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Review

3D modelling in anatomy teaching: state of the art and pilot investigations for its application

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A R T I C L E I N F O

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A B S T R A C T

Backgroud: Technological advancements have revolutionized anatomy education, introducing "virtual anatomy" as complement or alternative to traditional dissection. At the Faculty Unit of Anatomy and Morphology (UFAM) of the University Center of Legal Medicine Lausanne-Geneva (CURML), we integrated digital tools into musculoskeletal and embryology teaching for first-year medical students. Aim: This study presents a state of the art survey on the use of imaging technologies for anatomy teaching and a pilot pedagogical project on 3D imaging at UFAM. Our aims are to present the implementation of 3D printing in practical works on the musculoskeletal system, and the implementation of 3D models to complement embryology practicals.

Material&methods: Vertebrae were replicated using high-resolution 3D surface scanning and printing. 3D models of genitalia, brain hemisphere, and thoracic spine with spinal cord were created using photogrammetry. Printed vertebrae were used during musculoskeletal, and anatomical 3D models during embryology practicals. Students received interactive 3D PDFs and usage guidelines beforehand. Feedback was collected via an online questionnaire.

Results & discussion: Students reported high satisfaction, improved spatial understanding, and enhanced practical skills. However, large file sizes of 3D PDFs and software compatibility issues limited access. While 3D tools proved effective for anatomy education, improving accessibility and usability remains essential for broader implementation.

1. Introduction

Teaching anatomy and morphology is foundational in medical education, traditionally relying on cadaveric dissection and 2D resources [1]. However, advancements in 3D imaging (3D modeling and 3D prints) are revolutionizing the field. Several authors describe the introduction of the so-called "virtual anatomy" in their teaching, presenting the tools used, as well as their advantages and limitations. Some centers have implemented websites featuring 3D models of various anatomical structures, such as the liver, to facilitate learning of their anatomy and segmentation. According to the authors, these models provide interactive, high-resolution visualizations that go beyond what traditional illustrations and physical models can offer. They help learners better visualize and orient anatomical structures, which improves spatial understanding and increases engagement [2,3]. Some authors have created 3D printed pieces from 3D models of the heart, bones, pterygopalatine fossa, …[4–11]. Others have created their own 3D models of the inner ear, oculomotor system, heart/lung system, cerebrovascular system, knee, or forearm, often from CT scans or MRIs, as well as the softwares to run them [3,12–20]. They mostly compared 3D models with textbook contents and 2D images. 3D imaging supports early learning and enhances student confidence and consistency, with faster response times than 2D tools. However, the evidence does not consistently support its long-term advantage over traditional methods, as most studies show no significant difference in outcomes. Using 3D models and printing in anatomy education improves student understanding, engagement, and satisfaction. Learning quality, however, depends on the resolution of both 3D scanning and printing technologies, which can incur significant costs. In some medical universities, practical works and dissections are less and less practiced due to time restrictions and/or low availability of donated bodies and/or financial issues [12,14,17]. This observation is also linked with the increasing and overwhelming number of students. Some questionable changes in the educational system introduced by certain universities are also

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responsible of this situation. 3D technologies can partially compensate for the lack of access to real anatomical specimens by improving student motivation and spatial skills, though cadaver-based learning remains superior. Some studies highlight their potential to transform anatomy education by complementing or replacing traditional methods in specific contexts [3,19,21,22]. 3D technologies certainly can help maintain standards, but they are not without limitations.

In our article, we will first present a state of the art of the use of imaging technologies for anatomy teaching based on the literature, and then we present pilot projects linked to imaging and 3D printing introduced in our medical university for the teaching of morphology. Our aims are to present the implementation of 3D printing in practical works on the musculoskeletal system, and the implementation of 3D models to complement embryology practicals. We also share both student and instructor feedbacks regarding their perceived educational value and usability.

2. State of the art

The review of literature was conducted with four different keywords combinations: “anatomy teaching” + “3D technologies”, “anatomy teaching” + “3D printing”, “anatomy learning” + “3D modelling” and “anatomy teaching” + “3D models”. Search was made on Google Scholar Database in the English language.

2.1. Advantages of 3D models in anatomy education

A major advantage of 3D models, as reported by several authors, is the improvement of student’s spatial understanding; particularly for anatomically complex, small or visually inacessible regions or structures (such as the middle and inner ear, the oculomotor system, the heart, or the arterial system of the head [6,9,10,12,16,21,23–27]). For example, Tanner et al. [9] evaluated the educational value of a 3D printed model of the pterygopalatine fossa (PPF), a small and deep anatomical space that is notoriously difficult to conceptualize using traditional 2D images or partial cadaveric views. The authors demonstrated that students using the 3D printed PPF model performed significantly better on post-instruction quizzes than those who learned with conventional half-skull models. In addition to improved test performance, students rated the 3D model higher in terms of usefulness and clarity in a satisfaction survey, highlighting its effectiveness as a spatial learning tool. The 3D model allowed complete visualization of the PPF’s boundaries, communicating foramina, and neurovascular contents, thereby transforming a previously abstract anatomical space into a comprehensible, manipulable structure. Similarly, in the study by Cheung et al. [21], custom 3D printed arterial models of the head and neck were used to address the challenges students face in comprehending the spatial course and branching of arteries in this region, which is difficult to appreciate fully through textbooks or cadaveric dissection alone. Students engaged with these tactile models reported significantly improved understanding of arterial trajectories and relationships. More generally, the integrative review made by Silva et al. (2025) [27] highlights how 3D-printed anatomical models (from circulatory, skeletal, nervous, and reproductive systems) enhance spatial understanding, engagement, and academic performance.

