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An Experimental Study Conducted on Material Properties Used in A FDM Printer for Medical Models

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Abstract

3D Printing /Additive manufacturing holds a promising future in healthcare as it aids in visualizing things and making 3D objects which is very important in different areas of medicine. The concept of one size fits all has failed the quality of care delivered by us in healthcare which demands customised needs for patient care to create 3D printed tissues, make personalized prosthetics, implants and physical models of the human body. The materials used for printing models and other healthcare devices for medical education, patient needs, and prototyping are increasing. The application of different materials for use in healthcare is not studied. New materials are also available for the various applications in healthcare industry. This experimental study was conducted to review the nine distinct 3D printing filament materials like PETG, PA, ABS, PLA, HIPS, PMMA, Ceramic, Carbon Fiber, and (PLA + Metal Composite) with the help of a 3D printed physical model of T-12 thoracic vertebrae using all the abovementioned materials. The evaluation of materials was based on diverse mechanical properties, applications across medical fields, performance metrics, costs, accuracy, and quality. The assessment This study also focuses on comparison of mechanical properties such as tensile strength, compressive strength of the abovementioned materials with human bone. The study also reviews the 3D printing process and explores its utilization in biomedical applications. The Insights about the application of various materials holds a promising future for development of newer materials for healthcare industry.

Keywords: FDM, 3D printing, medical models, Additive manufacturing, Biomedical applications, PLA, ABS

Introduction

Additive manufacturing, commonly known as 3D printing, is a process of creating three-dimensional objects by successively adding material in a layer-by-layer pattern, based on a digital command. This is in contrast with traditional subtractive manufacturing process, which involves cutting the excess material from a solid block. Additive manufacturing allows for complex geometries, customization, and efficient use of material, making it suitable for various applications in industries such as aerospace, automotive, healthcare, and consumer products. Fused Deposition Modelling (FDM) is a process of manufacturing objects using 3D printing. The process of FDM is based on extrusion of a thermoplastic material in a layer-by-layer manner over a build plate to fabricate an object. This process is controlled by different settings, to obtain a good quality print.[1],[2]The raw material is in the form of a spool where a thin strand/filament is wound on a roll. It gets pulled into

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the extruder by a wheel and is then heated until melted in a controlled nozzle. This nozzle carefully puts out the material layer by layer to create the final object over the build plate. [3] The specific shape and details are directed from a Computer-Aided-Design (CAD) program, which guides the movement of the extruder. [4],[5] FDM is a useful process for making objects with complex geometries. [6], [7].

Accurate, customizable, and life-size models are useful healthcare for diagnosis and treatment planning. [8], [9], [10], [11], [12] Various materials can be utilised to create medical models using FDM process in 3D printing. Some of the commonly used materials include- PLA (Polylactic acid, ABS (Acrylonitrile Butadiene styrene), PETG (Polyethylene Terephthalate Glycol) nylon, composite materials etc. Some of the commonly used materials in FDM process of 3D Printing are described below. [13], [14], [15], [16]

1. **PLA (Polylactic Acid):** PLA is a popular thermoplastic material used in FDM process that has an extensive range of medical uses owing to its biodegradable characteristics. PLA is used especially in automotive, electronic fields, and healthcare industry [13]. It is sustainable for the environment because it can break down naturally and is derived from renewable sources like corn or sugarcane.
2. **ABS (Acrylonitrile Butadiene styrene):** ABS filament is another thermoplastic polymer which is a non-biodegradable material. It is a strong and tough plastic used in 3D printing [14]. It doesn't break easily and can handle high temperatures (thermoplastic) during printing. ABS is durable and lighter than PLA 3D printing material. It's also more resistant to impacts. ABS is hygroscopic but the amount of water absorbed depends on duration of environmental exposure.[15]
3. **HIPS (High Impact Polymer):** HIPS is a biodegradable amorphous thermoplastic material. It is commonly used as a dissolvable support for 3D printing [16]. ABS can handle higher temperatures and impacts better than HIPS. Just like PVA, HIPS is good for supporting 3D prints and is safe to handle.
4. **PETG (Polyethylene Terephthalate Glycol)** PETG, a copolymer of PET (polyethylene terephthalate) and glycol, which combines the strengths of both materials, addressing the overheating problems of PET. ABS is toxic when printed, whereas PETG produces no harmful fumes. Printing with PETG is convenient as it does not require ventilation or enclosure. [17] PETG offers greater impact resistance and flexibility than PLA and is easier to print than ABS. [18]
5. **PA (Polyamide):** Nylon (PA) is a synthetic material used in many industries. It is a special kind of plastic that can be turned into Fibers, films, and molded parts. It is commonly used in medical applications like stitches, catheters, and artificial teeth because it works well with the body [19]. Nylon is strong, flexible, and can resist damage from chemicals and corrosion. [20].
6. **Carbon Fiber:** A new type of plastic, combining the properties of both carbon and PLA called Carbon Fiber Reinforced PLA, has been created to make strong and lightweight materials for 3D printing [21]. This material is tough, sticks well together in layers, and does not bend easily. Compared to other 3D printing materials, Carbon Fiber PLA is very strong but not flexible. Its rigidity [22] comes from the added carbon Fiber, thereby providing extra support for structures. However, this also makes it a bit less flexible and somewhat more brittle than regular PLA. Despite these differences, Carbon Fiber PLA has similar properties to standard PLA and offers stable printing without warping [23].
7. **Ceramic:** Ceramic is a brittle material. Manufacturing 3D objects with ceramic materials is technique sensitive than other materials because of the need of high temperatures and special equipment's. Ceramic Fibers are useful for making new lightweight materials that can handle high temperatures [24]. In the past, people tried improving properties of plastics by adding small amounts of different powder or Fiber materials [25], [26], [27], [28]. Ceramic fillers improve the strength or heat resistance of plastics. There use in biology is also prevalent.
8. **PMMA:** PMMA, approved by the FDA, is a synthetic biomaterial commonly used for fabricating dental implants and artificial bone substitutes.[29], [30], [31] PMMA is the main component in acrylic sheets, thereby also called as acrylic filament.
9. **Metal composite:** Metal composite filaments are types of plastic, like PLA, mixed with metal powders such as bronze, copper, and magnetic iron. These filaments give a special and impressive look to 3D printed objects. The finished parts appear and feel like they are entirely made of metal. This type of filament is useful for creating hardware, jewelry, statues, replicas of artifacts, and many other items.

