of complex anatomical biomodels used in presurgical planning [5].

However, the successful implementation of 3D printing for medical purposes is not without its challenges. In recent years, the medical field has witnessed a growing demand for patient-specific biomodels, which has led to an increase in the complexity and volume of 3D printing tasks. The need to prepare surgeons adequately for procedures has become vital, especially as the number of surgical hours is reduced, and the training of medical interns becomes more intensive and expensive [6]. Additionally, there is a need to develop functional tissues that can simulate the actual conditions encountered during surgery. This necessity has driven the creation of accurate anatomical models and the development of prostheses using MEX 3D printing techniques.

In this context, the present paper focuses on parameter optimization for efficient 3D printing of biomodels, with a specific focus on three crucial parameters: the density of support structures, the pattern used for printing these support structures, and the choice of filament material. The final goal is to elucidate the intricate relationship between these parameters and their impact on crucial factors such as printing time, material consumption, and cost, all within the context of creating 3D skull biomodels.

Understanding the interplay between these parameters is vital not only for streamlining the 3D printing process, but also for optimizing resource utilization, minimizing costs, and ensuring that surgeons receive high-quality biomodels for preoperative planning. By identifying the ideal combinations of these parameters, this research aims to contribute to the ongoing efforts to improve the efficiency and cost-effectiveness of 3D printing in the medical field, ultimately enhancing the quality of care provided to patients.

2. METHODS AND MATERIALS

The present paper aims to address the pressing issue of parameter optimization for the efficient 3D printing of biomodels, specifically focusing on skull biomodels. The parameters under investigation - support structure density, support structure pattern, and filament material - are selected due to their pivotal roles in the 3D printing process. The choice to focus on the density of support structures and the pattern used for printing these structures arises from their high importance in MEX of complex models like medical biomodels. In MEX technology, support structures can account for a significant portion, often ranging from 50% to 70%, of the entire build. This can lead to substantial material wastage and increased costs, which is a significant concern in resource-constrained healthcare settings. Thus, optimizing these parameters is essential for cost-effectiveness and making 3D printing more accessible for medical applications. Support structure parameters are often overlooked in favor of more commonly discussed parameters like layer height or print speed. However, in the context of medical 3D printing, where anatomical precision is crucial, the quality of overhang surfaces is of paramount importance. Inaccurate or poorly supported overhangs can compromise the fidelity of biomodels and hinder preoperative planning and surgical success. Therefore, investigating support structure density and pattern becomes pivotal in ensuring high-quality biomodels for medical applications, where patient specific medical data must be accurately manufactured.

The paper seeks to elucidate how variations in these parameters influence critical aspects of the printing process, including the time required for printing, the amount of material consumed, and the overall cost associated with an STL file.

Three skull biomodels were selected for a thorough investigation consisting of their simulation in Cura UltiMaker 5.4.0., by varying the material (PLA, ABS and HIPS), the support density (5 %, 10 %, 15 %) and the support pattern (lines, grid, triangles, concentric, zig zag, cross, gyroid). A Creality CR-20 Pro 3D printer was used in all 189 simulations. Printing temperature was adjusted for each material and all other parameters were kept constant throughout the simulations.

To conduct a scientifically relevant study that ensures representativeness, three STL files representing models of human skulls were selected from open medical data bases.

This choice was made with the aim of comprehensively covering the various types of human skulls encountered in nature. To achieve this inclusivity, we specifically opted to examine three distinct skull models: one from an adult male (Fig. 1.), one from an adult female (Fig. 2.), and one from a child (Fig. 3.).

This selection strategy was driven by the desire to encompass the diversity of cranial anatomy that exists among different age groups and genders. By including a male, a female, and a child's skull, the study encompasses the anatomical variations that occur naturally across the human population.