Beyond test scores, numerous studies report that 3D models significantly enhance students’ engagement, motivation, and confidence compared to traditional tools. Interactive and tactile learning modalities are consistently well-received in anatomical education [14–17,19,25,27–36]. For example, Silén et al. (2008) investigated the integration of 3D visualizations derived from authentic clinical imaging, such as CT and MRI, into medical and physiotherapy education programs. Students were engaged with these interactive visualizations during lectures, demonstrations, and tutorial sessions. The findings indicated that the 3D images stimulated students’ motivation to deepen their understanding and facilitated insights into biological variations, spatial dimensions, and inter-organ relationships. Virtual dissections were perceived as providing clearer representations than conventional ones, and the ability to manipulate anatomical structures was considered highly instructive. Students expressed high satisfaction with this approach, emphasizing that 3D visualizations based on real clinical data introduced a new and valuable dimension to learn anatomy and physiology. For instance, in the study by Backhouse et al. [37], optometry students who co-created and personalized 3D printed skull models overwhelmingly preferred them over conventional teaching tools (lecture notes, textbooks, and anatomical models), and a greater sense of ownership over their learning. Similarly, Loke et al. [16] found that pediatric residents trained on 3D models of congenital heart disease reported higher satisfaction and self-efficacy than those taught with 2D diagrams, despite similar knowledge gains. This was demonstrated through a randomized controlled study in which residents were divided into two groups: one taught using 3D-printed models of tetralogy of Fallot and the other with standard 2D illustrations. While both groups showed comparable improvements in knowledge test scores, the 3D model group reported significantly higher learner satisfaction ($P = 0.03$) and slightly higher self-efficacy scores, highlighting the added educational value of hands-on, spatial learning tools. In a study conducted by Stepan et al. [17], immersive three-dimensional virtual reality (VR) was evaluated as a teaching tool for neuroanatomy among medical students. Medical students reported increased engagement, motivation. The ability to interact with and control 3D models promoted active learning and a sense of autonomy. Although learning outcomes were not quantitatively assessed, students favored the immersive experience over traditional methods, highlighting the educational value of 3D visualization tools. Starszak et al. (2025) [35] demonstrated that combining mixed reality with 3D printed models in heart anatomy teaching improved spatial understanding and engagement among medical students. Brumpt et al. (2024) [25] confirmed that such models not only improve test performance but also engagement, especially for complex areas. In their study, Tan et al. (2022) [36] conclude that color-enhanced 3D printing improves both learning efficiency and the clarity of anatomical communication, especially in complex regions like the heart. These findings align with those of Santos et al. (2021), Sisu et al. (2024) and Kiliç et al. (2025) [32–34], who highlighted improved student perceptions and autonomy when using interactive and 3D-based resources.

Another advantage of these technologies is the accessibility and the scalability of anatomical teaching resources [5,7,8,11,38]. As highlighted by McMenamin et al. [8], 3D printing allows a rapid and cost-effective reproduction of anatomically accurate models from CT or surface scan data, making it feasible to produce multiple high-fidelity copies of any specimen. This enables simultaneous access for large student cohorts, including institutions with limited access to cadavers. Bartikian et al. [7] further demonstrated that using consumer-grade 3D printers, individual skull bones could be printed at low cost and high anatomical resolution, allowing students to study detailed osteological structures at home—an option rarely feasible with fragile or limited anatomical specimens. Young et al. [11] extended this benefit to human developmental anatomy by producing replicable models of embryonic and fetal stages, offering an ethically alternative to the use of real specimens, which are both rare and sensitive. Stunden et al. (2021) [38] demonstrated that realistic, durable, and cost-effective anatomical replicas can be produced from CT/MRI data, offering a scalable and ethical alternative in settings with limited cadaver access. Additionally, the ability to scale models up or down according to pedagogical needs, as demonstrated in McMenamin’s and Young’s studies, provides flexibility in tailoring educational tools to highlight specific structures or relationships. Collectively, these findings underscore how 3D modeling expands the reach of anatomical education by overcoming limitations in specimen availability and enabling broader, equitable access to high-quality anatomical representations.

In terms of measurable learning outcomes, 3D models have shown significant benefits [4,39–45]. In a randomized controlled trial by Lim et al. [42], medical students who learned external cardiac anatomy using 3D printed models achieved significantly higher post-test scores (mean 60.83 %) than those taught with cadaveric materials (44.81 %) or a combination of cadaveric and 3D materials (44.62 %). Pre-test scores did not significantly differ across groups ($P = 0.274$), and the superior performance of the 3D group remained significant even after adjusting for baseline knowledge using ANCOVA ($P = 0.012$), suggesting that the observed benefit was attributable to the intervention rather than prior knowledge. Similarly, Chen et al. [39] showed that students using 3D printed skulls scored higher on both total and practical test scores than those using cadaveric specimens or atlases. The total test score referred to the combined results of an 18-point multiple-choice theory test and a 30-point practical lab test focused on structure identification, summing to a maximum of 48 points. While theory scores were comparable across groups, the 3D model group significantly outperformed others in the lab test and overall total scores. Furthermore, the study by Al-Badri et al. [46] demonstrated an improved long-term retention three weeks post-intervention when students used 3D printed models of craniosynostosis cases compared to traditional 2D learning methods. Similarly, Kong et al. [41] demonstrated that 3D visualizations and 3D-printed models of hepatic segments led to significantly better learning outcomes compared to atlas-based methods. Moreover, participants who used the 3D tools retained their performance over time, whereas those relying on the atlas showed a decline A meta-analysis by Salazar et al. [43] revealed that students using 3D printed models performed, on average, 11 % better on objective assessments than those taught through traditional methods, confirming the overall benefit of 3D tools in improving comprehension and test outcomes in complex anatomical education. Ye et al. (2020) [45] further validated these results through meta-analysis, emphasizing that printed models improve retention, especially when integrated into blended instruction. Eroglu et al. (2023) [44] demonstrated the usefulness of 3D PDFs in early learners, outperforming 2D atlases in short-term learning.

