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The 3D Printing in Material Research and Medical Physics Education and Its Accuracy Study

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Abstract

This study aims to construct prototypes using three-dimensional (3D) printing technology as a research apparatus and a physics education instrument, particularly in medical physics education. Two main designs of prototypes have been arranged. Two foam NaCl templates are drawn using computer-aided design (CAD) software. Image processing techniques achieve a 3D model of a thoracic vertebra. All 3D model data are printed using polylactic acid (PLA) filament. The prints of foam NaCl templates are utilized for holding the NaCl powder. The prototype of a human vertebra is used for visualization of the real condition of the human bone anatomy. The results of the prototypes are analyzed to investigate the similarity between the model and the prints. This investigation is done using a Vernier Caliper and CT Scan. The measurement using Caliper shows a higher percentage in likeness than the CT-Scan. All the accuracy study shows they have more than 83% in similarity. It can be concluded that all built prototypes have prominent exactitude and can support the material research using the printed NaCl templates. Hereafter, a bone mock-up's genuine perception can function for further application, such as implant or surgery planning.

Keywords: 3D printing, physics education, medical physics, accuracy study

INTRODUCTION

Three-dimensional printing (3DP) firstly adopted in the 1980s for industrial assembly by laying down layer per layer from the bottom to up using specific material (Savini & Savini 2015). The initial 3DP technology was replicating how the ink-jet printer works. Overtime, 3DP develops and becomes widely used in many fields, such as medicine, automotive, biotechnology, food technology, and educational tools. Scientists, students, teachers, practicians, engineers, and almost all occupations in the world have been affected significantly by 3DP, being a solution to their limitations on understanding objects (Fonda 2013). 3DP also brings ideas and innovation with low-cost effects and short time consumption. For example, in the education field, medical students use the 3DP in their medical physics class and anatomy class to have a replicate model of the human organ. This activity can replace the high expense of cadaver provision (Abou Hashem et al. 2015, p.1). When a physics teacher explains the structure of several lands on earth, such as granular, angular blocky, platy, prismatic, columnar, crumb, the students will be easier to figure out the study by having a 3D model using a 3D printer. In the research field, for instance, research of advanced material technology, scientists use 3DP to construct hierarchical porous silica and polycrystalline quartz for shaping the porous oxide material macroscopically (Putz et al. 2018, p.3). The utilization of 3DP on the research will impact the new form of silica-based material, and it is found saving time rather than other forming techniques.

In several cases, the 3DP implementation contains the mismatches between the 3D models and the expected models. As a tool of education, particularly in medical education or physics education, the lecturer believes that the mismatch between two objects must be very close as much as possible (Lynn et al. 2016, p.1183; Ciobotaru, Combes & Ternacle 2018). A review paper of 3DP technology reveals that each 3D printer has a different solution, for example, 10 μm for the printer based on stereolithography, 80-250 μm for powder bad fusion 3D printer, and 50-200 μm for fused deposition modeling 3D printer (Ngo et al. 2018, p. 172). These resolutions will eventually impact the closeness of the 3DP result and the original data. The closest 3D models with the 3DP results, the more student can sense the real condition of every human organ inside the body. This condition will assist the students in having parameters and considerations of future work, such as surgical training or implant planning. The resemblance of 3D models also gives a comprehensive understanding of biomechanical simulation in medical physics class. In a validation study of 3DP in anatomical models, the researcher found out that the result of 3DP is approximately 5 mm difference in many measurements all along the line in the plantar foot (Choi et al. 2002, p.23; Manmadhachary, Ravi Kumar & Krishnanand 2016; Brouwers et al. 2018, p.1013).