There are more materials that can be used in the process of FDM, however this study confines to the abovementioned materials as they are commonly used. There is a potential to develop newer materials and conduct research to authenticate the usability for biomedical applications.

Methods

This is an experimental study conducted at the Surgical Innovation Laboratory at AIIMS New Delhi. Surgical Innovation lab (SIL) is an ICMR-funded laboratory where

Kaul RP, et al., Fortune J Health Sci 2024
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Reconstructive Healthcare Solutions (RHS) provides consultation, designing, printing and scanning services. No patient was involved in the study. The study was conducted by a team of clinical engineers and designers housed at SIL. Nine different filaments which are commonly used were selected for study. The 3D model of the thoracic vertebrae bone (T12) was segmented from DICOM file (Digital Imaging and Communications in Medicine) of anonymized data using **Simpleware Scan IP** Imaging software. The region of interest which was the T12 was extracted from the pelvis (Figure 5.a). The threshold range for the sample was set at the range of bone segmentation [200-2800] (Figure 1a). Thereafter, the sample was exported to STL (Standard Triangle Language) format. To make a printed model, there are five important steps. First, choose the specific area of the body you want to create. Next, use medical images from a CT (Computed Tomography) or MRI (Magnetic Resonance Imaging) scan to build a 3D design (shown in Figure 1b). Then, optimize the file for physical printing. After that, get the right 3D printer and materials (Figure 4). This file guides the printing process by slicing the digital model into cross sections. These slices are sent to a 3D printer, which builds the object layer by layer, starting from the bottom of the surface. The printer uses FDM filament to create the object. In the end, you get a personalized model that accurately represents the anatomy from the imaging data[32].

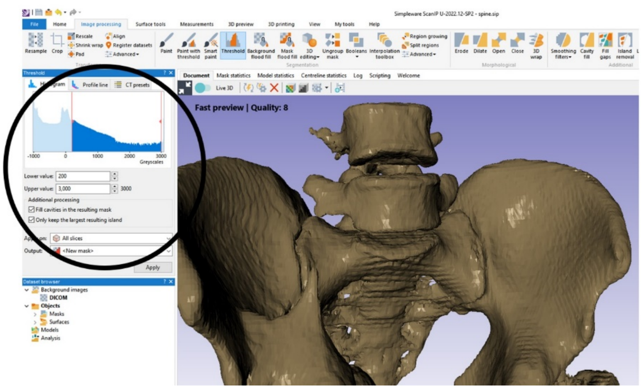

Figure 1a: Thresholding range for bone

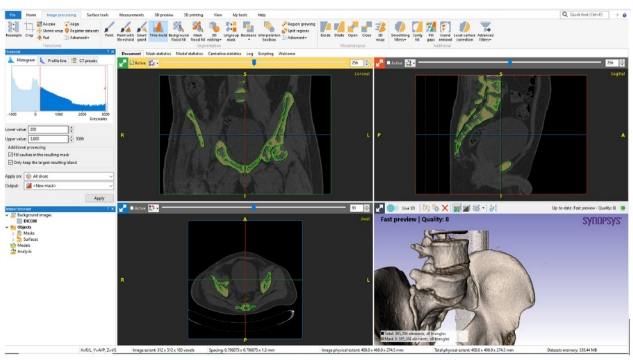

Figure 1b: Segmented T-12 Vertebrae

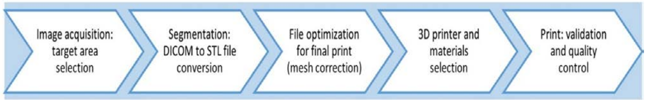

Figure 2: 3D-printing workflow.

