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3D Printing an Open-Source, Cost-Effective Didactic Human Skull Model: A Technical Report

Key words

anatomy

biology

anatomical model

fused deposition modeling

FDM

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Abstract

This is a technical report about the benefits of 3D printing didactic models from open-source files. It covers the costs of creating a 3D-printed model, including the cost of filament and magnets and the time associated with physically constructing the model. 3D printing an anatomical skull model that is freely available online is just five percent of the cost of a similar model and provides additional learning opportunities over purchasing a model. The endeavor to build a 3D-printed didactic model also uncovered the potential for cross-collaboration between educational departments.

3D Printing an Open-Source, Cost-Effective Didactic Human Skull Model

Classroom models in a laboratory setting are expected when studying Anatomy and Physiology. However, there are generally only enough models for every two to four students to utilize. While this may be sufficient, what if it could be improved? Using fused deposition modeling (FDM) 3D printing, anatomical models can be produced for a fraction of the cost of comparable (and sometimes inferior) models purchased through a vendor. 3D printed models can be used by students in the laboratory, improving the ratio of models to students. Also, the students participating in work-study programs can gain a deeper understanding of these anatomical models by engaging with them through slicing software. Slicing software is used to turn a 3D model into a language called G-code that is understood by the 3D printer. Slicing software allows one to manipulate the model and orient it with the build plate of the 3D printer. This allows users to view all the sides of the model in 3D, akin to having a physical model available (Bambu Labs, 2024).

Anatomy units of study, such as the skeletal system, allow many opportunities to use a 3D-printed model for learning. The bones of the skull and their features are particularly challenging to learn because only some of the bones are readily visible when viewing the skull anteriorly. An osteopathic didactic skull is an anatomical model of a skull in which individual bones can be manually disarticulated and rearticulated to adjacent bones, like a puzzle. Though these models can be purchased, they are costly, as seen in Table 1. The least expensive option cannot hold the separate bones together. The medium-priced and most comparable model holds the bones together magnetically. Lastly, the most expensive option is held together by pegs.

3D printing an osteopathic didactic skull using open-source, royalty-free G-code is an attractive means of reducing educational materials costs. Searching through the many online repositories of 3D printed files, known as stereolithography files (.stl files), yielded plentiful results for 'anatomical skull.' One, however, stood out as a fantastic learning tool and became a test case for learning Anatomy and Physiology through 3D printing. The skull was

TABLE 1

Vendor Costs for Similar Didactic Models

Manufacturer Name	**Item Name**	**Price**	**Vendor URL**
Axis Scientific	Life-Size 22-Part Disarticulated Human Skull Anatomy Model	$328.00	https://anatomywarehouse.com
Rudiger Anatomie	Premium 18-Part Didactic Human Skull	$645.00	https://anatomywarehouse.com
SOMSO	18-Pieces Model of the Skull, Didactic Colored	$920.00	https://gtsimulators.com

FIGURE 1
3D Printed 18-piece Anatomical Skull on Stand, Anterior View

designed by 'DaveMakesStuff' using models derived from 'The Database for Life Science' — A Japanese Life Sciences Database of 3D models of human body parts (DaveMakesStuff, 2021). Each .stl file represents a separate bone, and the complete skull model was printed using a Bambu Labs P1P. The final assembled model is shown in Figure 1. The skull is 18 separate pieces that articulate using magnets. The pieces were fitted with magnets after printing.

The project of building an anatomical skull began with choosing a material. For the type of material, a polylactic acid (PLA) filament in bone white was used to imitate a typical bone model. The material cost for generic PLA is about $18.99 per roll (a roll is 1 kg).

Though this model was printed in one color, if desired, each part can be printed in a separate color. Twelve unique colors are needed for the number of separate bones (and bone pairs) – the nasal and lacrimal bones are fused to the maxilla in this model but can be painted in post-processing. Twelve unique colors may limit the material options to PLA. PLA is ideal for someone new to 3D printing, as other materials like ABS tend to warp easily (All3DP, 2023) or PETG, which tends to string (Rhodes & Hullette, 2024). These parts do not require much infill (a filler pattern that makes up the inside of a 3D print and adds strength) because the model is magnetically articulated rather than mechanically. This reduces the cost of filament for each skull bone. Additionally, if a part breaks, a replacement can be made for a fraction of the cost of a new model, whether replacing a missing magnet or reprinting a broken 3D print.

Table 2 lists the weight of each skull bone by name. The total weight for each part includes the support material used during printing. Depending on the orientation of the print, the model may need support material for overhangs. Overhangs occur when material needs to be printed at a level that does not have a preceding level to provide support. The total weight for the anatomical skull project is a little over 500 grams (about 1.1 lb.), which equates to approximately $10.00 worth of generic PLA filament.

Table 2 includes the print time in minutes for each part and the total time in hours, which is about 40 hours (about one and a half days) of 3D printing time. This would require someone to remove parts between prints; however, this can be streamlined, especially if printing multiple parts in the same color simultaneously. This allows the machine to run for hours uninterrupted. When working on a project with longer print times, utilizing a camera and Artificial Intelligence (AI) monitoring software is helpful so you do not have to be physically present during the entire

TABLE 2

Anatomical Skull Model Parts Printing Weights and Times

Bone Name	**Weight (in grams)**	**Filament Cost**	**Print Time (in minutes)**
Ethmoid	15.29	$0.29	93.0
Frontal	82.71	$1.57	357.0
Inferior Nasal Conchae	3.09	$0.06	28.5
Mandible	32.43	$0.62	156.0
Maxilla Left	19.64	$0.37	106.0
Maxilla Right	19.36	$0.37	107.0
Occipital	65.12	$1.24	302.0
Palatine Bones	9.52	$0.18	68.0
Parietal Left	81.90	$1.56	323.0
Parietal Right	78.42	$1.49	308.0
Sphenoid	37.28	$0.71	208.0
Temporal Bones	50.89	$0.97	258.0
Vomer	5.43	$0.10	45.0
Zygomatic	9.62	$0.18	62.0
Total	**510.70**	**$9.70**	**2421.5**
	Total Print Time (in hours)		**40.4**

print time. The 3D printer used for this project was equipped with a camera but not AI monitoring software. AI monitoring software stops the 3D printer when it detects an anomaly in the extruded filament, which is beneficial in preventing wastage.

