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Qualitative Evaluation of the Use of 3D-Printed Anatomical Parts for Studying Neuroanatomy

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Abstract

This study investigates the use of 3D-printed models as an educational tool in neuroanatomy, comparing their effectiveness to traditional cadaveric specimens. It addresses the increasing medico-legal and ethical concerns surrounding cadaver procurement, the high costs associated with it, and the limitations in availability. The study aims to create a collection of 3D-printed human brain models for teaching and research, assessing their accuracy and educational impact through questionnaires administered to medical students. The research employs a descriptive, prospective, quantitative observational study design with convenience sampling. Data collection was performed at São Leopoldo Mandic College/Campinas, involving medical students who had completed the central nervous system neuroanatomy course and signed informed consent forms. 3D models were derived from imaging exams in WebGL and X3DOM formats from the EyeWire Neuroscience Collection database, converted to stereolithography (.stl) files, and sectioned into four pieces using Autodesk Meshmixer. Tessellation and slicing were performed using Simplify3D, and a "honeycomb" pattern was employed to fill the models, optimizing material usage while maintaining rigidity. The models were printed using a Sethi BB printer at 205˚C - 210˚C with PLA, a biodegradable thermoplastic polymer. The study printed six models: left and right hemisphere lateral and medial views, with two additional "left" pieces for color variation and calibration. The brain hemisphere pieces weighed between 69.77 and 438.24 grams, costing approximately US$ 5 per model. The questionnaire, adapted from Barretos (2018), comprised ten statements assessing the 3D models' impact, with five response options, and included open-ended questions for additional feedback. Results indicated that 89.5% of respondents agreed that using 3D-printed models positively impacts neuroanatomy study. However, 84.2% preferred cadaveric specimens for practical purposes. All respondents agreed that 3D-printed models could positively impact neuroanatomy teaching, learning, and knowledge retention. While 76.3% found the models helpful in visualizing brain structures, 15.7% were unsure, and 7.9% disagreed. A significant 92.1% supported applying 3D-printed models to the neuroanatomy course, and 97.3% believed other anatomy components could benefit from the technology. The participants suggested pathology (65.7%) and surgical techniques (47.3%) as other areas where 3D printing could be beneficial. The study concludes that 3D-printed models, while not replacements for cadaveric specimens, positively impact teaching and learning neuroanatomy and can supplement traditional education.

Subject Areas

Radiology & Medical Imaging

Keywords

Medical Education, 3D Printing, Anatomical Models, Neuroanatomy, Computer-Assisted Image Processing

1. Introduction

The use of cadavers for medical study, while essential, is the subject of heated medico-legal and ethical debates. In addition to highly bureaucratized procedures, obtaining cadavers is time-consuming and costly due to the high demand from medical schools and universities and the limited availability of bodies for scientific purposes. Thanks to advances in multimedia technologies, new forms of teaching and learning have emerged as substitutes or supplements to traditional anatomical education based on cadaver dissection. Three-dimensional (3D) printing stands out as a trend among these new alternatives [1].

Also known as additive manufacturing or rapid prototyping, 3D printing is a process in which a 3D modeled file is transformed into a physical object through the layer-by-layer deposition of a material by an extruder nozzle. Various materials can be used in additive manufacturing, including aluminum, polylactic acid (PLA), carbon fiber, and polyvinyl alcohol (PVA).

The use and potential of 3D printing in medical practices have been rapidly expanding. They can be divided into broad categories: surgical simulation and planning, tissue and organ manufacturing (bioprinting), implant and prosthesis manufacturing, pharmaceutical research (drug dosing and delivery), and anatomical models [2]. Rapid prototyping can reproduce replicas of separate anatomical structures or multiple combined structures that closely resemble cadaveric specimens. Literature findings suggest that 3D models can provide certain benefits to learning as a supplement to traditional curricula. These models can be used as a teaching tool to enhance the curriculum and complement established learning modalities, such as dissection-based education [3].