Simplify 3D slicing software was used for creating digital models and a Delta WASP 2040 3D FDM printer (Figure 4) to print physical models from nine filaments made of various materials (Figure 7). The temperature settings for each filament varied depending on the manufacturer. Table 1 provides details on the specific temperatures used. Nozzle diameter of 0.4mm and a 0.2 mm layer height was used for additive manufacturing, with a 20% infill. The base dimensions were set at 70x70 mm, as illustrated in Figure 5.b, serving as a reference for dimension accuracy comparison. Table 1 outlines the FDM printer parameters for the different filament materials.

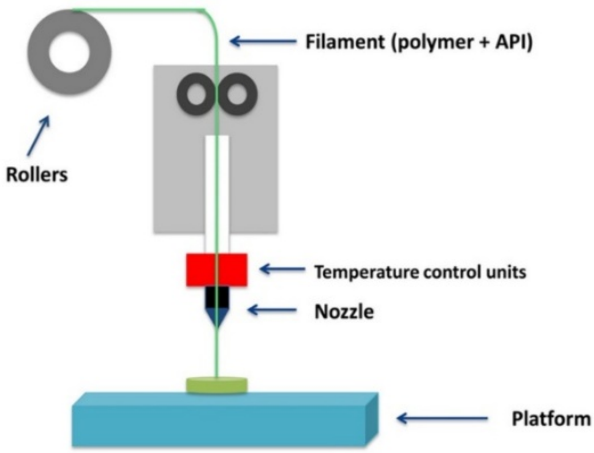

Figure 3: Process of FDM printing

Figure 4: Delta WASP 2040, FDM 3D Printer

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Kaul RP, et al., Fortune J Health Sci 2024
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Fused Deposition Modeling (FDM) is an additive manufacturing technique where an object is created by extruding melted material along a predefined path, layer by layer (Figure 3). The process involves the following steps:

1. A computer program slices a 3D object into hundreds of thin cross-sections.
2. The 3D printer receives the sliced 3D model and starts heating a metal nozzle.
3. A long strand of thermoplastic is fed into the heated nozzle by a gear system.
4. The nozzle, moved horizontally by two belts, deposits the melted filament onto a build platform according to the pattern of a single layer of the sliced model.
5. The build platform lowers by a fraction of a millimeter along with the deposited plastic layer.
6. The nozzle then prints the next layer.

This sequence continues until all layers are deposited, resulting in a completed model. Depending on the object's size and resolution, the process can take from 30 minutes to several days. On average, a print at the MIC takes around 3 hours of machine operating time.

Printer Specifications:

Build volume Ø200 x h 400 mm

Minimum layer height 50 micron

Print speed max (*) 500 mm/s

Travel speed max (*) 800 mm/s

Acceleration (*) 15.000 mm/s2

Bed temperature max 110 C°

Nozzle diameter standard WASP spitfire red extruder with LT cartridge, nozzle 0.4 mm