Table 3 shows the number and type of magnets needed for each piece and the total build. The total number of magnets

TABLE 3

Anatomical Skull Model Magnet Requirements

Bone Name	# ¼" Magnets	# ⅛" Magnets	Magnet Cost
Ethmoid	0	7	$1.33
Frontal	6	4	$2.26
Inferior Nasal Conchae	0	2	$0.38
Mandible	2	0	$0.50
Maxilla Left	0	5	$0.95
Maxilla Right	0	5	$0.95
Occipital	7	2	$2.13
Palatine Bones	0	10	$1.90
Parietal Left	7	1	$1.94
Parietal Right	7	1	$1.94
Sphenoid	3	13	$3.22
Temporal Bones	6	10	$3.40
Vomer	0	2	$0.38
Zygomatic	0	6	$1.14
Total	**38**	**68**	**$22.42**

needed is 38 ¼" x ⅛" magnets and 68 ⅛" x 1⁄16" cylindrical magnets. Magnets come in varying strengths. Initially, each 3D-printed skull bone was fitted with N50 magnets; however, the model required delicate handling to prevent disassembly. Replacing the N50 magnets with N52 magnets proved sufficient to maintain model stability when fully assembled. It is advised to purchase an N52 magnet rather than an N50 magnet for easier assembly of the model. The magnets used to build the anatomical skull model cost \$0.26 per ¼" x ⅛" cylindrical N52 magnet and \$0.19 per ⅛" x 1/16" cylindrical N52 magnet. The total cost of magnets for the model is \$22.04 (purchased from brands: Applied Magnetics for ¼" x ⅛" magnets and Boom Boom for ⅛" x 1/16" magnets on Amazon.com).

Cyanoacrylate glue (CA glue) is used to fasten the magnets to the facets of the 3D-printed model. CA glue is a strong super glue that uses an accelerant to speed up the bonding time between workpieces. However, this model was assembled without using the accelerant. Approximately two dozen skull models can be assembled using a single 2-ounce bottle of Starbond Medium CA glue, so the average cost per model is \$0.58.

This brings the total cost of goods to \$32.70, which is just 5% of the cost of the most comparable, mid-priced model, according to Table 1. However, there will undoubtedly be wastage in a production environment, as was the case with this project. In a perfect world, every print goes precisely as it should, but even an efficient machine may have a mishap or two during the printing process. Supports that do not make a connection with their overhangs may lead to features printing in midair, as was the case with the occipital bone. Magnets may also unintentionally be stuck together using CA glue or incorrectly oriented when set in the CA glue. Accounting for a filament wastage of \$1.24 for the occipital bone and \$2.08 of wastage for filament and magnets of the palatine bones due to incorrect magnet positioning, the total wastage was \$3.32 (or approximately 10%), bringing the total cost of goods to \$36.02.

While filament and supply costs are readily apparent when building a 3D model, labor must also be considered. Labor is spent manipulating the 3D model to print correctly and installing magnets in the printed pieces. This print is complex because the files are provided in anatomical orientation and need to be

FIGURE 2
Disassembled Anatomical Skull Model, Anterior View

orientated in a way that touches the build plate of the 3D printer, creates a smooth exterior surface, and hides the rough-textured supported areas (overhangs). These rough areas can be smoothed out, but that adds extra time to the project. The ideal scenario is that the part is printed in a manner that reduces overhangs to a minimum. Thankfully, advanced slicing software has this ability built in to orient the part to reduce the amount of overhanging material. Placing the magnets takes a significant amount of time to ensure correct polarity and order of assembly; however, this can be streamlined by making an assembly guide. Figure 2 shows the model partially disassembled to show the location of some of the magnets within the print. Four hours of labor allows for the

FIGURE 3

Disassembled Anatomical Skull Model

post-processing (removing support material) of the 3D printed part and ensuring magnet spaces are appropriately sized by removing excess material with a deburring tool or hobby knife and

fitting the magnet spaces with magnets in the correct orientation. Figure 3 shows the entire model disassembled.

3D printing an anatomical model for educational use is simple and can be completed by a student participating in a work-study program or laboratory technician. 3D printing has applications outside the skull — anatomically correct models of the scapula, pelvic girdle, and countless other bones can be printed for a fraction of the cost of a comparable model from a vendor. 3D printing additional anatomical models for students is an economical method of increasing accessibility without compromising quality.

Future applications include creating replacement parts for other anatomical models and designing new models to highlight unique views of structures of body systems. Additionally, there are opportunities to 3D print unique models of pathologies, like the models found on the NIH 3D print exchange. This application of 3D printing is just the beginning of the educational application and could open the door for cross-disciplinary collaboration.

Acknowledgments

Thank you to Dr. Schrader for your guidance and enthusiasm for this project and to my wife, Alissa, for her support during this project.

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