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Approaching diversity in anatomical education through metaverse

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ABSTRACT

Background: Human anatomy is a foundational and indispensable subject within health sciences education, particularly for students pursuing careers in medicine and nursing. The metaverse, a technological concept leveraging immersive technology, connectivity, and custom 3D experiences, offers an opportunity to address the challenges of diversifying anatomical education.
Methods: In this paper, we present insights from our extensive experience using the metaverse to integrate innovative pedagogical strategies and provide access to scarce educational resources and laboratory materials. We also explore the capacity of artificial intelligence for enhancing the metaverse. A new framework for addressing the challenges of diversification in anatomical education is proposed, outlining the design, key features, and core technologies of the educational metaverse.
Results: We present arguments that may answer common questions posed by anatomy educators regarding the adoption of this technology in their curricula. We then make a re-analysis of our findings from practical experiments within the metaverse, including quantitative and qualitative questionnaire interpretation, contrasting student experiences, and exploration of new AI-driven features, to focus on the role of the metaverse in fostering diversity in anatomical education.
Conclusions: Our work intends to introduce a novel technological resource for approaching diversity in anatomical education. We conclude that the metaverse can facilitate the diversification of anatomical education by providing access to scarce educational resources and laboratory materials. Furthermore, we pave the way for new tutoring approaches for non-standard student groups, the personalization of content, and the implementation of specific assessments. Finally, we provide essential takeaways and outline future directions and challenges for this ongoing research area.

1. Introduction

Health sciences programs need advanced and robust training in certain foundational subjects. Anatomy is one of them due to its practical relevance in the exercise of healthcare professions (Turney, 2007, Nzenwa et al., 2023).

However, a lack of integrated emerging technologies in anatomy education restricts the available diversity of teaching methods (Triepels et al., 2018). This limits the spectrum of accessible content and restricts students' use of high-cost equipment or scarce resources such as cadavers or tissue samples (Cheung et al., 2021, McMenamin et al., 2025, Thengal et al., 2024).

Within this framework, conventional anatomical teaching resources (such as cadavers, textbooks, and multimedia) are known to be demographically biased (Beresheim et al., 2024), which presents a significant challenge for healthcare (Nzenwa et al., 2023). This is manifested, for

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instance, in a prevalence of male subjects, individuals of white Caucasian ancestry, or particular age demographics, thereby failing to adequately address the inherent anatomical variations across diverse populations, the diverse needs of students, or the cultural backgrounds present in educational settings. Consequently, these biased contents give rise to several challenging circumstances:

- Biased and limited understanding of anatomical variability across populations (Nzenwa et al., 2023).
- An absence of diversity in acknowledging the extensive array of human body configurations, underlying conditions, and anatomical features (Brown and Finn, 2024).
- A probable bias in the identification of anatomical structures for diagnostic and therapeutic purposes in post-graduate professional practice.
- Limitations in access to anatomical diverse teaching resources (Chang Chan et al., 2025, McMenamin et al., 2025). For instance, the use of cadavers, mainly male subjects, as a central component of anatomy education, although essential, may not be feasible for all educational institutions due to cost, ethical considerations, health concerns, or logistical challenges in their instructional management.
- Conventional teaching approaches present human anatomy as static, which complicates the effective transmission of structural functionality, functional variations, and the implications in various medical conditions to students.

Moreover, traditional approaches are vulnerable to extraordinary events like COVID-19 (Iwanaga et al., 2021). They also present challenges in adapting to diverse student needs (e.g., for wheelchair users or deaf students), scaling content, ensuring accessibility, delivering international or localized material, and fostering pedagogical innovation.

The metaverse refers to an immersive environment enabling users to engage in both physical and digital interactions within a hybrid space. This concept, implemented as a synthetic 3D-space generated by immersive technology that engrosses students in a common interactive and connected setting, has been proposed for educational purposes across several disciplines (Kye et al., 2021, Chen et al., 2023, Wang et al., 2023). Particularly in medicine and nursing education it presents a wealth of opportunities (Zhao et al., 2020, Sandrone, 2022, Massetti and Chiariello, 2023, Moro, 2023,Rodriguez-Florido et al., 2024a, Sacchini et al., 2024).

In this paper, we explore how the metaverse can serve as a versatile tool to address both the diversification challenges in anatomical education and complement traditional teaching methods. We propose that the metaverse, leveraging its technical capacity, can provide a broad and diverse array of anatomical models for students, encompassing variations in ethnicity, age, gender, anatomical variants, and pathological conditions. This technological resource also allows for personalization, enabling educators to customize models to specific learning objectives or diverse student needs. The metaverse further facilitates the creation of collaborative learning groups, grants access to scarce resources like cadavers, addresses ethical or cultural challenges, and captures objective learning metrics for student assessment.

