Technical note

A filament 3D printing approach for CT-compatible bone tissues replication

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KEYWORDS

PLA—polylactic acid, FDM—Fused Deposition Modelling, CT—Computed Tomography, Bi 2 O 3

ABSTRACT

Purpose: The aim of this study is the development of a methodology for manufacturing 3D printed anthropomorphic structures, which mimic the X-ray properties of the human bone tissue. A mixing approach of two different materials is proposed for the fabrication of a radiologically equivalent hip bone for an anthropomorphic abdominal phantom. The materials employed for the phantom were polylactic acid (PLA) and Stonefil, while a custom-made dual motor filament extrusion setup and a custom-made software associating medical images directly with the 3D printing process were employed.

Methods: A mixing approach of two different materials is proposed for the fabrication of a radiologically equivalent hip bone for an anthropomorphic abdominal phantom. The materials employed for the phantom were polylactic acid (PLA) and Stonefil, while a custom-made dual motor filament extrusion setup and a custom-made software associating medical images directly with the 3D printing process were employed.

Results: Three phantoms representing the hip bone were 3D printed utilizing two filaments under three different printing scenarios. The phantoms are based on a patient’s abdominal CT scan images. Histograms of CT scans of the printed hip bone phantoms were calculated and compared to the original patient’s hip bone histogram, demonstrating that a constant mixing composition of 30% Stonefil and 70% PLA with 0.0375 extrusion rate per voxel (93.75% flow for fulfilling a single voxel) for the cancellous bone, and using 100% Stonefil with 0.04 extrusion rate per voxel (100% flow) for the cortical bone resulted in a realistic anatomy replication of the hip bone. Reproduced HU varied between 700 and 800, which are close to those of the hip bone.

Conclusions: The study demonstrated that it is possible to mix two different filaments in real-time during the printing process to obtain phantoms with realistic and radiographically bone tissue equivalent attenuation. The results will be explored for manufacturing a CT-compatible abdominal phantom.

1. Introduction

The abdominal area is characterized by both bone and soft tissues, and a large amount of free gas, which is: (a) in the lumen of the bowel; (b) in the peritoneal cavity but outside the lumen of the bowel (due to bowel perforation); and (c) in the soft tissues in case of evisceration. The bone, soft tissues and the free gas or air attenuate the X-rays quite differently, which results in difficulties reproducing the attenuation correctly in the 3D printing process, when anthropomorphic abdomen phantoms are produced. The fused deposition modelling (FDM) technique offers a low-cost method for the production of anthropomorphic radiological phantoms. Commercial FDM materials, such as PLA (polylactic acid) and ABS (Acrylonitrile Butadiene Styrene) do not suitably represent the X-ray properties of the human bone tissues. For instance, a high-resolution 3D model of pelvic bones was produced for surgical planning [1], however, bone structures were replicated by ABS [2], a material, which is inappropriate for CT imaging applications. Similarly, PLA was used by Koh et al. [3] to reproduce the bone and intervertebral disks. All these models may be successfully used to educate clinicians on surgical techniques and patient preparation. However, for optimisation of reconstruction algorithms [4], image segmentation [5], testing of novel techniques such as dual-energy CT [6], performing accurate radiation dosimetry [7] and QA applications, the bone structures should be represented by 3D printing materials with X-ray properties close to the X-ray properties of the respective bone tissues.

In the last few years, efforts have been put towards developing new materials by the inclusion of add-ins containing a high Z-value element. Reports showed that ABS filaments were doped with BaSO 4, CaCO 3 [8], Bi 2 O 3 [9], and CaTiO 3 [10] to bone structures, such as pelvis, spine, and cortical bone, with FDM technology. In all these approaches, the bone structures were segmented prior to 3D printing, rather than using clinical CT data to directly print the structures. In addition, all these approaches require knowledge about both materials and necessary equipment to initially produce the new filament. Further, in some cases, the obtained filaments as the one achieved from ABS pellets doped with BaSO 4 resulted in a maximum Hounsfield Unit (HU) of cortical bone in

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the phantom lower than that of the filament [8]. The inclusion of water in the produced bone did not result in air elimination. Other researchers used PLA doped with gravitational stone [11,12], BiO3 [13] and ferromagnetic particles [14,15]. Amongst the preferred filaments for 3D printing pelvis bone is the StoneFil. Giacometti et al. 2021 [7] represented the cortical bone by 100 % infill solid StoneFil filament, while the trabecular bone corresponded to an infill percentage of 65 %. Okkalidis et al. [12] proposed a method to control the filament extrusion rate during the 3D printing process. The maximum HU values obtained with their approach are an average of 523 ± 259 HU, which is limiting the application of the cortical bone. Iron PLA was used by Mille et al. [15] in printing a torso paediatric phantom. However, all bone structures were printed with Iron PLA with an infill density of 50 %.