Although the anatomical features in 3D models are less realistic compared to specimens, these models can be used in anatomy education as a teaching tool. Furthermore, it has been demonstrated that they provide an easy and intuitive roadmap for planning procedures and surgeries, complementing conventional imaging modalities. In the field of neuroanatomy, additive manufacturing through 3D printing offers new ways to represent delicate parts of the nervous system, as imaging studies can be materialized through this method.

This study aimed to create a collection of 3D-printed human brain models for anatomy teaching and research. The project is an observational study, and the models were evaluated using a questionnaire administered to a sample of 38 medical students from the institution.

2. Materials and Methods

2.1. Study Design and Ethical Aspects

This is a descriptive, prospective, quantitative observational study with convenience sampling. Data collection was conducted in the anatomy laboratory at São Leopoldo Mandic College/Campinas, with a sample of medical students who had already completed the central nervous system neuroanatomy course. All participants signed the informed consent form. The Research Ethics Committee (CEP) approved the study (#3,779,246).

2.2. Digitization and Modeling

The study models were obtained from imaging exams in WebGL and X3DOM formats from the EyeWire Neuroscience Collection database, an anatomical and histological mapping project of the nervous system developed by the Computational Neuroscience Laboratory at Princeton University. All 3D models obtained are public domain materials with unrestricted use [4]. The files obtained from EyeWire were converted into stereolithography (.stl) files. The models were exported to Autodesk Meshmixer and were sectioned into four pieces for each imported brain file: left hemisphere medial view, left hemisphere lateral view, right hemisphere lateral view, and right hemisphere medial view (**Figure 1**).

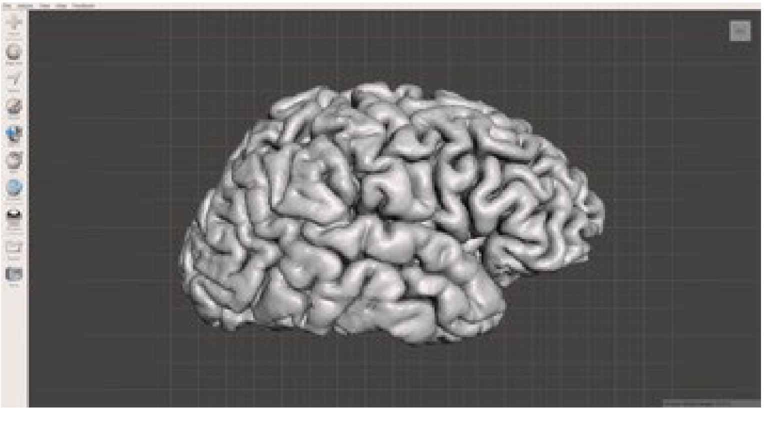

Figure 1. Digital version of the medial view of the right hemisphere in Autodesk Meshmixer software.

2.3. Tessellation and Slicing of Files

Tessellation is the process of covering a surface with polygons (geometric shapes) without gaps between them for exporting to.stl format. First, the slicer divides the object into layers according to the desired thickness and filament used, a process known as slicing. The "honeycomb" pattern is used to fill the model. For this approach, the software generates hexagonal structures that overlap each layer, which provides resistance to stress in all axes while using minimal material. The goal is to reduce material usage without compromising the rigidity and solidity of the piece (**Figure 2**).

The files were imported into Simplify3D, where tessellation and slicing were performed, and the final file was exported.

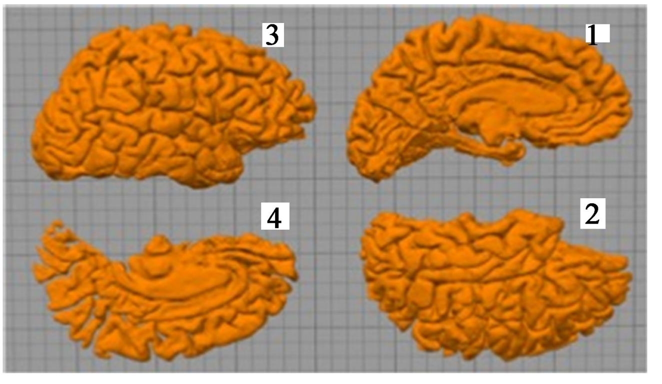

Figure 2. MRI files already exported as.stl files and imported into Simplify3D. Left hemisphere medial view (1), Left hemisphere lateral view (2), Right hemisphere lateral view (3), and Right hemisphere medial view (4).