Despite these advantages, the relevance of so-called “virtual anatomy” remains debated by several authors, and most of the references show that it is as effective as “traditional teaching” [2,15–18,28,47–49]. For instance Ref. [15], demonstrated that students taught musculoskeletal forearm anatomy using a 3D virtual reality (VR) model performed comparably to those taught via traditional dissection and textbooks, with no statistically significant difference in test scores. Similarly, Stepan et al. [17] found that immersive VR led to significantly higher learner satisfaction and motivation, although learning outcomes were equivalent to those achieved with conventional 2D resources. The review by Ruiz et al. [48] further confirmed that e-learning modalities, including virtual anatomy, consistently yield knowledge gains similar to those of instructor-led methods, particularly when integrated as part of a blended learning strategy. These findings are echoed by Cook [28], who emphasized that the most notable increase is observed in learner satisfaction. Similarly, Hallgren [49] argues that the effectiveness of web-based learning remains uncertain because study results may be influenced by external factors like student motivation, time spent studying, or selection bias - particularly the self-selection of students who chose to activate and use the web-based learning tool. These confounding variables make it difficult to determine whether learning improvements are due to the digital tool itself, limiting the reliability and generalizability of the findings [16].

Based on the current literature, a growing number of papers support the implementation of a hybrid model for anatomy education that combines traditional teaching methods, particularly cadaveric dissection, and practical laboratory sessions, with 3D technologies, such as printed and digital models. Cadaveric dissection remains the pedagogical gold standard due to its unmatched ability to convey anatomical variability, tissue texture, and spatial depth, while also promoting professionalism and manual dexterity [9,50]. However, logistical constraints, including reduced curricular time and cadaver availability, have driven the need for complementary solutions. Vandenbossche et al. [51] showed that students perceived manipulable 3D models as valuable adjuncts, especially when used alongside cadavers and digital platforms. The authors argue that each modality—dissection, 3D printing, and digital visualization—has distinct pedagogical strengths. This supports the concept that a multimodal educational ecosystem provides a richer, more flexible learning experience and allows students to engage with anatomical content from different perspectives and through multiple sensory channels. Finally, while most students appreciate 3D models, some prefer cadaveric dissection for its realism. Smith et al. [52] explored the use of 3D-printed anatomical models as supplementary tools in undergraduate anatomy teaching. The study focused on students' perceptions after using these models during practical sessions.The findings revealed that 3D printing enhances traditional anatomy education, especially by extending access to anatomical material beyond the dissection room. Considering the approaches described above, several medical schools are incorporating 3D printing into their anatomy curricula to enhance student access and engagement [9,51–53].

2.2. Challenges and limitations of 3D models in anatomy education

Despite the pedagogical benefits of 3D printed anatomical models, one consistent limitation reported across multiple studies is the absence of realistic tactile feedback compared to cadaveric specimens [11,21,46,54]. Cheung et al. [21] noted that while 3D printed models facilitated the visualization of vascular topography in the head and neck, students found it more challenging to identify structures on wet specimens afterward, partly due to the oversimplification and material rigidity of the printed models. Similarly, Al-Badri et al. [46] emphasized that although 3D models significantly improved long-term retention in the study of craniosynostosis, they could not fully replicate the textural and physical nuances of real bone and soft tissue. Young et al. [11] also acknowledged that while 3D printed fetal specimens allowed for repeated handling and preserved fragile originals, the lack of biological consistency in materials limited their realism. As summarized by Aimar et al. [54], most 3D printing materials fail to accurately mimic the elasticity and mechanical behavior of soft tissues, and current rigid polymers do not reproduce the haptic properties essential for surgical and anatomical training. As Starszak et al. (2025) [55] also underline, virtual anatomy offers promising supplemental learning opportunities, especially when integrated into blended learning environments, but cannot fully replicate the tactile and spatial realism of cadaveric dissection. Consequently, although 3D models enhance spatial understanding and accessibility, their tactile limitations restrict their ability to fully substitute cadaver-based learning, particularly in fields where palpation and tissue resistance are educationally significant.