The methods for controlling an FDM 3D printer for the replication of the soft and bone tissues presented so far in the literature comprise the use of printing patterns and specific infill densities [16,17], or by depositing estimated amounts of melted filaments per voxel volume [12,18,19]. In all the aforementioned cases, a single material has been used for the fabrication of each organ. A basic limitation of this method is the presence of air gaps in the produced phantom since the more or less melted filament is deposited on each predefined voxel according to the voxels HU. Hence, the properties of the produced phantoms derived from the common filament materials are limited concerning applications in X-ray imaging modalities. Recently, Tino et al. [20] presented a bone-equivalent HU phantom, where two different filaments were combined by adjusting the printed layer ratio of the two materials based on a standard number of layers. However, their method can replicate only 13 different mean HU for each bone. Karin et al. [21] investigated the use of a dual-head printer to deposit two different filaments, PLA and StoneFil PLA, at several different in-fill densities, to achieve quasi-simultaneous 3D printing of muscle-, lung- and bone-equivalent media. The approach was applied to print one thoracic and one cranial phantom slab. However, the two extruders were used to print different tissue: soft or bone, rather than combining the two filaments in the fabrication of a bone structure.

A study by Ma et al. [22] with 26 FDM materials showed that pure PLA, PET (polyethylene terephthalate) and PETG (polyethylene terephthalate glycol) filaments have higher HUs compared to the HU of the breast tissues [23]. On the other hand, the polypropylene (PP) showed that the adipose tissue can be represented adequately. The latter material, when combined with PLA in appropriate ratios, is suitable to represent all the HU values of the soft tissues in the abdomen region, while failing in the case of bone structures. Finally, the use of PLA filled with 50 % powdered stone filament can be used to replicate the bone tissues.

The overall objective of the interdisciplinary team at the Medical University of Varna is the development of physical anthropomorphic abdominal phantoms for CT applications. The first step in reaching this goal is the development of a methodology for creating physical bone phantoms from appropriate materials, which can be utilized to replicate accurately the X-ray properties of the bone tissue. This study presents a novel approach employing a custom-made dual motor filament extrusion setup for the fabrication of realistic and radiologically equivalent bone tissues. The proposed approach mixes two commercially available filaments during the printing process.

2. Materials and methods

2.1. 3D printing technique

The Geeetech A30T 3D printer (Shenzhen Getech Technology Co. ltd, Shenzhen, China) with a printing volume of 320 mm × 320 mm × 420 mm was used for the fabrication of an anthropomorphic phantom. The extruder attached to the printer could employ three different filaments during the 3D printing process, while there was a single brass nozzle of 0.6 mm as an exit for the filament. This type of FDM printer can use one filament at a time or combine two or three filaments of the same type such as only PLA. However, two materials of different compositions cannot be used simultaneously resulting in extrusion of the dominant material only. For example, the final extrusion filament when using simultaneously PLA and Stonefil (consisting of 50 % PLA and 50 % powdered stone) will be only PLA. The reason is that the melted PLA in the heating inner chamber of the extruder has a lower viscosity than the melted Stonefil, and thus it blocks the second material. In this study, it was found that it is possible to have an extrusion of both filaments during a 3D printing process by amplifying the input force of the second material enough to overcome the blocking from the dominant material, in this case, the PLA. An extruder commonly uses a single Nema 17 stepper motor of around 0.4 Nm accompanied by a gear train of 3:1 speed ratio, known as ‘Titan’ filament drive gear. Particularly, after a series of experiments, it was found that by using a chain of two stepper motors with holding torque at 0.6 Nm each, it was possible to use two different materials at the same time (Fig. 1).

A custom-made software written in Matlab was used to send commands to the printer for the fabrication of the phantom. The g-code commands were used for the mixing of the two materials were the following:

\[ \text{M165S0PA} \]

\[ \text{M165S1PB} \]

where, M165 denotes the mix of an active extruder (S0, or S1, respectively), P denotes the mixing factors (A and B), which could be from 0.0 up to 1.0. Particularly, M165 is a predefined command on a Marlin firmware, which sets the mixing ratio of the utilized filaments. The custom-made software was used for the association of medical images directly with the 3D printing process and was utilized during the whole study controlling the filament extrusion rate per voxel for the fabrication of the phantoms [12,18,23].