2.4. Support Structures

A fused deposition modeling (FDM) 3D printer heats a thermoplastic filament and extrudes it through a nozzle. However, a scaffold must be created before printing when a piece has a part that needs to be suspended in the air. This material is called support and will be printed to hold the suspended parts, preventing them from falling into the void. After printing, the support must be manually removed during the finishing phase.

Among the structures that make up the cerebral hemispheres, the cortical sulci require a support structure to maintain the integrity and prevent deformation of the piece. The support generation was performed through the analysis of three prominence variables: contact tol (contact area between the support and the piece), angle thresh (angle in the modeling zone), and Y-offset (Y displacement). The maximum support twist angle, density, height, and diameters (tip, body, and columns) desired for the layers were also considered. The solidified pieces were exported in.stl format to compress the 3D files.

The 3D models were converted from a 3D object model.stl format to g-code format. The g-code format contains instructions for the printer's extruder to move along the print area and deposit the thermoplastic to create an individual layer.

The final files were saved to a MicroSD card (Figure 3).

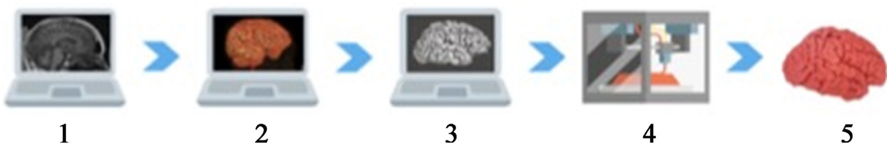

Figure 3. Stages of the printing process for the models. Stage 1: Downloading MRI models; Stage 2: Digitization and modeling; Stage 3: Tessellation and slicing; Stage 4: Printing the models with PLA; Stage 5: Evaluation of the models.

2.5. Printing

The pieces were printed at 205˚C - 210˚C using a Sethi BB printer, and the support removal was done manually with tweezers and pliers. The material used was PLA, a biodegradable and compostable thermoplastic synthetic polymer. Some initial tests and pieces were printed on a Sethi AipA3 printer (Figure 4).

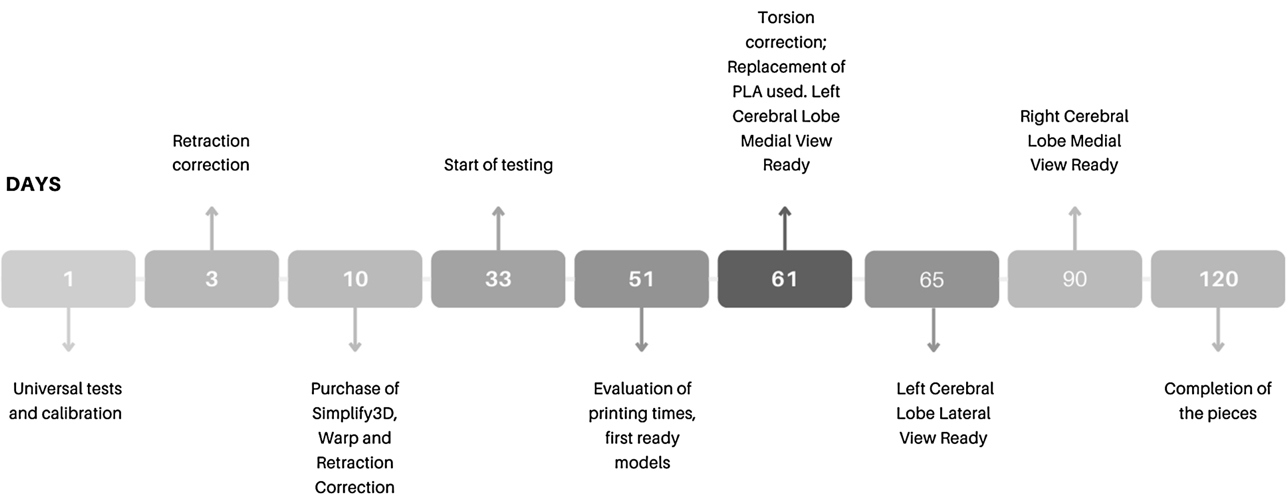

Figure 4. Diagram of printer preparation and calibration and printing of the models.