Another limitation is the high initial costs associated with implementing the technology. As outlined by McMenamin et al. [8], the acquisition of a high-resolution, full-color 3D printer can range from $65,000 to over $400,000, depending on the model and functionality. Additional expenses include specialized software, technical staff, scanning equipment, and consumables, which collectively represent a substantial financial investment for institutions. Although material costs per model are relatively low once the system is in place, the startup expenses and technical requirements can be prohibitive, particularly for smaller or resource-limited institutions. Similarly, Mahmoud and Bennett [6] acknowledge that despite the growing affordability of desktop 3D printing, producing accurate and durable anatomical models still requires specialized equipment, post-processing, and design expertise, which can further elevate costs. Consequently, while 3D printing holds strong pedagogical value, its cost barrier may limit equitable access and broad implementation across anatomy curricula, especially in settings without existing technological infrastructure. Leung et al. [56] emphasized the importance of institutional support to overcome these barriers. McMenamin et al. [8] proposed shared printing facilities as a practical and cost-effective solution. They suggested a centralized model, in which multiple departments within a university or even regional networks of institutions, could collaborate and share access to a single, well-equipped 3D printing facility. This approach would not only reduce duplication of expensive resources but also foster interdepartmental collaboration in the creation and distribution of anatomical teaching models. Additionally, such shared facilities could be supported through pooled funding or grant-based models, improving cost-efficiency while expanding access to advanced 3D printing technologies for teaching and research purposes.

A point raised by some authors is that the educational impact of 3D models depends on the complexity of the anatomical structure [9,21,22,44,52,57]. This argument was already mentioned earlier and developed by Tanner et al., Cheung et al., and Smith et al. Mogali et al. [22] demonstrated that students greatly benefited from multi-material 3D models of the upper limb, especially in understanding intricate spatial relationships between muscles, vessels, and nerves. The students appreciated the ability to manipulate layered structures and to visually distinguish tissue types through color coding. However, they also acknowledged limitations in fine anatomical detail, such as the inability to represent muscle fiber orientation or hollow vascular structures. These findings suggest that 3D models are especially useful in areas where 2D resources or traditional plastic models fail to convey spatial complexity, such as the elbow or cubital fossa. At the same time, the pedagogical advantage of such models may be less significant for simpler anatomical structures. Thus, the complexity of the anatomical region plays a key role in determining the added value that 3D printed models can bring to anatomy education.

Many studies attempt to evaluate the effectiveness of using 3D models and prints; however, as some authors point out, methodological inconsistencies limit the interpretability and generalizability of the findings [50,53,58]. Wang et al. [58] conducted a meta-analysis of 39 randomized controlled trials and found that although 3D visualization technologies moderately improved satisfaction and enjoyment, the effect on test scores varied significantly depending on geographic region, particularly due to a strong positive bias in Chinese studies. Infact, their analysis revealed high heterogeneity ($I^2 > 90$ %, where I^2 represents the percentage of total variation across studies that is due to heterogeneity rather than chance.) in most outcomes, suggesting that variables such as course content, student level, prior anatomical knowledge, and evaluation design were not adequately controlled. Similarly, Chytas et al. [53] highlighted that the educational effectiveness of 3D models likely depends on the complexity of the anatomical region studied, yet most comparative studies fail to stratify outcomes accordingly. Zargaran et al. [50] further emphasized that while many students report high satisfaction with technological tools, this does not always translate into improved academic performance, pointing to a discrepancy between perceived and measured learning. These findings underscore the need for more rigorously designed studies that account for confounding factors and clearly define outcome measures when assessing the pedagogical value of 3D technologies in anatomy teaching.

In summary, 3D models and 3D printing technologies have proven to be pedagogically valuable by increasing accessibility, improving students' spatial understanding, and promoting interactive, student-centered learning—especially when teaching anatomically complex or spatially limited regions. They seem to serve as valuable complements to cadaveric dissection, particularly for complex anatomical regions and for situations where access to cadavers is limited. When integrated into hybrid curricula alongside dissection and practical sessions, they contribute to a more flexible and engaging educational experience. Their growing integration into medical curricula could enhance the quality and accessibility of anatomy education for future medical professionals. However, their implementation is not without challenges. High initial costs, lack of haptic realism, and variability in study designs limit both widespread adoption and the ability to draw definitive conclusions about their overall effectiveness. Moreover, their educational impact appears to depend on factors such as anatomical complexity, instructional context, and learner needs, background, motivations, …. As research in this field continues to grow, future studies should employ more rigorous and standardized methodologies to clarify the role and limits of 3D technologies in anatomy education.

2.3. *Ongoing at the Faculty Unit of Anatomy and Morphology in Lausanne*

At the Faculty Unit of Anatomy and Morphology (UFAM) of the University Center of Legal Medicine Lausanne-Geneva, in Lausanne, we benefit from several resources for 3D modelling: a CT-scanner, an MRI, a 3D surface scanner, and photogrammetry. Since 2020, we have investigated the possible contribution of these technologies to our morphology teaching. In this article, we present two pilot pedagogical projects of our Unit, addressed to first-year medical students of the Faculty of Biology and Medicine (FBM) of the University of Lausanne: 1. the use of 3D-printed vertebrae in locomotor system practicals, and, 2. the implementation of 3D models in embryology practicals.

During practical works on the locomotor system, first year students examine and manipulate anatomical parts of bones, joints, muscles, including their vascularization and innervation. The aim is to integrate knowledge of the skeleton, joints, ligaments, and associated muscles to precisely describe the various joints' movements. Regarding the vertebrae, the available specimens are showcase pieces prepared several years ago, of which we have very few fragile pieces. We also have some samples of entire vertebral columns, formed by vertebrae that are wire-bound together. With hundreds of students participating to these practical sessions, the risk to damage these delicate specimens is significant. Therefore, there is a need of a more important number of anatomical pieces. To address these challenges, high-resolution 3D surface scanning was used to create digital models of vertebral columns, which were then reproduced using a high-quality 3D printer. This approach provided students with multiple replicates of the original specimens, allowing for safe and repeated handling during practical exercises, preserving the integrity of the original pieces.