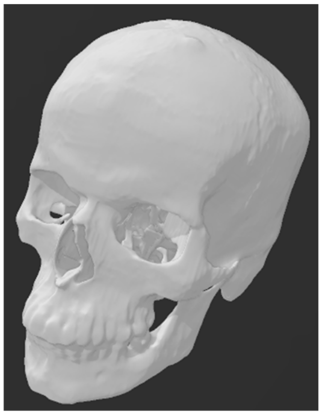

Fig. 1. *.Stl file of a male skull used in simulations [7]

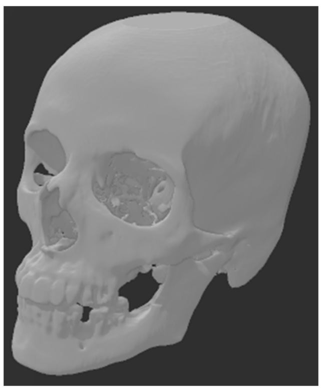

Fig. 2. *.Stl file of a female skull used in simulations [8]

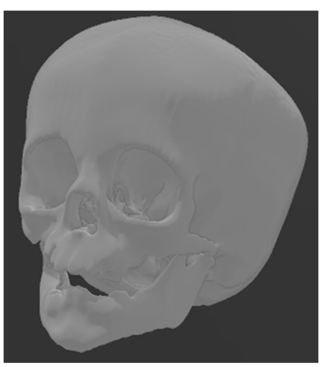

Fig. 3. *.Stl file of a child skull used in simulations [9]

Such diversity ensures that the research findings are not confined to a narrow subset of cranial structures but can be more broadly applicable to a wide range of patients and medical scenarios. Additionally, the utilization of these three distinct skull models aligns with the goal of creating a robust and comprehensive dataset for analysis. The availability of medical databases, such as the one provided by the National Institutes of Health (NIH), facilitates access to these representative skull models, further enhancing the scientific rigor of the current study.

3. RESULTS AND DISCUSSIONS

Three simulations were undertaken for the adult male (Table 1), female and child skulls.

Table 1

Variable 3D printing parameters for MEX of an adult male skull

Material	Support density [%]	Support pattern	Time [d h m s]	Material consumption [g]	Cost [€]
PLA	5	Lines	3d 01h 26m	411	12.32
		Grid	3d 12h 07m	487	14.6
		Triangles	3d 12h 10m	488	14.63
		Concentric	3d 04h 18m	456	13.67
		Zig Zag	3d 05h 32m	464	13.91
		Cross	3d 03h 19m	437	13.10
		Gyroid	3d 01h 20m	443	13.28
	10	Lines	3d 17h 54m	515	15.44
		Grid	4d 03h 52m	587	17.60
		Triangles	4d 03h 43m	587	17.60
		Concentric	3d 17h 22m	554	16.61
		Zig Zag	3d 17h 04m	561	16.82
		Cross	3d 16h 55m	518	15.53
		Gyroid	3d 14h 52m	548	16.43
	15	Lines	4d 10h 12h	618	18.53
		Grid	4d 18h 24m	689	20.66
		Triangles	4d 18h 32m	688	20.63
		Concentric	4d 06h 38m	655	19.64
		Zig Zag	4h 05h 43m	663	19.88
		Cross	4d 05h 20m	585	17.54
		Gyroid	4d 04h 04m	653	19.58
ABS	5	Lines	3d 01h 26m	365	10.94
		Grid	3d 12h 07m	432	12.95
		Triangles	3d 12h 10m	433	12.98
		Concentric	3h 04h 18m	405	12.14
		Zig Zag	3d 05h 32m	411	12.32
		Cross	3d 03h 18m	387	11.60
		Gyroid	3d 01h 20m	398	11.93
	10	Lines	3d 17h 54m	456	13.67
		Grid	4d 03h 52m	521	15.62
		Triangles	4d 03h 44m	521	15.62
		Concentric	3d 17h 23m	492	14.75
		Zig Zag	3d 17h 04m	498	14.93
		Cross	3d 16h 55m	460	13.79
		Gyroid	3d 14h 52m	486	14.57
	15	Lines	4d 10h 12m	548	16.43
		Grid	4d 18h 25m	611	18.32