Six of the proposed models were printed: Left hemisphere lateral view, left hemisphere medial view, right hemisphere lateral view, and right hemisphere medial view, and two additional models of the "left" pieces for color variation and calibration. In the study, the brain hemisphere pieces weighed between 69.77 and 438.24 grams, with an average cost of approximately 30 reais per printed model (R$ 0.12/gram, with 20% internal infill) (Figure 5).

2.6. Application of the Questionnaire

The questionnaire was formulated based on the work of Barreto (2018), who sought to quantify and qualify the accuracy of the 3D-printed models. It contains ten statements related to the 3D models, with participants having five response options to choose from 1) strongly agree, 2) agree, 3) unsure, 4) disagree, and 5) strongly disagree. Additionally, the questionnaire included open-ended questions where participants could express their opinions, suggestions, and criticisms of the method [5].

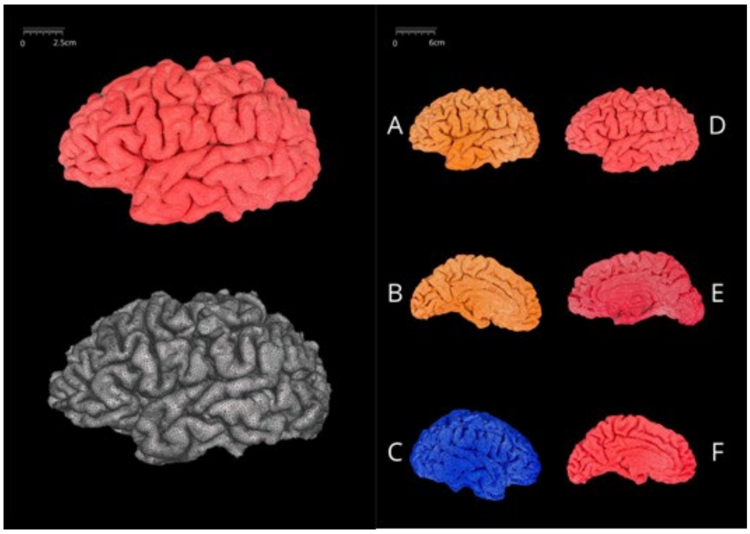

Figure 5. Digital model and 3D printed model using FDM technology. Lateral view of the right hemisphere, both from the same patient.

3. Results

When analyzing the questionnaires, the data collected revealed that the vast majority of respondents (89.5%) agree or strongly agree that using 3D printed models positively impacts the study of neuroanatomy. However, 32 students (84.2%) preferred using cadaveric anatomical specimens for practical purposes. Additionally, all respondents agreed that using 3D-printed models in the classroom can positively impact neuroanatomy teaching, learning, and knowledge retention (Figure 6).