During the embryology classes, first year students observe microscopic slides and anatomical parts of male and female genitalia, as well as part of the thoracic spine, showing the spinal cord and the brain hemispheres. They are also provided with preparatory material, i.e., photographs of anatomy specimens and a list of structures to be recognized during practicals on anatomy specimens and histological slides. The aim is that they recognize the structures of interest and make the link with the embryology courses they are being taught. Unfortunately, at FBM, changes in teaching plans have led to a reduction of the time slots for practicals (from 2 h to 1h30/session). In addition, we face a constant increase in the number of students in the curriculum, which further limits the amount of time available for each student to study the anatomy pieces in the classroom (from 30min to 12min). We therefore decided to create 3D models of these anatomical parts by photogrammetry, to make them available to the students to prepare their practical works, thus optimizing the time slots in the classroom. We also collected students' feedback through a questionnaire to verify whether this approach was helpful in their learning.

It is worth precising some ethical aspect and principles we apply at our Unit, concerning the use of human bodies and parts in teaching. Ethical aspects related to anatomy teaching have been addressed at the Faculty of Biology and Medicine in Lausanne for the past 15 years. They have been implemented within our Unit and integrated into the medical curriculum as follows. In the first year, 2 h of ex-cathedra lectures are devoted to presenting historical, medical, and ethical aspects related to death and medical practice around death. Subsequently, first-year medical students are introduced, in small groups, to human bodies during a practical session in the dissection room. During this session, anatomy teachers present either (1) anatomical parts used in regular practical courses or (2) whole fixed bodies. In this way, students are progressively and respectfully introduced to cadavers, allowing them to reflect personally on death and the use of the human body in dissection. This introduction is highly valued by the students, as it helps them cope with the challenge of confronting their own mortality. In the second year, before starting the practical course on the head, students receive a dedicated introduction addressing the specific ethical aspects related to this part of the body. From the 3rd to the 6th year of the curriculum, death is approached from clinical perspectives during hospital rotations with patients. Thus, students are gradually exposed to the different dimensions of the human body: from fixed cadavers in the early years to clinical encounters with death later in their training. They are also made aware of the profound significance of body donation for their education and of the constant respect that must be shown to donors."

3. Materials and methods

3.1. 3D printed vertebrae for locomotor system practicals

The 3D surface acquisition was conducted using the non-contact optical 3D digitizing system GOM ATOS COMPACT SCAN 5M (GOM, Braunschweig, Germany), which produces high-resolution, accurate 3D models derived from real-world data. Our institute routinely employs this instrument for 3D surface acquisitions of bones and injury-causing objects. While it offers excellent resolution, it does not generate 3D color models [59,60]. Since the details on bones can be extremely fine (often less than 1 mm), achieving the highest possible resolution is critical, allowing the entire piece to be scanned within a reasonable timeframe. Since bones exhibit minimal color variation, a 3D surface scanner that does not capture color information suits this purpose. A suitable measurement volume (MV) and scanning parameters (GOM: minimum fringe contrast 10, use of points at substantial brightness differences, use of points on shiny surfaces, avoid Mx viewing angle sensor/surface, exposition time: 2.) were selected based on our experience [61,62].

This scanner operates by projecting fringe patterns of blue light onto the surface, creating an array of stripes that conform to surface geometry. Two cameras, each with a resolution of 5 megapixels, record the deformation of the stripes caused by the surface contours. By employing the triangulation principle, the data from both cameras are merged into a high-resolution point cloud that represents the surface geometry [59,60]. The acquisition process was managed using the ATOS Professional V7.5 SR2 software package, which also facilitated preliminary data processing, along with additional treatments performed in 3ds Max 2013. A measurement volume (MV), determined by the pair of camera lenses used, was selected based on the requirements of the scan. For this study, the MV150 (150 × 110 × 110 mm) was chosen, offering a resolution of up to 0.062 mm. Scanning an individual bone required approximately 15–30 min. Calibration of the scanner was performed before scanning to ensure minimal measurement deviation. Bones were marked with reference points and scanned on a black turntable in a controlled environment maintained at approximately 21 °C with stable lighting conditions. Efforts were made to minimize external vibrations by securely mounting the camera components on a tripod and working in an isolated room. The acquired 3D data were polygonized without post-processing, apart from minimal treatments such as smoothing and thinning to remove background noise. Additionally, the 3D models were optimized by reducing data complexity in accordance with surface curvatures, thereby minimizing file size without compromising geometric fidelity.

The ProJet SD 3510 printer was selected for this process [63]. This device can produce parts with maximum dimensions of 298 × 185 × 203 mm, achieving a maximum XY resolution of 0.025 mm and a maximum Z resolution of 0.03 mm. The printer utilizes MultiJet (MJP) 3D printing technology, which involves depositing a thin layer of photo-sensitive resin onto the printing platform, followed by curing with a UV head to solidify the material. It is compatible with the VisiJet M3 range of materials, characterized by mechanical strength, temperature resistance, watertightness, and biocompatibility [63]. For this application, the transparent VisiJet M3 Crystal material was used. The 3D models were imported into the printer's software, adjusted to fit the print area, and prepared for fabrication. Five replicas of each vertebra were printed, including the atlas, axis, cervical, thoracic, and lumbar vertebrae. After printing, the parts were placed in an oven at 100 °C to melt the support material, leaving only the final printed components.