Hence, before the phantom fabrication process, a calibration based on the different mixes and extrusion rates was accomplished by 3D printing a group of cubes and measuring the average HU for each mixing and filament extrusion rate. For the evaluation of the proposed method, three phantoms were produced, which corresponded to three different printing approaches: (a) Phantom 1: the whole entity was printed using a constant extrusion filament rate per voxel providing an average mean HU; (b) Phantom 2: the whole entity was printed by reading each HU value and extruding a calibrated amount of melted filament, i.e. varying the filament extrusion rate per voxel [12,18]; and (c) identification of two entities and printed with two different printing patterns, i.e. linear

Fig. 1. The modification on the 3D printer consists of a dual motor filament extrusion setup.
and perimetric, while a constant extrusion filament rate per voxel was used [23]. The calibration cubes and the phantoms were made by PLA filament (Easyfil, Formfutura, Sweden) with a density of 1.24 g/cm$^3$ and Stonefil filament (Stonefil, Formfutura, Sweden) with a density of 1.70 g/cm$^3$. The printing parameters such as the layer height, printing speed, temperature of the extruder and the temperature of the bed were 0.25 mm, 15 mm/s, 200 °C and 60 °C, respectively.

2.2. Calibration procedure

Initially, the calibration procedure comprised the 3D printing of a group of 11 (eleven) cubes with dimensions of 20 × 20 × 20 mm under different mixes of PLA and Stonefil. The physical unit of the extrusion rate is defined as the distance of the utilized filament per a predefined printed distance. Initially, the extrusion rate ($E$) was defined as constant at 0.04 mm filament per voxel. Each voxel was defined at 0.6 mm × 0.6 mm × 0.25 mm, i.e. it was defined by the size of the nozzle and the layer height. A 0.04 mm filament per voxel can be considered as a 100 % extrusion flow for fulfilling a single voxel predefined by the aforementioned dimensions. Fig. 2 shows 11 (eleven) 3D printed cubes with a step of 10 %, starting with a cube made by 100 % of Stonefil and ending up with a cube made by 100 % of PLA.

Furthermore, three additional cubes under three different extrusion rates per voxel (0.35 mm, 0.30 mm and 0.25 mm) were produced for each mixing and CT scanned. By reducing the amounts of the melted filaments for the same predefined volume, i.e. in this case a voxel, it is possible to lower the HU to be produced. Fig. 3 shows CT scan images of the calibration cubes printed with 10 % PLA and 90 % Stonefil up to 90 % PLA and 10 % Stonefil with 10 % step and under three extrusion rates, 0.035, 0.03 and 0.025, and 87.5 %, 75 %, and 62.5 % flow for fulfilling a single voxel, respectively. From the same figure, it can be noticed that the HU, i.e. the pixel’s intensity, have been decreased in a diagonal direction, as expected.

The printed cubes were CT scanned with a Siemens SOMATOM Definition CT, at 120 kV. The chosen protocol was HEAD; the filter type was FLAT, while the X-ray current was 102 mA. The HU were measured by defining a 100 mm$^2$ region of interest (ROI) on the CT images of the 3D printed cubes. Finally, the use of a 0.6 mm nozzle instead of a 0.4 mm nozzle has aided in preventing any potential clogging of the nozzle and in a better flow during the mixing of both materials. Fig. 4 shows the least squares lines fitted on plots of all the printed cubes under all the extrusion rates against the resulting HU. Table 1 shows the corresponding equations fitting the lines on Fig. 4, and the $R^2$ value for each mixture. The HU for each extrusion rate derived from the measurement during the calibration process can be estimated using the following equation:

$$HU = k*E + d \quad (3)$$

where, $E$ is the extrusion rate, and $k$ and $d$ are the linear parameters estimated from the measurements derived during the calibration process (Table 1).

For the validation of the proposed 3D printing approach, a series of anonymised DICOM images of a patient’s pelvis were utilized with a slice thickness of 3 mm, resolution of 512 × 512 pixels and pixel size of 0.71 mm × 0.71 mm. The study is approved before its beginning by the Ethics Committee of the Medical University - Varna (Protocol# 82/28.03.2019). The right hip bone of the pelvis was chosen, while two entities, the cortical and the cancellous bone, were segmented using a threshold technique as shown in Fig. 5a. Fig. 5b shows a histogram of the CT scan of the patient including only the hip bone (red contour). The objective of this study was to evaluate the proposed approach and replicate the two identified entities providing morphology and texture close to bone tissues.