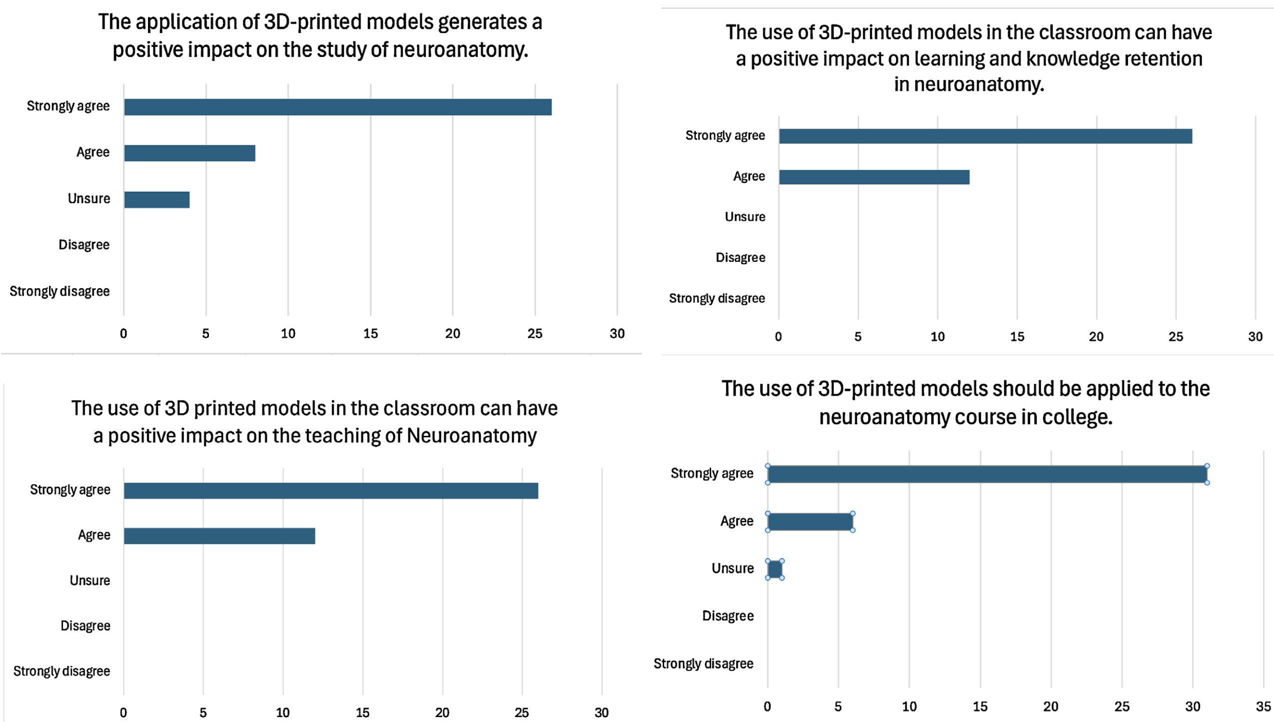

Figure 6. Applicability of 3D technology in neuroanatomy.

Regarding the use of 3D models during theoretical classes enabling a better understanding of the topic and the visualization of the main structures of the human brain being possible in the printed models, 15.7% of participants were unsure if it is possible to visualize the main structures of the human brain in the models. Moreover, three participants (7.9%) disagreed that it is possible. The remaining 76.3% of respondents agreed or strongly agreed that it is possible to visualize the main structures of the human brain in the printed models (Figure 7).