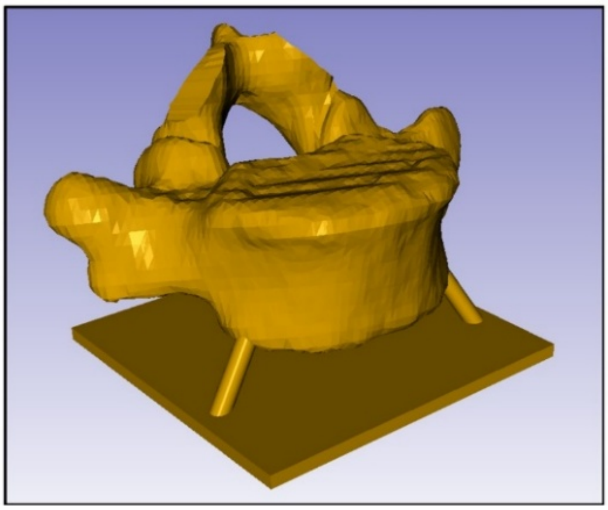

Figure 5a: Segmented 3D model

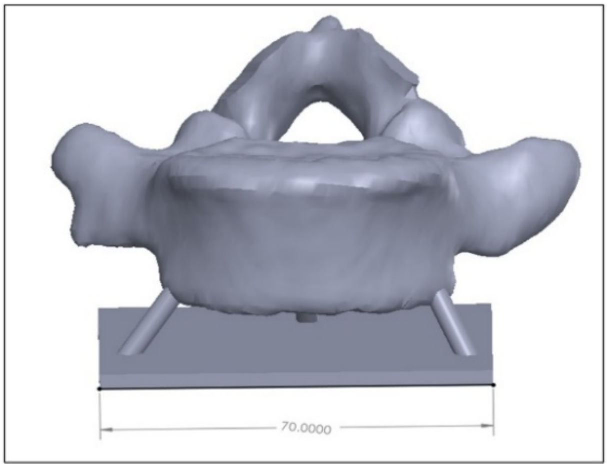

Figure 5b: CAD model Dimension

Printing parameters for this study

The characteristics of all filaments are presented in Table 1. The highest printing temperature was observed for PA (280 °C), while PLA and Metal composite had the lowest temperature (220 °C). A consistent nozzle diameter of 0.4mm was maintained for all nine samples. Printing speed, ranging from 30-100 mm/sec, depends on the printer type and its precision. Slower speeds increase printing time but enhance accuracy. A speed of 70 mm/sec was found to be optimal for balancing time and accuracy. Bed temperature varies among filaments, and the values (Table 1) were obtained from referenced research articles [33], [34], [35], [36], [37], [38], [39]. The layer thickness was 0.2mm, and the density ranged from 1030 kg/m³ to 1520 kg/m³. Figure 6 illustrates a comparison of all filament materials based on Printing Temperature, Bed Temperature, and Density.

Accuracy, quality and printing time

The accuracy of printed parts depends on various factors such as bed temperature, printing temperature, fan speed, initial layer height, shrinkage, printing speed, layer height, and more. All models were printed using the settings in Table 2, based on the default specifications of the material, 3D printer, and slicer software. In Figure 8, the side wall of specimens at different printing temperatures is shown. The optimal printing temperature for PLA filament, providing the best tensile behavior while maintaining dimensional accuracy, was found to be T=220°C, with a bed temperature of 50°C [40]. For ABS, the maximum tensile strength and peak load carrying capacity occurred at a nozzle temperature of 260°C and a bed temperature of 100°C [41], [42] . According to a study on pure HIPS, the recommended parameters for FDM printing are a nozzle temperature of 250°C and a bed temperature of 100°C [43].Similarly, bed temperature and printing temperature of remaining filaments, PETG [44], PA [45], Carbon Fiber [46], Ceramic [47], PMMA [31], Metal composite [48] , as provided in table 1.

Kaul RP, et al., Fortune J Health Sci 2024
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Properties	PLA	ABS	HIPS	PETG	PA	Carbon Fiber	Cerami c	PMMA	Metal Composite
Printing Temperature	220°C	260°C	245°C	250°C	280°C	230°C	250°C	260°C	220°C
Bed Temperature	50°C	100°C	115°C	110°C	90°C	60°C	100°C	110°C	60°C
Density	1240kg /m³	1030kg/ m³	1030 kg/m³	1270 kg/m³	1520 kg/m³	1300 kg/m³	1270 kg/m³	1180 kg/m³	1200 kg/m³