Moreover, to understand whether a 3D printer can replicate the 3D model in several printer types, the study of 3DP results accuracy has been studied beforehand. A validation study of 3DP results based on fused deposition modeling (FDM) 3D printer in human organs of the gallbladder have been conducted and shows that the 3D models and the 3DP result have been almost same with the original data both in size and the volume (Asmaria, Sajuti, and Ain 2020). Another validation study conducts using two types of technology: polyjet system and stereolithography (SLA) to construct a digital orthodontic model (Dietrich et al. 2017). These studies show that the validation study or accuracy about trueness or precision in the 3DP technology keep under investigation to boost the function of 3DP results in specific cases. This study aims to construct prototypes using 3DP technology, a particular 3D printer based on fused filament fabrication, as a research apparatus in material science and a physics education instrument, particularly in medical physics education. Since the accuracy study of 3DP results is also an exciting topic in 3DP, in this research, the accuracy study of several points in the 3D prints will be investigated as a quantitative measurement.

METHODS

The study comprises of three steps methods. Those are design preparation, the 3DP process, and the accuracy study.

Design Preparation

Two templates have been designed. A computer-aided design (CAD) generated a template for foam NaCl. The design of NaCl templates is shown in FIGURE 1 and FIGURE 2. TABLE 1 explains the description of each parameter on the templates, respectively.

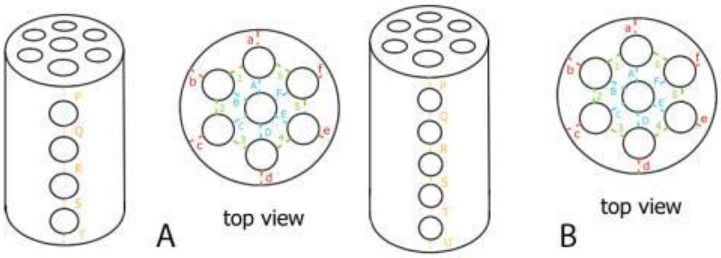

FIGURE 1. NaCl template for material research apparatus. (A) Design 4 holes. (B) Design 5 holes.

TABLE 1. Description of NaCl template design.

Template	Parameters	Distance (mm)
	P=T	1
	Q=R=S	2
A	a=b=c=d=e=f	1.5
	A=B=C=D=E=F	1.5
	1=2=3=4=5=6	1.5
	P=U	1.5
	Q=R=S=T	3
B	a=b=c=d=e=f	1
	A=B=C=D=E=F	1.5
	1=2=3=4=5=6	1.5

The second design is a thoracic vertebra (T12) model. A thoracic vertebra (T12) isolated from an available patient scan under the name the AMNESIX. The AMNESIX is a freely 3D imaging data from the modality of computed tomography scanning (CT scan) provided by OSIRIX. FIGURE 2 presents the loaded data using Radiant Viewer (Medixant Co., Poznan, Poland).

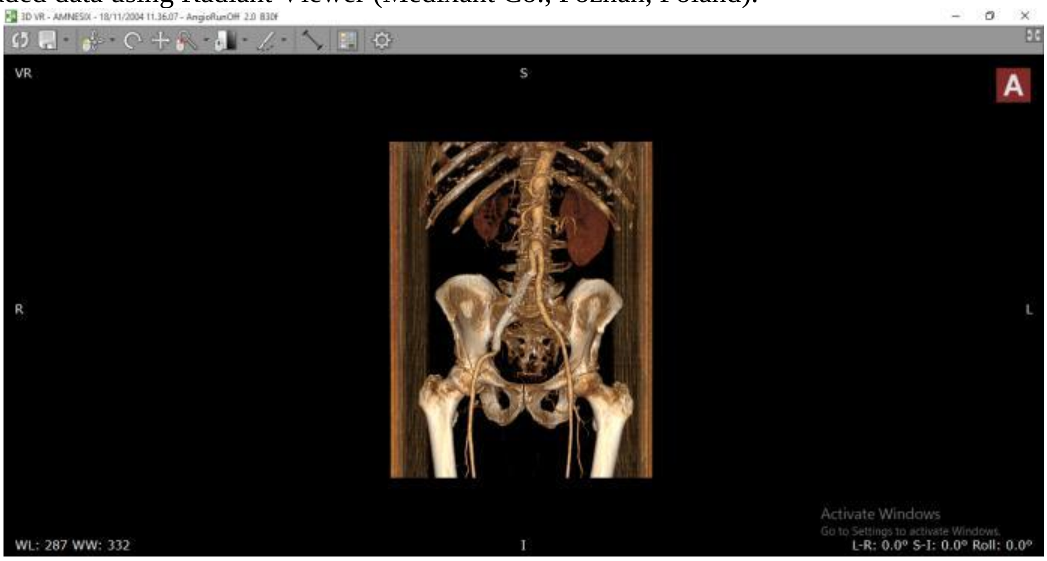

FIGURE 2. The low-extremities imaging data of CT-scan.