		Triangles	4h 18h 32m	611	18.32
		Concentric	4d 06h 38m	581	17.42
		Zig Zag	4d 05h 43m	588	17.63
		Cross	4d 05h 20m	519	15.56
		Gyroid	4d 04h 03m	579	17.36
HIPS	5	Lines	3d 06h 00m	411	18.20
		Grid	3d 16h 52m	487	21.56
		Triangles	3d 17h 01m	488	21.61
		Concentric	3d 07h 36m	456	20.19
		Zig Zag	3d 08h 55m	463	20.50
		Cross	3d 06h 43m	436	19.30
		Gyroid	3d 04h 24m	443	19.61
	10	Lines	4d 00h 02m	515	22.80
		Grid	4d 10h 03m	587	25.99
		Triangles	4d 10h 06m	587	25.99
		Concentric	3d 21h 05m	554	24.53
		Zig Zag	3d 20h 31m	561	24.84
		Cross	3d 21h 11m	518	22.94
		Gyroid	3d 18h 06m	548	24.26
	15	Lines	4d 18h 19m	619	27.41
		Grid	5d 01h 50m	689	30.51
		Triangles	5d 02h 01m	688	30.47
		Concentric	4d 10h 57m	655	29.00
		Zig Zag	4d 09h 19m	663	29.36
		Cross	4d 10h 10m	586	25.95
		Gyroid	4d 07h 36m	654	28.96

Full simulation data is available on request. Costs were calculated based on prices available at https://formfutura.com/shop/ for 750g and 1000g material spools of white standard materials: PLA – 29.995 € (1000g), ABS – 29.995 € (1000g), HIPS – 33.216 € (750g).

Table 1 provides a comprehensive overview of the influence of selected 3D printing parameters, namely material (PLA, ABS, HIPS), support structure density, and support pattern, on key aspects such as printing time, material consumption, and cost. This data highlights the critical importance of these parameters in the context of 3D printing, particularly for medical biomodels.

The choice of material has a noticeable impact on all three factors: time, material consumption, and cost. Notably, HIPS consistently exhibits longer printing times compared to PLA and ABS, resulting in increased material consumption and higher costs. ABS on the other hand, generally requires the least amount of time, material, and cost across various support structure configurations. PLA falls in between, offering a compromise between speed and economy.

Support structure density significantly affects all three varying parameters. As the density increases from 5% to 10% and 15%, the printing time shows a consistent upward trend, as expected. This leads to a proportional increase in material consumption and overall cost. For instance, higher support density configurations, especially at 15%, substantially extend the printing time and escalate both material usage and costs across all three materials. The selected support pattern also plays a role in influencing the printing parameters. Different patterns have varying impacts on time, material consumption, and cost. For example, "Lines" support patterns tend to result in shorter printing times, but higher material consumption and costs compared to patterns like "Concentric." Patterns such as "Grid" and "Triangles" generally exhibit moderate values across all parameters, making them more balanced choices.

These findings are consistent with all three simulations.

Costs were analised individually and in correlation to materials for all three skull *.Stl files. The results presented in Fig. 4. illustrate the cost implications of various combinations of 3D printing parameters, specifically focusing on material (HIPS, ABS, PLA), support structure density (5%), and skull biomodel (SK1, SK2, SK3).

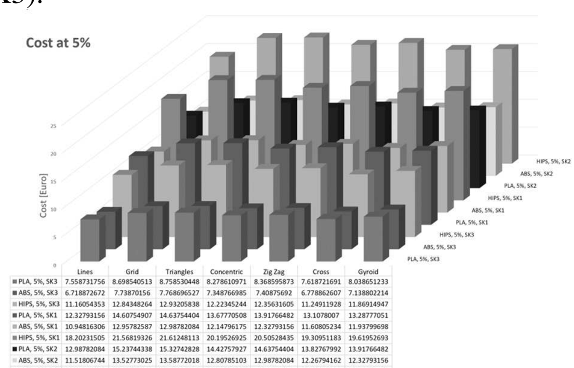

Fig. 4. Cost evolution at 5% Support density across all three skull print jobs

One of the most prominent findings is the substantial influence of material choice on the cost of 3D printing. Among the materials considered, ABS consistently emerges as the most cost-efficient option across all three skull biomodels. It consistently yields the lowest cost values compared to HIPS and PLA.