Table 1: Properties of filaments used in 3D printing

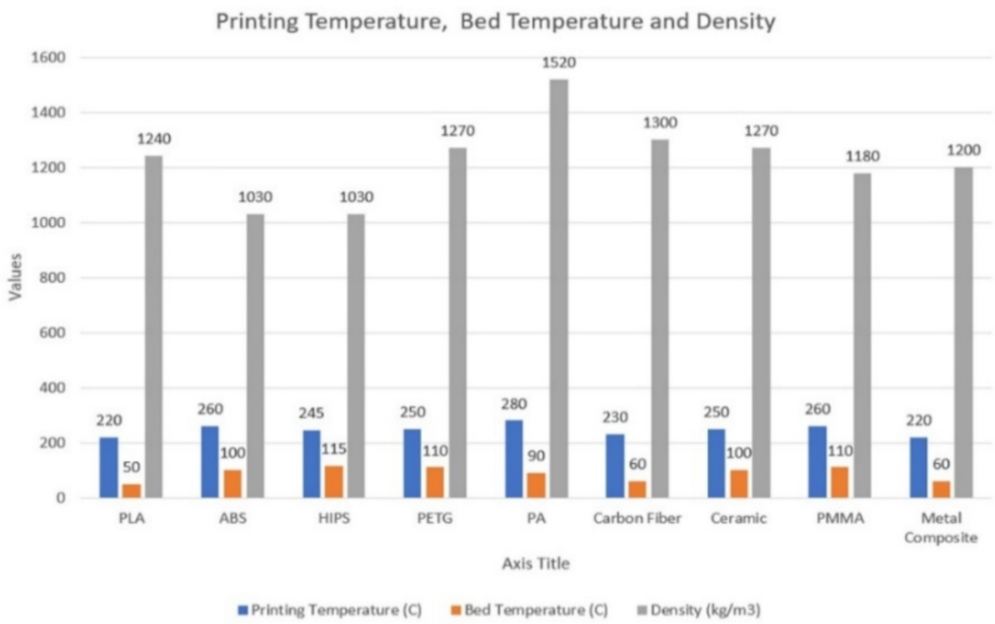

Figure 6: Comparison of the Filaments

Table 2: Parameters used for 3d printing

Parameter	Value
Temperature	Values as Table 1.
Bed Temperature	Values as Table 1
Layer height(mm)	0.2
Material Diameter	1.75
Infill (%)	20
Pattern	Lines
Printing Speed (mm/s)	70
Fan Setting (all layers) %	100
Nozzle Diameter	0.4

Using vernier calipers to measure models shows a strong connection with the corresponding features determined from CT CAD design. To guarantee the precision of sample evaluations, Vernier calipers were used to check dimensions. The dimensions of nine printed (figure 9) samples were compared with the digital dimensions (Figure 5b) obtained from CT/DICOM files. The evaluation included comparing one side of the base square dimensions (70mmx70mm) using Vernier calipers, with a specific focus on the front side dimension. Table 3 displays the percentage errors in dimensions, calculated using the formula:

$$\text{Percentage error} = \frac{(\text{Dimensions of printed Part} - \text{Actual CAD dimensions})}{\text{Dimensions of printed part}} \text{x}100$$

--------------(equation 1)

Figure 7: **3D printed part of Vertebrae bone: Thoracic T12 with all Nine Materials. (**Figure 7a. PLA printed part, Figure 7b. ABS printed part, Figure 7c. HIPS printed part, Figure 7d. PETG printed part, Figure 7e. PA printed part, Figure 7f. PLA+Carbon Fiber printed part, Figure 7g. Ceramic printed part, Figure 7h. PMMA printed part, Figure 7i. PLA+Metal printed part.)

Figure 8: Side wall of specimens at different printing temperatures printed with PLA material. (a) 180°C, (b) 190°C, (c) 220°C

Table 3: Percentage error in dimension

Fig No	Filament Material	Printed part dimension	Percentage error as compared to original CAD dimensions i.e. 20mm
1	PLA	19.73	-1.35 %
2	ABS	20.05	+0.25%
3	HIPS	20.09	+0.45%
4	PETG	20.16	+0.8%
5	PA (Nylon)	19.85	-0.75%
6	Carbon Fiber	19.79	-1.05%
7	Ceramic	19.80	-1.0%
8	PMMA	19.65	-1.75%
9	Metal Composite	20.25	+1.25%

Shrinkage

In 3D printing, shrinkage happens when the final model becomes smaller due to temperature changes during the process. The printer melts the filament to create the 3D model, and as the material cools, it becomes denser and reduces in size. This shrinkage is not noticeable for artistic models like artworks and toys. However, when precision is crucial, such as in phone cases or connecting parts, shrinkage becomes a problem. It occurs in almost every 3D printing process due to temperature variations, and the rate of shrinkage depends on factors like the material used, temperature, printing technology, and curing time for resin prints. Among these factors, the material used is perhaps the most critical in influencing shrinkage. The error percentage in table 4, is because of the shrinkage values of the filament materials. The extent of shrinkage varies from seller to seller. In our case, we purchased the filaments from WOL3D company, and they provided the shrinkage values of the filament, as indicated in Table 4.