3.2. 3D models for embryology practicals

As part of the embryology teaching for first year medical students, *ex-cathedra* classes cover gametogenesis, fertilization, and embryological development. Specific classes are also given on the development of the nervous system. Practical works are intended to reinforce and illustrate the knowledge acquired during these classes. Various histological and anatomical preparations of the concerned organs are presented: male and female genitalia, brain, and spinal cord. The anatomy parts of interest are three pieces of male genitalia (external, internal, and sagittal section), two pieces of female internal genitalia (the whole genitalia and one sagittal section), one piece of the right brain hemisphere, and a part of the thoracic spine showing the spinal cord. All these parts are studied during the embryology practicals. They are all conserved in a 50 % water and 50 % ethanol solution.

Each part was hung with a nylon thread on an expressly created stand. The photographs were then taken with a NIKON D750. Photographs were taken from different points of view and with an overlap area of about 80 % minimum. No tripod was used. The photographic parameters vary according to the size of the room, its configuration, and the ambient light: ISO between 1250 and 2500, focal length between f/8 and f/14, and focal distance between 50 mm and 98 mm. White balance was automatically set. No flash was used. Between 60 and 100 photographs were taken, depending on the size and complexity of the piece. Each part was also scanned with the 3D surface scanner Go!SCAN 20 from CREAFORM [64]. However, due to the brightness of the parts the scanner could not scan the surface completely, therefore many holes were present. As this 3D model was directly full-scale, it was thus possible to transfer markers on its surface and their coordinates to the 3D model from the photogrammetry to scale it up. Agisoft Metashape processed the photographs into a textured, real-to-scale 3D model. Then the final 3D model was exported as a 3D PDF that can be easily opened in Adobe software. A 3D model can be moved, rotated, and measured in this software.

The 3D PDF files were available to students on our e-learning platform few days before the practical. A document containing instructions on how to use Adobe and the structures to be identified was also made available on the same platform.

At the end of the practical sessions, an online questionnaire containing four closed and one open questions was made available to the students in order to collect their feedback on these 3D models. Of the 210 students who took part in the practicals, 76 completed the questionnaire.

4. Results

4.1. 3D printed vertebrae

The 3D models of the vertebrae have been used successfully in several practical sessions over the past three years. These 3D prints have not been damaged. In fact, both students and teachers appreciated the print quality, and that all structures could be visualized on them, just as they could be on real parts. The teachers also appreciate the introduction of these 3D prints, which they consider to be of high quality. These replicas help preserve delicate anatomical specimens that are difficult to replace and, due to the ability to produce multiple copies, make these structures more accessible to a larger number of students simultaneously. An example of printed vertebrae is shown in Fig. 1.

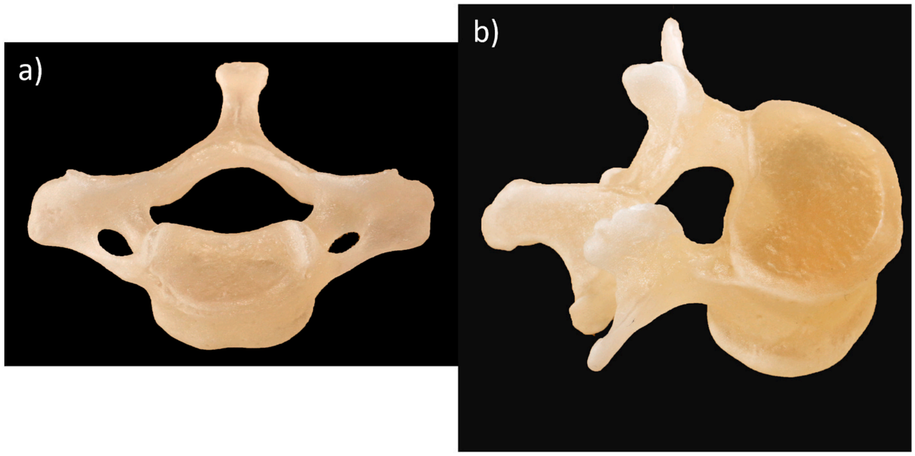


Fig. 1. 3D print of: a) atlas and b) lombal vertebrae.

4.2. 3D models for embryology practicals

Examples of the 3D PDF files are shown in Fig. 2 (female internal genitalia) and Fig. 3 (right brain hemisphere). The answers to the four closed questions are shown in Table 1. Concerning the open question "Which are the positive aspects and the points to improve regarding the use of 3D PDF files?", we summarize the most relevant comments below.

Most of the students greatly appreciated the use of these 3D models because they found them useful for preparing the practical sessions (80 % "Yes" + "Rather Yes", Question 1 in Table 1) and allowed them to better link theory and practice. They indicated that they could better visualize the structures in 3D and understand certain elements shown in the class (ex. real size of the uterus, the structure and spacing of the different meninges, …). Moreover, the 3D models gave them a better spatial representation of the structures of interest (95 % "Yes" + "Rather Yes", Question 3 in Table 1).