The choice of support pattern also plays a significant role in cost variation. While the impact varies across materials, it is clear that certain support patterns consistently result in higher costs compared to others. For instance, "Concentric" and "Zig Zag" support patterns tend to yield higher costs, while "Lines" and "Cross" support patterns are generally more cost-effective. This variation emphasizes the importance of selecting the appropriate support pattern based on the desired balance between cost and other factors.

Examining the results more closely reveals that the influence of support patterns can differ depending on the chosen material. For example, while "Lines" is consistently cost-effective across materials, the "Concentric" pattern is more expensive for HIPS and PLA but less expensive for ABS. This highlights the nuanced relationship between material and support pattern choices and their combined impact on cost.

When comparing the three different skull models (SK1, SK2, SK3), it is evident that the choice of model can affect the cost. However, this effect is relatively consistent across materials and support patterns. This suggests that while the specific anatomical features of a given model may influence material usage and printing time, the overall cost differences are driven more by material and support pattern choices. This is a key finding of the study, as it gives the opportunity of streamlining 3D printing of complex surface parts.

Cost results align consistently across all three simulations, for 10% and 15% support structure density. And due to the fact that, in this case, the cost is proportional with the material consumption and print time, the findings can be extrapolated to them as well.

These findings underscore the importance of meticulous parameter selection in 3D printing, especially for medical biomodels. Depending on the specific requirements of a project, such as time constraints, budget considerations, or material availability, researchers and practitioners can tailor their parameter choices accordingly. For instance, when rapid production is essential, PLA with lower support structure density and efficient support patterns like "Lines" may be the preferred option. Conversely, when cost-effectiveness and material conservation are top priorities, ABS with appropriate support structure settings might be more suitable.

These insights are valuable for decision-making in 3D printing projects, allowing for cost-effective and budget-conscious production of medical biomodels and other applications.

4. CONCLUSION

As the medical community increasingly relies on 3D printing for preoperative planning and the creation of patient-specific biomodels and prosthetic implants, the need for parameter optimization becomes paramount. This paper embarks on a comprehensive exploration of how varying support structure density, pattern, and filament material influences key printing parameters within the context of creating 3D skull biomodels. The selection of support structure density and pattern as primary parameters for investigation stems from their significant influence on material usage, overall costs, and the quality of overhang surfaces in 3D printed medical biomodels. These parameters, often underappreciated but essential for achieving precision and patient-specific anatomical models, have the potential to drive progress in the field of medical 3D printing and enhance the quality of patient care.

The insights gained from this research holds the potential to elevate the precision and cost-efficiency of 3D printing in medicine, ultimately benefiting both medical professionals and patients alike.

Beyond the scope of medical biomodels, the implications of this research extend to the broader field of 3D printing. Efficiently managing support structures is crucial not only in healthcare but also in industries like aerospace and architecture, where complex 3D printing tasks are common. Therefore, the insights gleaned from this research may find application and relevance beyond the medical sector, contributing to advancements in 3D printing technology across various domains.

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OPTIMIZAREA PARAMETRILOR PENTRU FABRICAȚIA 3D EFICIENTĂ A BIOMODELELOR

Rezumat: Fabricația aditivă, în special în domeniul medical, a cunoscut dezvoltări remarcabile, permițând imprimarea 3D a pieselor precum biomodele specifice unui pacient sau proteze medicale și implanturi. Pentru a aborda nevoia urgentă de optimizare a parametrilor în imprimarea 3D, această cercetare investighează influența densității structurilor de suport, a modelului de suport și a materialului asupra unor factori critici, precum timpul de imprimare, consumul de material și costul. Utilizând trei biomodele distincte ale unor cranii, care prezintă anatomii diferite, cercetarea evidențiază rolul crucial al acestor parametri în obținerea de rezultate rentabile și de înaltă calitate. În mod deosebit, ABS reiese ca fiind cel mai eficient material din punct de vedere al costurilor, iar selecția modelului de suport influențează semnificativ costurile. Aceste descoperiri oferă insight-uri esențiale pentru optimizarea informată a parametrilor în imprimarea 3D în domeniul medical, asigurând producția eficientă și economic viabilă a biomodelelor specifice pentru pacienți.

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