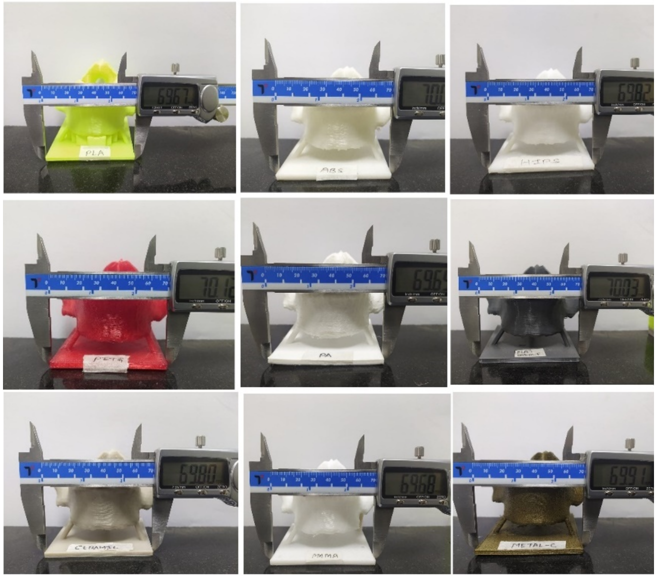

Figure 9: Dimension of printed samples using vernier caliper

Table 4: Shrinkage Values

Sr. No	Material	% shrinkage during cooling
1	PLA	0.3-0.5
2	ABS	0.4-0.7
3	HIPS	0.4-0.6
4	PETG	0.3-0.6
5	PA (Nylon)	0.7-0.8
6	Carbon Fiber	0.1-0.2
7	Ceramic	0.1-0.5
8	PMMA	0.2-0.6
9	Metal Composite	0.1-0.2

Kaul RP, et al., Fortune J Health Sci 2024
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Tensile Strength and Compressive strength

In this study, nine different filament materials underwent both tensile and compressive testing, resulting in a comprehensive evaluation of their mechanical properties. For tensile testing, each filament material was subjected to experimentation, with nine specimens produced and tested individually

Tensile testing

In this research, the nine material specimens were tested using the UTM Instron 25kN UTM (Universal Testing Machine), [49], for both stretching and squeezing assessments. The specimen sizes followed the guidelines set in ASTM D638 [50] (Type 1 flat sheet dog bone) for tensile study and ASTM D695 [51] for compressive study. Ultimate tensile strength refers to the maximum stress a material can handle while being stretched or pulled before breaking. It is determined by conducting a tensile test and recording the engineering stress versus strain. The highest point on the stress–strain graph represents the ultimate tensile strength, measured in stress units. The equivalent point for compression, rather than tension, is called compressive strength.The ultimate tensile strength values range from 9.18 to 0.93 MPa. Table 5, demonstrate the tensile values in MPa.

Table 5: Ultimate Tensile Strength Values for various materials used in this study

No.	Filament Material	Ultimate tensile strength [Mpa]
1	PLA	44.09
2	ABS	35.42
3	HIPS	17.47
4	PETG	39.01
5	PA	9.18
6	Carbon Fiber	38.43
7	Ceramic	34.31
8	PMMA	15.21
9	Metal Composite	20.19

Compressive testing

The compressive test is a fundamental mechanical test used to determine the behavior of materials under a compressive load. This test is critical for assessing the strength, deformation, and failure characteristics of materials when subjected to compressive forces. During a compressive test, a material specimen is subjected to a controlled compressive force until it deforms or fails. The stress (σ) and strain (ε) relationship is recorded, providing insights into the material's mechanical properties. Compressive tests are conducted according to standardized ASTM D695 methods to ensure consistency and accuracy. The recorded data was stored in an Excel file and subsequently analyzed. Table 6. shows the compressive stress value for different materials used in this study.

Table 6: Compressive Stress Values for various materials used in this study

No.	Filament Material	Compressive Stress [MPa]
1	PLA	62.28
2	ABS	57.2
3	HIPS	52.47
4	PETG	50.51
5	PA	70.13
6	Carbon Fiber	57.3
7	Ceramic	58.63
8	PMMA	32.70
9	Metal Composite	52.12

Results and Discussion

This study involved experiments on nine FDM based 3D printing materials, namely PETG, PA, ABS, PLA, HIPS, PMMA, Ceramic, (PLA + Carbon Fiber), and Metal composite. A single human vertebra (Thoracic T12) was printed, after segmentation using imaging software called Synopsys Simpleware ScanIP. The printed bone was then compared to the dimensions of its digital model using a vernier calliper (refer to Figure 9). The T12 thoracic vertebrae sample took approximately 3 hours and 41 minutes to print, as shown in Figure 10. This printing duration remains consistent for all filament materials. The printing time is influenced by factors such as layer height, speed, acceleration, infill percentage, infill pattern, number of raft layers, support pattern, support infill percentage, and printing position.

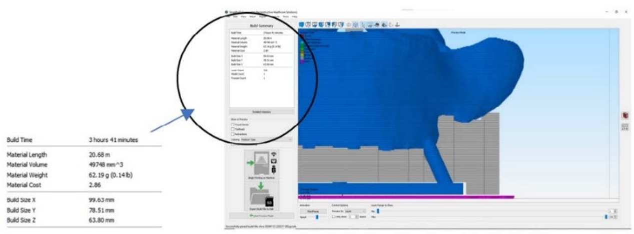

Figure 10: Printing time

Since the printing material and bed temperatures vary for each of the nine materials, it is crucial for the bed to be sticky. To maintain the attachment of model to the bed and prevent failures in printing, ABS was dissolved in ethanol solution

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Kaul RP, et al., Fortune J Health Sci 2024
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which was coated on the bed before printing was initiated. The printing temperature needs to be accurate to ensure the best outcome, as shown in Figure 7. Before starting the printing process, the printer is levelled and then the print bed is coated with ABS ethanol solution. The dimensions of the printed model were measured and compared with the dimensions of the actual digital model using a vernier calliper (Figure 9). Table 7 provides information on the percentage error in dimensions when printed with different materials. The values of percentage error were calculated using Equation 1.