The model of a thoracic vertebra is built by two main image processing techniques: segmentation and refinement. The segmentation technique separates the thoracic bone from all body areas. A software of Radiant Viewer using a toolbox of cutting is utilized the segmentation of the bone. The refinement process is essential for reconstructing the model,. The refinement steps are done using 3D Blender (Blender Foundation) and Autodesk Powershape 2020 (Autodesk, Inc., San Rafael, CA). After the segmentation process, the most immediate issue with the segmented STL is noise. This noise appears as free-floating bits detached from the model that rendered printing impossible. Edit mode of vortices and faces was utilized to erase the free-floating objects in the Blender. Three methods are used to tackle the issue: vortex view, line view, and face view.

Vortices was used to remove the small debris, whereas the faces were used to remove the large debris. FIGURE 3 shows the refinement process using vortices, whereas FIGURE 4 demonstrates the refinement process using faces. The top surface of the vertebrae in FIGURE 4 is not closed because of the erasing steps. The software of Autodesk Powershape was utilized to complete the erasing noises and patch up any holes resulting in poorly generated geometry. To do so, the object, that is, the STL, is blown up so that each unconnected surface is its separate object. The main body, namely the vertebra model's surface shape, is then placed into a new layer. Selecting all unnecessary forms will remove the debris and noise in the initial layer. Surfaces that intersect due to model generation done by the DICOM viewers can also be deleted and re-closed with ease, and its tools, though limited to only bodies and not vortices, are robust.

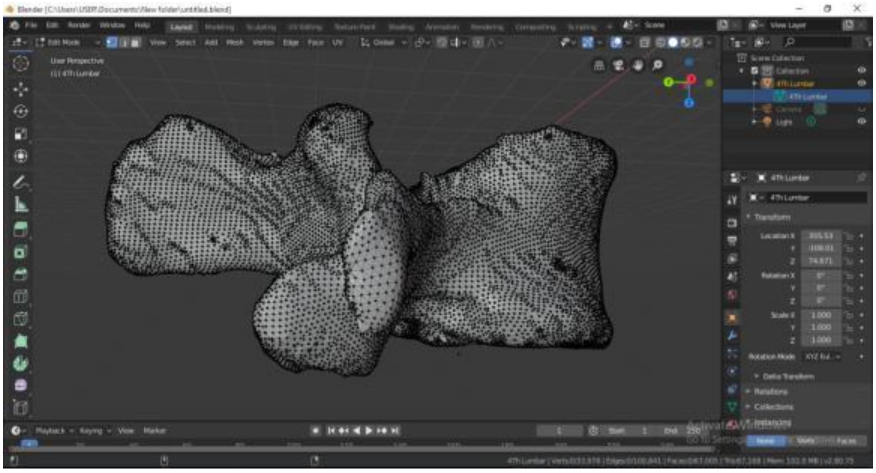

FIGURE 3. Blender's edit mode using vortices.