Fig. 2. 3D model of female internal genitalia.

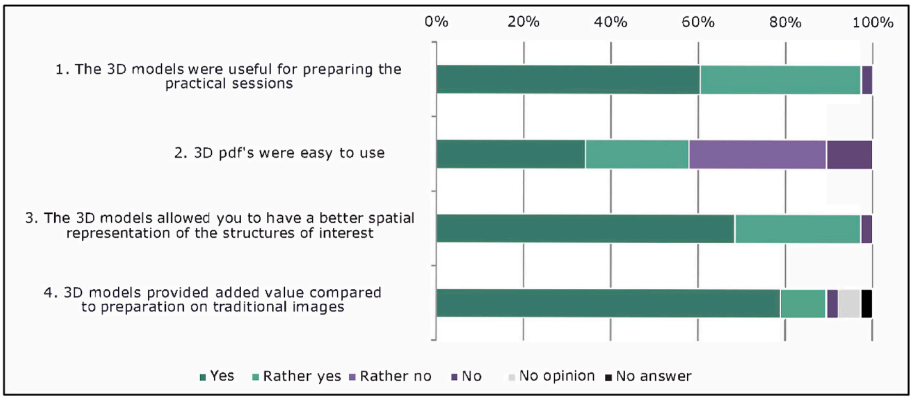
Fig. 3. 3D model of the right brain hemisphere.

Some students also indicated that preparing the practicals at home did not give them the impression of a reduced time slot in the classroom, although this time has been effectively reduced compared to previous years.

On the other hand, certain students encountered difficulties with 3D PDF files due to their large file sizes (42 % "Rather No" + "No", Question 2 in Table 1). This resulted in prolonged download times and caused technical disturbances, such as system slowdowns during opening and manipulation.

The three teachers found that during the practicals, the students

Table 1
Students' responses to the closed questions.



asked more relevant questions after preparation with 3D models than in previous sessions (with "classical" 2D image preparation).

5. Discussion

We aimed to test the implementation of 3D printing in practical work on the locomotor system. The 3D prints of vertebrae met the teachers' expectations in terms of their quality. The students also appreciated them as they were realistic and accurate enough to find all the structures asked for during the practical and could be easily manipulated. This feedback aligns with previous studies' reports [8,14–17,19,28–31,37]. O'Reilly et al. [30] reported that 3D printed models of the lower limb significantly enhanced anatomy teaching by providing scalable, anatomically accurate, and durable alternatives to cadaveric material. Similarly, Backhouse et al. [37] emphasized that the ability to replicate anatomical structures in multiple copies enhances accessibility and engagement during practical sessions, particularly in large cohorts. Furthermore, McMenamin et al. [8] noted that the mass production of 3D anatomical models from imaging data allows for broader dissemination and individualized learning, facilitating hands-on experience without compromising original specimens. In our experience, the integration of printed vertebrae preserved delicate samples and reproduced anatomical variation and natural irregularity. It enabled simultaneous, repeated use by large student groups, thereby improving practical engagement and structural recognition—an outcome corroborated by the cited studies.

Another important consideration from our experience is the resource-intensive nature of producing high-quality 3D printed anatomical models. In our project, the fabrication of vertebrae replicas required advanced imaging equipment, specialized software, technical expertise in 3D modeling, and several hours of dedicated work by specialized teaching staff. These demands, in terms of time and cost, are consistent with the challenges highlighted by other authors. As metionned before, McMenamin et al. [8] emphasized that the high initial costs of 3D printers and materials and the need for skilled personnel may limit the broader adoption of 3D printing in anatomy education. Similarly, Leung et al. [56] noted that while 3D models enhance learning, their integration requires institutional investment in infrastructure and personnel training. In the same way, Santos et al. (2022) [33] mentioned that logistical barriers in implementing 3D and virtual technologies, such as lack of equipment or trained staff in developing countries. Mahmoud and Bennett [6] also reported that producing detailed, colored 3D pathology specimens was technically achievable but costly. Tan et al. (2022) [36] highlighted the significant costs, technical skill requirements, and time-consuming nature of high-quality full-color 3D printing, especially in resource-limited settings. These examples underline the need for sustainable solutions—such as shared printing facilities or exploring the pedagogical value of more cost-effective, lower-resolution prints—when planning to expand the use of 3D models to other anatomical topics. In our particular case, although commercial models exist at reasonable prices, we had access to high-precision 3D modeling and printing technologies in our university, so it seemed more worthwhile to replicate our existing, real parts, for the sake of durability and highest precision.

Concerning the 3D models for embryology practicals, the results of our questionnaire show that the vast majority of students appreciated this tool. They found that the 3D models gave them a better spatial representation of the pieces than traditional pictures. Once they were in front of the real parts, they could orient themselves easily and better localize the structures in relation to each other. This aspect has been tested and described in several studies [13,65,66]. In their study, Eroglu et al. (2023) [44] conclude that 3D PDFs are more effective than 2D atlases for teaching complex anatomical content to novice learners and offer a practical, accessible alternative for anatomy education. According to Garg et al. [65], notably, their results demonstrate that the study of multiple views of an object improved the mental representation. The authors conducted a spatial representation test on students recruited for their study before its commencement. Based on their findings, they were able to assert that students' spatial ability is a significant predictor of learning success. We did not investigate this aspect, but it has been acknowledged by several authors [13,44,65,66].