Fig No	Filament Material	Actual CAD dimension (mm)	Printed part dimension (mm)	Percentage error as compared to original CAD dimensions i.e. 20mm
1	PLA	70	69.67	-0.47 %
2	ABS	70	70.04	+0.06%
3	HIPS	70	69.82	-0.26%
4	PETG	70	70.12	+0.17%
5	PA (Nylon)	70	69.65	-0.50%
6	Carbon Fiber	70	70.03	+0.04%
7	Ceramic	70	69.80	-0.29%
8	PMMA	70	69.68	-0.46%
9	Metal Composite	70	69.91	-0.13%

Table 7: Percentage error in dimension with different materials

The negative percentage indicates that the size of the printed model was smaller than its actual dimensions. On the other hand, positive percentages mean the model's overall size increased by the respective percentage. The variations in these values are caused by factors like shrinkage (refer to Table 4), influenced by printing temperature, layer height, and the speed of the cooling fan within the printer. For PLA, the dimension turned out to be 69.67 mm, with a shrinkage of **0.3-0.5%.** Our results show a percentage error of -0.47%, which falls within the expected shrinkage range (0.3-0.5%).

Among the nine materials tested, three (ABS, PETG, and Carbon Fiber) exhibited positive deviations (Figure 11). The analysis highlights that PETG had the maximum error with a positive deviation of +0.17%, while PA(Nylon) had the least error with a negative deviation of -0.50%. Importantly, the overall percentage error in dimensions did not exceed ±0.5%. Figure 7 displays the model's quality effectively by illustrating variations in filament density as outlined in Table 1. The filaments also differ in weight, with PA being the heaviest and ABS+HIPS being the lightest.

The quality of a 3D printed model relies on the printing settings and the characteristics of the materials used. In Figure 7, it is observed that PA material exhibits undesired filament printing because of its flexible nature. While some printed parts have good finishing, PLA with Metal composite provides a finish resembling real metal. However, Metal composite is more prone to breaking as it is more brittle. On the other hand, PA is less brittle, but it may not last for an extended period.

In this research, we used a layer height of 0.2mm. However, if we increase the layer height to 0.3mm (see figure 12.c), the printing time will decrease by about 1 hour, the surface quality of the printed sample will be poor. On the other hand, if we decrease the layer height to 0.1mm (see figure 12.a), the printing time will approximately double to 8 hours compared to the 0.2mm layer height. however. We will achieve more accurate print with higher surface quality. The ultimate tensile strength of the filaments ranged between 9.18 and 38.43 MPa, with Carbon Fiber exhibiting the highest value and Polyamide (PA) the lowest. Graphical representation of the experimental results illustrated the diverse mechanical behaviors of the filaments under tensile stress, highlighting PA's exceptional resistance compared to others