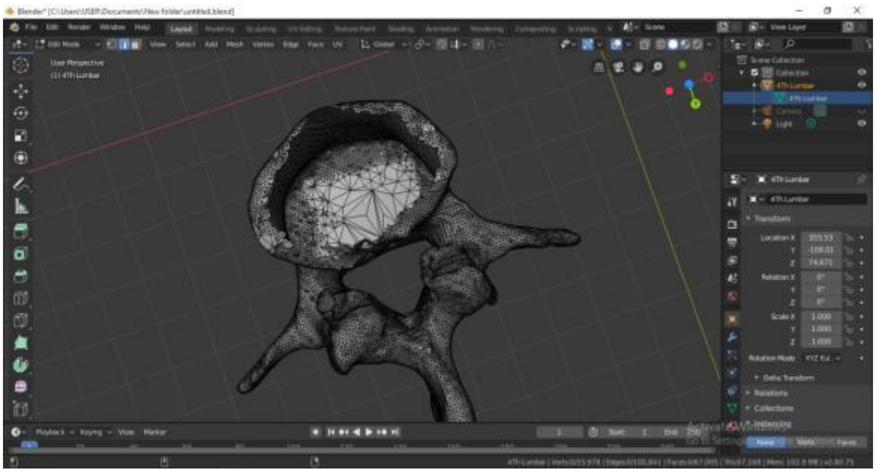

FIGURE 4. Blender's Edit Mode using faces

3D Printing

In this project, the printer used is Flashforge Creator Pro by Zhejiang Flashforge3D Technology Co., LTD, using polylactide acid (PLA) filament with 0.12 mm layer thickness and otherwise standard settings. There are three 3D models are printed, those are two types of NaCl templates and one 3D model vertebrae. FIGURE 5A shows the 3DP process in this study.

Accuracy Study

After printing, all models are scanned (Leybold® X-Ray apparatus with CT module, made by Didactic) and measured using a digital caliper and inbuilt CT scan program measurement tools. The visual model of the thoracic vertebra was also measured in RadiAnt Viewer. In this study, there are two tools to measure NaCl templates' accuracy: an a vernier caliper and a CT-scan. The measurement will be two comparisons between the set size parameter and a vernier caliper measurement result and between the set size parameter and the CT measurement tool results. In vertebrae bone evaluation, there are three utilized tools: an a vernier caliper, a digital caliper based on Radiant Viewer, and CT-Scan. Since the model is based on patient data, there is no specific information on the initial bone's size. For this reason, the bone's size was initially measured using Radiant Viewer. The accuracy study for vertebrae will be two types of comparisons: between radiant viewer results and the vernier caliper and between the radiant viewer results and the CT measurement tool results. FIGURE 5B presents the CT-scan 3D projection on the vertebrae as one of several ways to measure the closeness between the 3D model and the 3D prints.

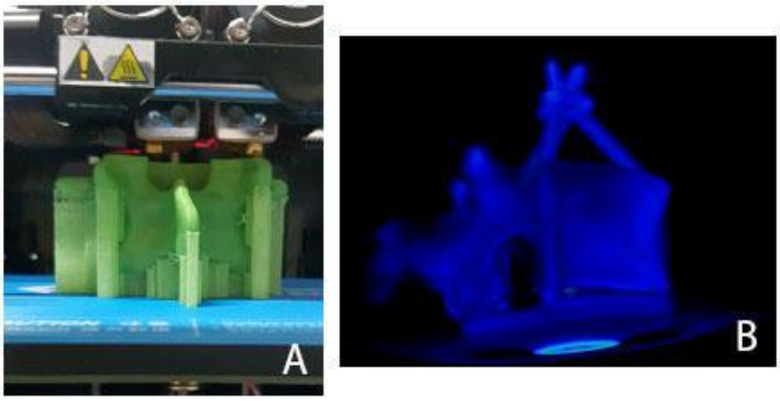

FIGURE 5. (A) 3DP process. (B) CT-Scan projection as a closeness measurement

RESULTS AND DISCUSSION

Constructing a specific design of the 3D model in a research area can be performed CAD software, such as Solidworks (Dassault Systemes, Velizy-Villacoublay, France), Catia (Dassault Systemes, Velizy-Villacoublay, France), Autodesk, and many more. In this study, it was employed two software of CAD: Solidworks and Autodesk Powershape. In composing the NaCl templates, the author considers drawing it in the Solidwork software because it is convenient and user friendly. The NaCl template was organized to meet a porous material foam target with an approximate pore size of 1-3 mm. To create a design based on the real object, people tend to do scanning and then exporting to the raw 3D model. This raw model will be processed using several image processing steps. In this study, the author uses the 3D scanning data from CT-Scan, do segmentation, image processing followed by refinement process using a CAD software of Autodesk Powershape to improve the result from the image processing technique.