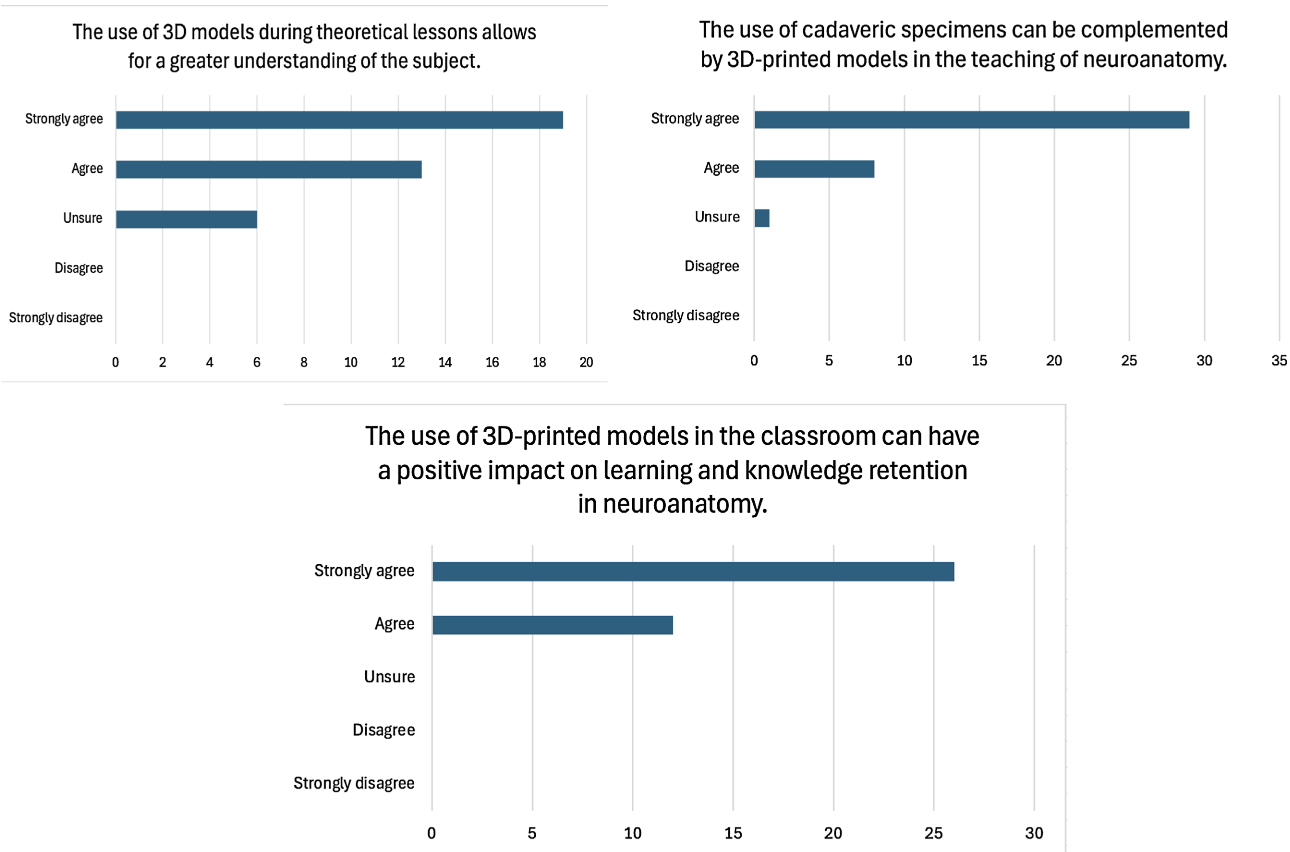

Figure 7. Use of 3D models in learning and complement to cadaveric specimens.

Finally, 92.1% of the students agree that 3D-printed models should be applied to the neuroanatomy course at São Leopoldo Mandic College, and 97.3% believe that other components of human anatomy could benefit from 3D technology (Figure 8).

When asked about ideas or other examples for using 3D printing in medical education at São Leopoldo Mandic College, the main responses were the subjects of pathology (65.7%) and surgical techniques (47.3%). Other disciplines mentioned included vascular and respiratory anatomy, gynecology and obstetrics, semiology, neurophysiology, and medical skills.

Participants in the survey were also able to express themselves and evaluate the activity in general, identifying what was especially important and what should be improved.