Moreover, using the 3D models, our students were better prepared for the practical session. 3D models provided high-quality, detailed representations of the actual anatomical specimens, which helped students engage more confidently with the material. This observation is consistent with findings by Loke et al. (2017) [16] who investigated using 3D printed heart models to teach congenital heart disease, specifically tetralogy of Fallot. In their randomized study, although no significant difference in immediate test scores was found between students who used 3D models and those who learned via conventional 2D diagrams, the group exposed to the 3D models reported significantly higher levels of satisfaction and self-efficacy. Importantly, Loke et al. emphasized that these positive subjective experiences are closely associated with improved long-term retention, suggesting that students who feel more confident and engaged during learning are more likely to internalize and retain the information over time.

As mentioned earlier in our article, an increasingly supported consensus in anatomical education highlights the complementary value of combining traditional cadaveric dissection with 3D printed and digital models [9,50–53]. While cadavers provide unmatched exposure to tissue variability, texture, and dissection techniques, 3D models offer enhanced accessibility, spatial clarity, and repeatable learning experiences. Kılıç et al. (2025) [32] reported high student satisfaction with 3D modeling platforms but emphasizes the need to complement (not replace) cadaveric dissection. In the article of Ye et al. (2020) [45], systematic review and meta-analysis confirming improved outcomes with 3D printed models, especially for spatial understanding, but recommends their use as complements rather than replacements. At our institution, the implementation of high-resolution 3D-printed vertebrae models to supplement practical sessions on the musculoskeletal system and the use of 3D PDF files before embryology practice allowed us to make the same observations. Students reported improved spatial understanding and engagement, particularly when digital models were introduced prior to in-lab sessions. These experiences confirm that the integration of 3D technologies enriches the learning environment, but should not replace real anatomical specimens. Instead, hybrid teaching approaches that combine physical dissection with 3D-enhanced tools offer the most pedagogically robust framework, enabling learners to access multiple representations of anatomy that reinforce each other both cognitively and practically.

We have to underline that, as our questionnaire was completed voluntarily, we received a low respond rate. Thus it is plausible that we predominantly received responses from the most motivated students, introducing the potential for selection bias, as noted by Stepan et al. (2017) in their study. Consequently, it is possible that the respondents were the most comfortable with this technology and possessed the greatest familiarity with the investigated tool.

Furthermore, several studies have already mentioned that the novelty effect could influence student satisfaction and their impression of being more successful [50,53,58]. Indeed, it is plausible that students provided positive feedback on this experience mainly thanks to the novelty of the approach. Moreover, as discussed previously, positive feedback about a learning experience does not necessarily imply improved exam performance. We would need a comparative, separate study to verify the last aspect. In future research, we will ensure that we create a more robust study by comparing the exam performance between groups of a defined size with different teaching methods.

The limitations of 3D PDF files include their large file size and the lack of data security, as students can freely download the files, resulting in a loss of control over their distribution and use. This ethical issue has been raised by Craik et al. [19]. They emphasize the necessity of considering this data's digital storage and ownership, especially regarding security. Access to human-derived data should be restricted, ensuring it is used exclusively for specific educational purposes. According to these authors, guidelines should be issued for 3D imaging of human anatomy, particularly concerning their visualization. To overcome these issues, we are looking for browser-based 3D viewers. We are currently working with a team who created an online interface enabling consultation, manipulation, and annotation of 3D models (with various formats), by secure logging using university/institutional identifiers. No download will be possible. This will also eliminate the problem of having to download large files, as they will be stored on a dedicated secured server and accessible via a secured browser based viewer.

Finally, we would like to emphasize that we have only briefly addressed the importance of 3D models in neuroanatomy. In this paper, we provided a general overview of the various areas in which 3D technologies are applied in anatomy teaching, along with their benefits and limitations. We acknowledge that neuroanatomy education represents a key domain for the use of 3D models in this context [67,68]. Accordingly, we are currently developing 3D models and prints as complementary tools for neuroanatomy teaching and plan to publish a dedicated paper on this topic."

6. Conclusions

The use of 3D prints of vertebrae proved helpful during locomotor system practicals, motivating us to enrich our pedagogical material by introducing 3D prints of other complex or fragile anatomical structures. 3D models of anatomical parts also proved helpful in preparing embryology practicals for first-year medical students at our University. However, the file used for these 3D models needs to be changed to secure access to sensitive data and to facilitate its use by the students, regardless of the configuration of their computer hardware. We would also like to point out, as many other authors that although 3D modelling is a powerful tool for teaching morphology, it must be used as a complement, and not a replacement, of dissection or demonstration on real anatomical parts. Real bodies/anatomical parts remain the best 3D we can get, thus the gold standard in the learning process of human anatomy, and the best way medical students can prepare themselves to work on patients.

CRediT authorship contribution statement

Stella Fahrni: Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Sara Sabatasso:** Writing – review & editing, Supervision, Project administration, Conceptualization.

Data availability statement

The data supporting this study's findings are available on request from the corresponding author. However, due to privacy or ethical restrictions, the data are not publicly available.

Ethics statement

The anatomical specimens used for photogrammetry were obtained from individuals who provided written informed consent during their lifetime for their bodies to be used for education and research, according to the Swiss law.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Chat GPT in order to improve the readability and language of the manuscript. After using this tool, the authors reviewed and edited the content as needed and takes full responsibility for the content of the published article.

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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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