Based on the literature, Autodesk Powershape also provides a robust system to support a specific or irregular surface (Milde, Morovič & Blaha 2017; Mikolajczyk et al. 2018, p.160), which is very suitable to refine the surface of vertebrae. FIGURE 6A provides the segmentation results, whereas FIGURE 6B shows the 3D model vertebrae that have been well repaired and ready to be printed.

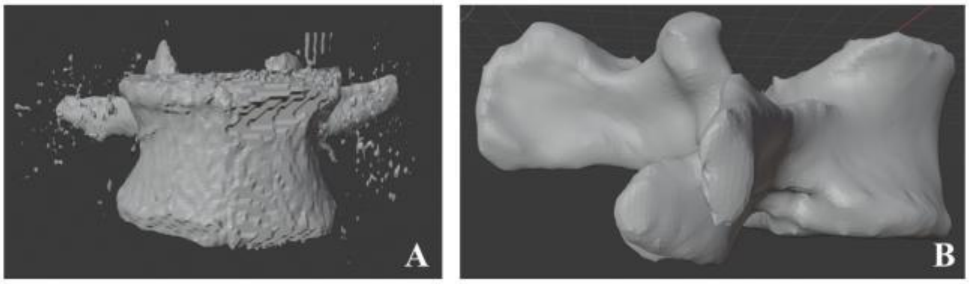

FIGURE 6. (A) Segmentation result. (B) Image refinement process result.

A current literature review of additive manufacturing (AM), a.k.a 3DP technology, reveals how 3DP has been the primary modality of many fields, such as construction, apparel, dentistry, medicine, electronics, automotive, robots, military, oceanography, aerospace, and others (Dizon et al. 2018, p.44). Day by day, the adoption of 3DP technology is overgrowing. From the first beginning, 3D printing limited in the material it can use, namely an acrylic-based material known as photopolymer (Gokhare, Raut and Shinde 2017). Although it has been developed in several types of material such as metal and natural materials, the most popular material used for 3DP is still held by polymer and its derivatives such as PLA and Acrylonitrile Butadiene Styrene (ABS). PLA and ABS have advantages for use in 3DP because of their malleability characteristic and can produce high dimensional accuracy (Popescu, Stan, & Miclea 2014; Dizon et al. 2018, p.44). As we know that FDM is also one of the most popular technology works in the 3DP besides SLA and Selective Laser Sintering (SLS). FDM utilizes a continuous thermoplastic filament of PLA and ABS (Popescu, Stan, & Miclea 2014). FDM and FFF are two technology that exactly similar but altered by different brands (Popescu, Stan, & Miclea 2014). The benefit of using FDM and FFF 3D printers is remarkably less costly than other techniques. This study uses the 3D printer of Flasforge based on FFF and use PLA, whereby this technique has successfully produced the prototypes as desired. In Indonesia, the utilization of 3DP has benefits in several sectors, such as fashion, automotive, anatomical model, clinical training, and scaffold for bone (Gharini et al. 2018; Kuswanto, Iftira & Hapinesa 2018; Rochman & Anwar 2020; Wibowo et al. 2020). However, there is no further question whether their prototypes have good quality, particularly in size and look precision. Albeit several studies overseas has proven that the 3DP result might leave slight differences between the expected 3D model and the 3D prints (Manmadhachary, Kumar & Krishnanand 2016; Dietrich et al. 2017, p.78; Brouwers et al. 2018, p.1013), the research for accuracy of the 3D model is limited (Asmaria et al. 2019; Asmaria, Sajuti and Ain 2020). In fact, as a research apparatus as well as educational tools, 3DP must close to the expected object. Closeness means the shape and the dimension's precision on several points or lines on the objects. This study shows how 3DP technology has been successfully applied for two material research sectors and an educational tool. FIGURE 7 displays the result of 3D printing for all models. TABLE 2 and 3 provide the accuracy measurement on NaCl templates with four and five holes, respectively, based on the parameter in FIGURE 1 and TABLE 1.