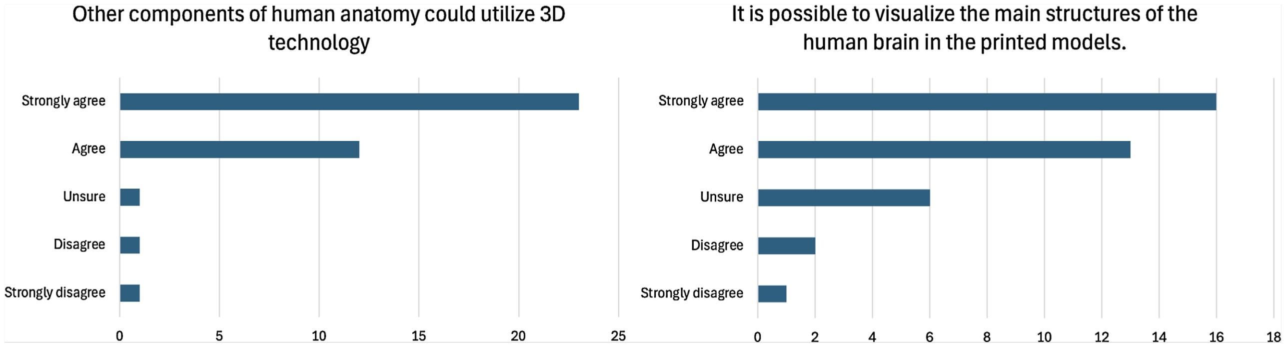

Figure 8. Use of 3D technology in other anatomical structures.

Participant I—"3D modeling facilitates and allows for a better understanding of the subject."

Participant II—"The idea of using synthetic structures in neuroanatomy is very valid. However, for other areas of anatomy, I believe cadaveric specimens are irreplaceable."

Participant III—"Better understanding compared to the acrylic boxes where cadaveric specimens are placed."

Participant IV—"Printed models can preserve cadaveric specimens."

Participant V—"Overall, the 3D models of the brain impressed me. Some details can, I believe, be improved [...]."

Participant VI – "Very good pieces, excellent rigidity, very similar to the real thing. However, I think there could be more details."

Participant VII—"The 3D model does not replace the cadaveric one but complements it."

Participant VIII—"I think it is very important to see the anatomical variants of cadaveric specimens."

4. Discussion

Three-dimensional printing can produce objects in various shapes based on imaging exams or digital 3D models. With the popularization of this technology in recent decades, processes that were once limited and less accessible have found a new field of application—the printing of anatomical models. As observed in the study, using printed models in neuroanatomy positively impacts learning the subject and offers a different tool for teaching it.

In the past, the object of medical study was often restricted to the human body itself. Indeed, the roots of the Greek word "anatomy" mean 'to cut into parts'. Concerning anatomical study, the use of cadavers has been dated back to the Renaissance [6]. Today, almost all doctors have studied or worked with models or cadaveric material at some point in their medical training. The use of cadavers serves not only to generate academic knowledge but also to promote humanistic values.

Despite being indispensable, the use of cadavers for medical study is the subject of heated medico-legal, ethical, and cultural debates. Highly bureaucratized procedures and high costs make obtaining cadavers time-consuming, compounded by the high demand from medical schools and universities and the low availability of bodies for scientific purposes.

Around the world, some studies have already been conducted to determine the level of learning of human anatomy using printed models compared to traditional cadaveric specimens [7]. However, their role in teaching and learning neuroanatomy is less discussed. Among these studies, the conclusions suggest no detriment to medical learning in some applications when comparing traditional and printed models [8].

According to Wu's study [9], although no differences were found in test scores for upper or lower limbs, the scores of students on the pelvis and spine tests were significantly lower in the traditional radiographic imaging group compared to the printed model group. Additionally, according to O'Reilly's study [10], when comparing accuracy scores on external cardiac anatomy between students using 3D models and traditional cadaveric specimens, the accuracy percentage was 60.83% for the printed models versus 44.81% and 44.62% for the cadaver and combined study groups, respectively. The results found in the literature indicate that 3D models can offer certain benefits to learning as a supplement to the traditional curriculum. These models can be used as a teaching tool and represent a method to enhance the curriculum and complement established learning modalities, such as dissection-based education.

At Macquarie University and Western University in Sydney, 3D-printed bones are successfully utilized in anatomy education [11]. According to the research, the osteometric analysis revealed no differences in shape and dimensions between the printed models and the real bones from which they were printed. The application of 3D printing will extend to pathology and radiology classes at both universities and involve other anatomical structures, particularly those that are difficult to observe and manipulate, as mentioned in the article.