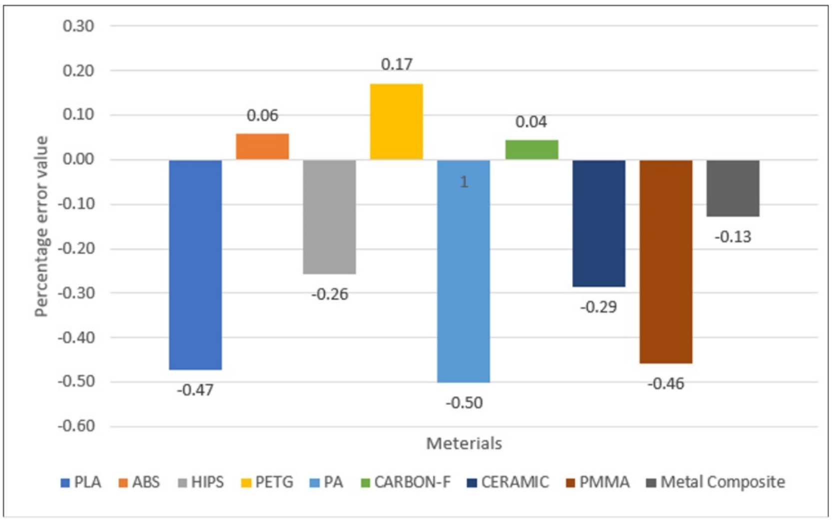

Figure 11: Percentage error

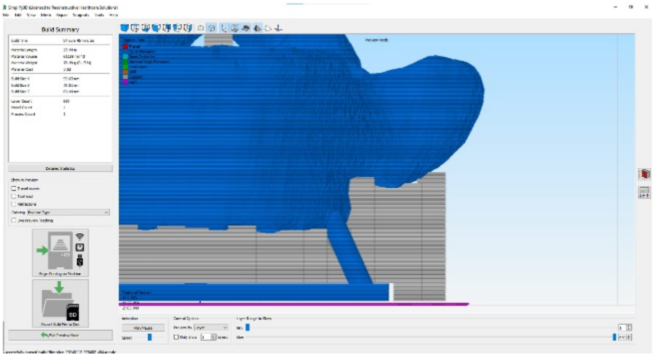

Figure 12a: Layer height of 0.1mm

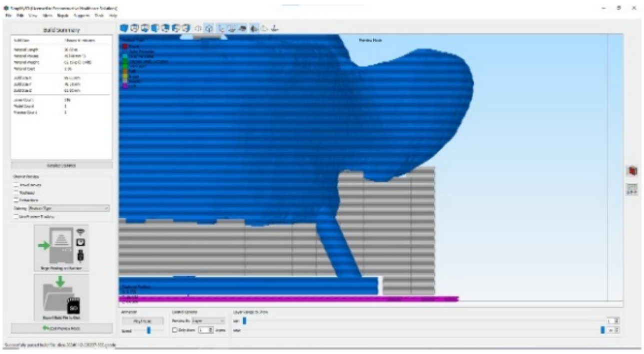

Figure 12b: Layer height of 0.2mm

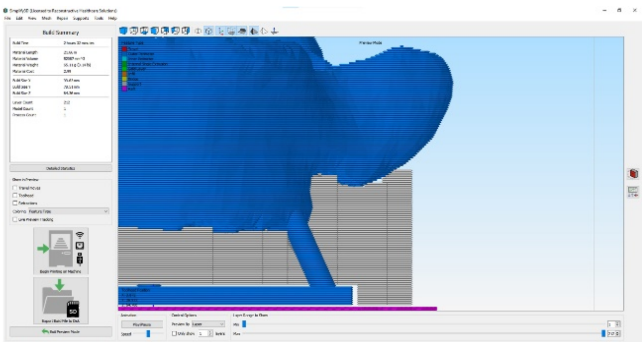

Figure 12c: Layer height of 0.3mm

Similarly, compressive testing involved the same set of filament materials, with nine parts produced and tested for each material. Statistical analysis facilitated data interpretation, revealing a range of compressive stress values between 52.12 and 70.13 MPa. PA demonstrated the highest compressive stress, while PMMA exhibited the lowest. Graphical representation of the results underscored the varying mechanical behaviors of the filaments under compressive stress, emphasizing PA's remarkable resistance compared to others. These findings provide significant insights into the mechanical properties of different filaments, essential for applications in diverse fields such as manufacturing, engineering, and material science. The study's meticulous methodology and comprehensive analysis contribute valuable information for future research and practical applications in various industries.

Conclusion

The article provides a comprehensive overview of commonly used materials using Fused Deposition modelling as a process of additive manufacturing. The research systematically compares nine distinct 3D printing filaments through the printing of T-12 thoracic vertebrae models using each material. Various properties, applications across medical fields, performance metrics, costs, accuracy, and quality are evaluated and compared. Application of all the material is dependent on different properties and applications for healthcare. The results of the study reveal insights into the mechanical properties like tensile strength and compressive strength, which vary significantly among different filament materials. For example, Polyamide (PA) exhibits high tensile strength, while Metal Composite shows low resistance to stretching. Similarly, PA demonstrates the highest compressive stress, indicating its strength under compressive forces. If an application requires flexibility and strength, then PA is preferred. Conversely, if a printed part needs to be rigid and maintain its original shape over an extended period, then ABS is preferred. These characteristics can help in material selection using FDM technology for various applications. Various other properties like dimensional accuracy, shrinkage and quality of printed models can help to access the need of material based on the application. The conclusion drawn from the study emphasizes the importance of selecting appropriate filament materials and optimizing printing parameters to achieve desired outcomes in medical applications of 3D printing. It underscores the potential of 3D printing technology in revolutionizing healthcare by enabling personalized solutions and advancing various medical procedures, including surgery, prosthetics development, and tissue engineering. Overall, the article contributes valuable decision-making concepts when selecting material for different applications in the healthcare industry.

Declarations

1) Ethical Clearance was not required in this study as this did not involve any human or animal subject.
2) Patient consent was not needed in this study as it did not involve human subjects.
3) The authors have no competing interests to influence the results and/or discussion reported in this paper.

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Kaul RP, et al., Fortune J Health Sci 2024
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