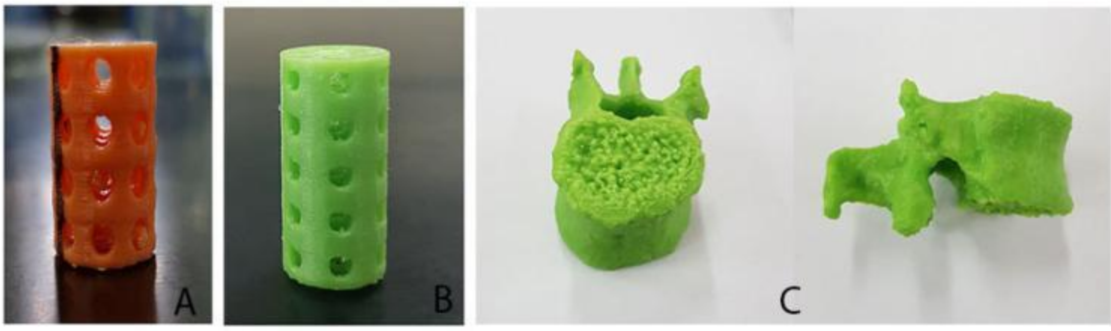

FIGURE 7. 3D prints. (A) NaCl template with 4 holes. (B) NaCl template with 5 holes. (C) Vertebrae bone.

TABLE 2. Accuracy measurement on NaCl template with 4 holes

Design	CAD (mm)	Vernier Caliper (mm)	CT-Scan (mm)	Percentage of Closeness between CAD and Vernier Caliper (%)	Percentage of Closeness between CAD and CT Scan (%)
a	1.5	1.64	1.70	91.46341463	88.2352941
b	1.5	1.63	2.10	92.02453988	71.4285714
c	1.5	1.60	1.60	93.75	93.75
d	1.5	1.57	2.00	95.54140127	75.00
e	1.5	1.54	1.70	97.4025974	88.2352941
f	1.5	1.64	2.10	91.46341463	71.4285714
A	1.5	1.68	1.70	89.28571429	88.2352941
B	1.5	1.65	1.70	90.90909091	88.2352941
C	1.5	1.71	2.00	87.71929825	75.00
D	1.5	1.71	1.80	87.71929825	83.33
E	1.5	1.72	2.00	87.20930233	75.00
F	1.5	1.68	2.00	89.28571429	75.00
P	1	1.08	0.90	92.59259259	90.00
Q	2	2.09	1.80	95.6937799	90.00
R	2	2.07	1.80	96.61835749	90.00
S	2	2.07	1.80	96.61835749	90.00
T	1	1.06	1.00	94.33962264	100.00

(Cont.) TABLE 3. Accuracy measurement on NaCl template with 4 holes

Design	CAD (mm)	Vernier Caliper (mm)	CT-Scan (mm)	Percentage of Closeness between CAD and Vernier Caliper (%)	Percentage of Closeness between CAD and CT Scan (%)
1	**1.5**	**1.69**	**1.30**	**88.75739645**	**86.6666667**
2	**1.5**	**1.65**	**1.10**	**90.90909091**	**73.33**
3	**1.5**	**1.78**	**1.70**	**84.26966292**	**88.2352941**
4	**1.5**	**1.66**	**2.00**	**90.36144578**	**75.00**
5	**1.5**	**1.69**	**1.30**	**88.75739645**	**86.66667**
6	**1.5**	**1.72**	**2.00**	**87.20930233**	**75.00**
		AVERAGE		91.30	83.38