The use of cadaveric specimens for education extends beyond the university and directly impacts the doctor-patient relationship and clinical and surgical practice. This scenario is demonstrated by the study by Bernhard JC *et al.* [12], which used 3D models of renal tumors to guide patients about their conditions and analyzed comprehension levels before and after using the models. Patients showed a 16.7% improvement in understanding basic renal physiology and a 50% improvement in anatomy. Similarly, the research by Yang, T., Lin, S., Xie, Q. *et al.* [13] demonstrated that using printed models of hepatic tumors to understand the surgical anatomy of the liver increased the tumor location detection score from 34.50 on CT scans to 80.92 when using the models, among 45 surgical residents. Other positive aspects highlighted included improved accuracy of proposed resections and reduced surgical time.

The progress in multimedia technologies allows for new forms of teaching and learning that have emerged as substitutes for or supplements to traditional cadaver dissectionbased anatomical medical education. One factor that could play a significant role in implementing printed models in anatomy education is cost, which, although variable depending on the material used and the country, is lower than cadaveric specimens. Furthermore, complementary teaching tools, such as 3D printing, help promote "deep learning" as students can interact with content more quickly and directly, apply concepts to daily practice, and capture students' attention, aiding in better information retention [14].

Educational research requires a robust framework of evidence and experimental processes for validation. This study had some limitations in its execution.

The 3D-printed models also have limitations. In addition to variations in the proportions, colors, and sensations of the real human body, more research needs to be done before they can be safely used as part of a multimodal curriculum, as the results of this study are limited to brain models. However, it is becoming clear that 3D-printed brain models may be the next step in expanding anatomy education.

5. Limitations of the Study

This study has several limitations that should be considered when interpreting the results.

1) Lack of Qualitative Feedback on Student Preferences

While the questionnaire revealed a student preference for cadaveric specimens over 3D models, no qualitative feedback was collected to explore the underlying reasons for this preference, particularly regarding tactile differences between the two methods. This limits our understanding of whether students valued realism, depth perception, or other experiential factors in their learning process.

2) Technical and Educational Challenges of 3D Models

The use of 3D models presents inherent challenges:

- Model Complexity: The human brain is a highly intricate organ, and even detailed 3D models may struggle to accurately represent fine anatomical distinctions if resolution or rendering techniques are insufficient.
- Lack of Familiarity: Participants without a strong neuroanatomy background may have difficulty identifying structures, even if the model is well-designed, due to insufficient contextual guidance.
- Occlusion and Overlap: Some brain structures are deeply embedded and may be partially or fully obscured by surrounding tissues in a 3D model, reducing clarity compared to dissection-based learning.

3) Financial and Logistical Considerations

A comprehensive cost-benefit analysis is necessary when comparing 3D models to traditional cadaver-based learning. While 3D printing may seem cost-effective at first glance (e.g., $5 per model), several factors must be considered:

- Initial Investment: High upfront costs for printers, software, and personnel training.
- Recurring Expenses: Materials, maintenance, electricity, and labor for model production.

- Cadaver Costs: Traditional methods involve procurement, preservation, storage, and ethical/logistical challenges, which may increase long-term expenses.
- Scalability & Sustainability: Bulk production may reduce costs, but material waste and energy consumption must also be evaluated.

While 3D models offer advantages in accessibility and reproducibility, their financial feasibility depends on institutional resources, scalability, and whether they can sufficiently replace, or supplement cadaver use without compromising educational outcomes.

Future Directions

To address these limitations, future research should:

- Incorporate qualitative feedback to better understand student preferences.
- Improve 3D model resolution and interactivity to enhance structural clarity.
- Conduct long-term cost-benefit analyses comparing 3D printing and cadaver-based methods.

These steps would help determine the optimal balance between innovation, cost efficiency, and educational effectiveness in anatomical training.

6. Final Conclusion

The use of 3D printed models for studying neuroanatomy, although not a replacement for traditional cadaveric specimens, has a positive impact on teaching and learning the subject, according to the results found, and can supplement traditional education. It is possible to visualize the main structures of the human brain in the printed models; however, the resolution of the medial surface of the hemispheres requires further details. The application of 3D pieces as a teaching tool in other subjects of the medical course can contribute to medical learning.

Conflicts of Interest

The authors declare no conflicts of interest.

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