For the evaluation of the proposed approach, three phantoms under three different scenarios based on the patient’s CT scan images were 3D printed:

(a) Phantom 1: The whole hip bone (red contour (Fig. 5a)) was printed line-by-line with a predefined average mean HU. The chosen mixing composition was 80 % Stonefil and 20 % PLA with a 0.04 mm extrusion rate per voxel resulting in an average value of 700 HU, approximately (Fig. 4).

(b) Phantom 2: The whole hip bone (red contour (Fig. 5a)) was printed line-by-line, controlling the extrusion filament rate voxel-by-voxel [18] and using the least square line fitted for the mixing composition of 50 % Stonefil and 50 % PLA with a maximum value at 500 HU or 0.04 mm extrusion rate, approximately (Fig. 4).

(c) Phantom 3: The cancellous bone (the yellow contour (Fig. 5a)) was printed with a constant mixing composition of 30 % Stonefil and 70 % PLA with 0.0375 extrusion rate per voxel resulting in an average value of 300 HU, approximately. The cortical bone (i.e. the red contour removing the yellow contour (Fig. 5a)) was printed using a concentric/perimetric printing pattern [23] and 100 % Stonefil with a 0.04 mm extrusion rate resulting in an average value of 800 HU.

3. Results

Fig. 6 presents the three produced phantoms, while Fig. 7 shows selected CT scan images from the middle of the printed phantoms obtained with a Siemens SOMATOM Definition CT, at 120 kV and slice thickness of 0.5 mm. Fig. 8 depicts histograms of the selected CT scan images of the produced physical bone phantoms. The histogram in Fig. 7a matches accurately with the conditions applied in the first scenario, since a peak around 700 HU can be noticed for the whole hip bone area (Fig. 8a). Furthermore, the same applies to the second scenario shown in Fig. 8b, where a cut-off at 500 HU is observable. Finally, the histogram in Fig. 8c demonstrates to be visually closer to the histogram of the real hip bone, with a pronounced peak at 300 HU and a smaller one at 800, as expected.
4. Discussion

In this study, we investigated the simultaneously use of two FDM filaments of a different type, i.e. PLA and Stonefil (a filament consisting of 50% PLA and 50% powdered stone) during a 3D printing process for the replication of bone tissues to be used in an anthropomorphic abdomen phantom. A custom-made software was used for the direct association of the images with the 3D printing process depositing melted filament voxel-by-voxel according to the corresponding HU from the medical images. The extruder attached to the printer could employ three different filaments during a 3D printing process, while there was a single nozzle as an exit for the melted filaments (Fig. 1). In this type of FDM printer, when two materials of different compositions are used simultaneously, the result will be an extrusion of the dominant material only. Therefore, when PLA and Stonefil filaments were used simultaneously, the final extrusion result was only PLA. The reason is the lower viscosity of the melted PLA compared to the melted Stonefil in the heating chamber of the extruder. By increasing the input force of the second material enough to overcome the blocking from the dominant material, it was possible to have an extrusion of both filaments during a 3D printing process.

Three phantoms were produced based on three different scenarios.
The results from the first scenario (Fig. 8a) showed that it is possible to produce entities with a homogeneous result instead of using specific infill patterns and infill densities [8,16]. A high degree of correlation was achieved between the various filaments ratios with the corresponding HU resulting in R² values between 0.9877 up to 0.9998 (Table 1). This means that the proposed custom-made dual motor filament extrusion setup demonstrated a high performance in keeping constant the chosen ratios during the whole printing process. The CT scan images of the calibration cubes and phantoms (Fig. 3 and Fig. 7) showed a high uniformity after combining the two filaments, while the retrieved histograms from the three phantoms (Fig. 8) revealed the expected uniformity under the chosen parameters shown in the section ‘Phantom’, (a) to (c) scenarios.