TABLE 4. Accuracy measurement on NaCl template with 5 holes

Design	CAD (mm)	Vernier Caliper (mm)	CT-Scan (mm)	Percentage of Closeness between CAD and Vernier Caliper (%)	Percentage of Closeness between CAD and CT Scan (%)
a	1	0.96	1.10	96	90.90909091
b	1	1.05	1.20	95.23809524	83.33333333
c	1	0.95	1.00	95	100
d	1	0.99	1.10	99	90.90909091
e	1	1.02	0.90	98.03921569	90
f	1	0.99	1.00	99	100
A	1.5	1.56	1.40	96.15384615	93.33333333
B	1.5	1.46	1.50	97.33333333	100
C	1.5	1.49	1.20	99.33333333	80
D	1.5	1.50	1.40	100	93.33333333
E	1.5	1.52	1.50	98.68421053	100
F	1.5	1.56	1.30	96.15384615	86.66666667
P	1.5	1.59	1.60	94.33962264	93.75
Q	3	3.09	2.90	97.08737864	96.66666667
R	3	3.16	3.00	94.93670886	100
S	3	3.19	2.90	94.04388715	96.66666667
T	3	3.09	3.00	97.08737864	100
U	1.5	1.47	1.20	98	80
1	1.5	1.51	1.50	99.33774834	100
2	1.5	1.47	1.50	98	100
3	1.5	1.54	1.40	97.4025974	93.33333333
4	1.5	1.51	1.60	99.33774834	93.75
5	1.5	1.62	1.60	92.59259259	93.75
6	1.5	1.52	1.50	98.68421053	100
		AVERAGE		97.11	94.01

So far, the utilized Leybold CT-Scan only functions as a CT-scanner for 3D mini objects replication (Prša 2018). It turns out that this modality can accommodate as a digital ruler and be functioned to understand the extent of similarity between the 3D model and the 3D prints. FIGURE 8 shows the parameter of the vertebrae prototype for accuracy measurements described in TABLE 4. Based on all accuracy measurements, it concludes that measuring the distance using Vernier caliper is more accurate than overusing the CT-scan digital measure system. The average results on the NaCl template using CT-scan only mean less than 8% or around 0.08 mm. However, the vertebrae prototype's average result has a dramatic difference of 12.25% or roughly 5 mm. Improving the accuracy measurement using CT-scan as the next examination, the practitioner needs to ensure the modality has been calibrated. 3D visualization is proven to enhance student argument in physical learning (Oktasari et al. 2018). This can be further encouraged for 3DP to be applied in other physical learning activities. The utilization of 3DP in the education area can be extra investigated in the future.

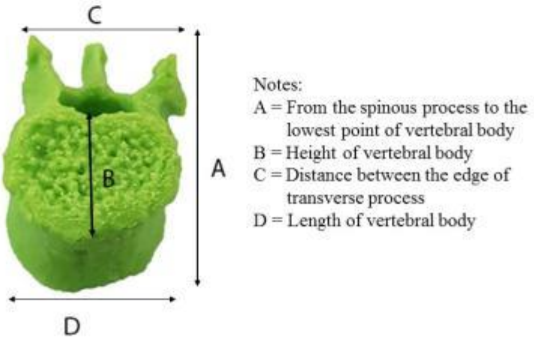

FIGURE 8. Accuracy measurement parameter on vertebrae bone

TABLE 5. Accuracy measurement on vertebrae

Lines	Radiant Viewer (mm)	Vernier Calliper (mm)	CT-Scan (mm)	Percentage of Closeness between Radiant Viewer and Vernier Caliper (%)	Percentage of Closeness between Radiant Viewer and CT-Scan (%)
A	77	77.1	63.8	99.87029831	82.85714286
B	43.4	43.3	38.3	99.76958525	88.24884793
C	31.6	33.3	27.5	94.89489489	87.02531646
D	17.5	16	13.8	91.42857143	78.85714286
AVERAGE				96.50	84.25

CONCLUSION

Two designs of the 3D model have been successfully constructed as an apparatus of 3DP technology in the material research area and a simulation tool in the medical physics education; those are the NaCl templates and the vertebrae bone. The similarity between all 3D models and the 3D prints has been evaluated using two vernier caliper and CT-Scan measurements. Since the similarity between 3DP results and the original data has a high percentage of accuracy study ranging from 83% to 97%, 3DP technology can be further applied as a new alternative in teaching aids.

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