It has been shown that there are two ways to produce the same HU for each entity, either by changing the mixing ratio of the two materials or by using a single material and selecting a constant but lower filament extrusion rate per voxel (Fig. 4). For Phantom 1, the chosen mixing composition was 80 % Stonefil and 20 % PLA with 0.04 mm extrusion rate per voxel resulting in an average value of 700 HU as shown in Fig. 8a. The same mean value at 700 HU could be achieved by using only Stonefil with a constant filament extrusion rate of approximately 0.0375. The results from Phantom 2 demonstrated that it is also possible to print an entity of a phantom by manipulating the filament extrusion rate per voxel based on the correlated HU of the medical images. The whole hip bone was printed line-by-line (Fig. 5), controlling the extrusion filament rate voxel-by-voxel [18] and using the least square line fitted for the mixing composition of 50 % Stonefil and 50 % PLA with a maximum value at 500 HU, approximately (Fig. 4). Although, the replicated morphology was visually close to an actual hip bone (Fig. 7b), it can be noticed that the replicated HUs start from 100 HUs approximately, while much lower HUs can be observed in the original patient histogram (Fig. 5b). This leads to the conclusion that the response of the filament extrusion rate per voxel is low enough to create high concentrations of the Stonefil filament inside the cancellous bone and lower concentrations on the cortical bone making the printed boundaries of the two entities visible after the CT scanning (Fig. 7b). The first reason is that the specific extruder has a wide heating chamber where the two materials are concentrated before the extrusion creating delays on the deposition of the melted materials per voxels. The second reason is that the replicated entity is thin enough to affect the response of the proposed approach. Finally, the results from Phantom 3 showed that it is possible...
The cancellous bone (the yellow contour (Fig. 5 a)) was printed with a constant mixing composition of 30% Stonefil and 70% PLA with 0.0375 mm extrusion rate per voxel resulting in an average value of 300 HU. The cortical bone (i.e. the red contour removing the yellow contour (Fig. 5)) was printed with FDM technology combined with new curable resins. These two different materials and by adjusting the printed layer ratio to a standard volume. However, this method can replicate only 13 different mean HU for each entity, while the method proposed in this work presented a much higher resolution and the ability to print an entity voxel-by-voxel.

Other approaches for producing bone structures with X-ray properties close to those of human bones are 3D-printed in gypsum, a calcium sulfate mineral (CaSO₄·2H₂O), by using binder jet technology and PolyJet 3D printing technology combined with new curable resins. Of these approaches, the most popular is the use of gypsum to create bone structures. For instance, Javan et al. [27] printed osseous structures from gypsum. Further, a pelvis phantom was developed by Niebuh et al. [6], represented by a PMMA cylindrical phantom and bone structures, which were 3D plastic hollow models covered by strong gypsum in order to produce the needed HU numbers. The cortical bone in a paediatric pelvis phantom developed by Ali et al. [28], and the radiodense of bony lumbosacrum [29] were also created by gypsum. However, the approach of utilizing gypsum has limitations concerning the reproducibility of the trabeculae. The other technology, the PolyJet 3D printing, combined with a new ultraviolet curable 3D printing resin with added ZrO₂ nanopowder to print a 3D model of a hand [30]. Similarly, Hatamikia et al. [31] developed an epoxy-based amalgamate for printing the various skeletal structures in the thorax. Results showed that structural densities in the range of 42–705HU could be achieved. A similar approach is undertaken by [32]. A limitation of these approaches is the cost of the printed anthropomorphic phantoms in comparison to those printed with FDM technology.

The developed method will be exploited in the manufacturing of a CT-compatible abdomen phantom to be used in several major applications such as optimizing CT protocols for colorectal cancer screening, development and tuning of 3D reconstruction techniques [33], evaluating precisely the dose delivered in megavoltage X-rays [34] and checking the accuracy of radiotherapy treatment plans [11]. Furthermore, this method is intended to assess the results of the surgical operation and follow-up of operated by robotic surgery patients, by printing phantoms before and after the operation and thus validating the robotic surgery results. The proposed new methodology opens possibilities for manufacturing anthropomorphic phantoms, which can be successfully used for surgical planning, training and simulation of robotic needle-positioning and guidance systems for CT-guided puncture [35]. The abdomen phantoms, built on CT images would allow the creation of physical models, which accurately replicate the patient-specific anatomy. These physical anthropomorphic models are the perfect choice to initially set up and test the new technologies, such as the navigation system of the surgery robot, before conducting costly cadaveric studies and use of expensive virtual reality simulators.
5. Conclusion

This study resulted in a new methodology for manufacturing of 3D bone phantoms, by combining PLA and Stonefil filament with an FDM technology. The new methodology was demonstrated with three phantoms, developed under three different printing setups. From the studies setups, the one incorporating constant mixing composition of 30 % Stonefil and 70 % PLA with 0.0375 extrusion rate per voxel gave the best results in approximating the range of HUs of the cortical bone. The new development will be exploited in the design and manufacturing of an anthropomorphic abdomen phantom to be used in CT and robotic surgery applications.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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