Following this introduction, we describe the key factors and features that make the metaverse a diversified learning environment. We then present our experiments and results with students and educators, including quantitative and qualitative questionnaire analysis, contrasting student experiences, and exploration of new AI-driven features, to focus on the role of the metaverse in fostering diversity in anatomical education. After discussing our proposals, we outline conclusions, limitations of this study, future research directions and challenges.

2. Making the metaverse a diverse education environment

The metaverse is a broad concept that must be well-designed and clearly defined to be a helpful pedagogical tool in healthcare sciences (Rodriguez-Florido et al., 2024a), even more for diversifying anatomical education. Due to the non-standard conditions that we have in those cases, we need flexible educational resources that support anatomy educators for mitigating diversification challenges. In this section, we describe the key factors and components of the metaverse that enable us to achieve this goal.

2.1. Design

Practical use of the metaverse in health sciences education needs a specific design that accounts for the needs and attributes of both educators and students in this area (Avidan et al., 2021, Rodriguez-Florido et al., 2024a, Rodriguez-Florido, Maynar, 2024). This configuration has demonstrated that medical students can utilize the metaverse's underlying technologies without impeding their access to knowledge (Rodriguez-Florido et al., 2024a). Consequently, the metaverse emerges as a valuable supplementary resource within curricula of anatomy (Rodriguez-Florido et al., 2024b).

In the context of educational diversification, these design features are especially important, as our goal is to address a wider student population, including those with varying cultural backgrounds, religious affiliations, gender identities, and disabilities. Therefore, user experience (UX) must be straightforward for both students and anatomy teachers, enabling them to easily manage academic features and content, and adapting them to several profiles of students in a common classroom. Furthermore, the software platform utilized for metaverse application development needs to provide developers with the flexibility to seamlessly integrate new functionalities and scale the application with ease. Thus, we propose using open-source technologies due to their extensive development communities and readily accessible content for designing new virtual academic scenarios (Rodriguez-Florido and Maynar, 2024).

2.2. Features

The key features we propose for a metaverse environment to diversify human anatomy education are:

- Accessibility. Students and anatomy educators need to be able to access the metaverse environment easily and intuitively. This includes providing digital support (for instance, on-screen prompts, color adjustments, or specific symbols) when necessary (for example, for those with color blindness or hearing impairments), regardless of their physical condition or geographical location.
- Interactivity. Students should have the capability to interact and collaborate among themselves during the learning process independently of their conditions. This includes the teacher, who can leverage the resources and capability within the metaverse to facilitate student instruction.
- Connectivity. The system must have access to a device communication network. This connection can be either local (without internet access) or global (with internet access). In either scenario, such connectivity enables access to specific, static learning assets (e.g., 3D models of non-conventional parts of the anatomy, personalized academic information) and facilitate the real-time generation or processing of data to provide users (students or educators) with useful information (e.g., guidance prompts, success or error signals) pertaining to anatomy education.
- Personalization. These environments should have the capacity to tailor each student's specific circumstances, the teaching methodology, and the assigned tasks. This may involve, for instance, interlanguage translations, the selection of relevant anatomical examples, cultural sensitivities, whether a student is right- or left-handed, or providing digital support to enhance user integration.

2.3. Technology

Using metaverse platforms involves underlying technologies that create the immersive sensation of the environment and support the features outlined in Section 2.2.

Head-mounted devices (HMDs) and handheld controllers are essential for immersing users in the virtual environment (e.g., a simulated anatomical dissection room). These controllers also enable users to perform specific tasks and interact with the virtual environment (e.g., selecting a tissue, or performing any gesture) and other users (e.g. passing an object to a peer).

These devices can operate in either Virtual Reality (VR) mode, fully immersing users in a synthetic environment, or Augmented Reality (AR) mode, which overlays the virtual scenario onto the physical world. The choice between modes depends on the specific learning objective and the anatomy teacher's pedagogical interest in utilizing the metaverse.

In Figs. 5 and 6d, HDMs models and handheld controllers, VR mode and AR mode, are displayed.

- A desktop computer is typically used for external control (from outside the metaverse environment), student management, and graphical processing. This technological component is crucial for the educator, allowing them to manage the entire teaching process. This includes tasks such as registering students, setting up student circumstances (e.g. primary language, disabilities, guidance prompts for some specific students, etc.) and viewing performance metrics. It also enables the teachers to interact with students immersed in the metaverse without being fully immersed themselves. Furthermore, it can offload demanding technical, like processing or graphical services, that require more computational power than the individual HMDs worn by each student. Ultimately, this external control system provides essential technical support to each HMD and the other peripherals within the technological framework necessary for creating the metaverse learning environment.
- A Network Attached Storage (NAS) device is utilized to store content information within the metaverse, such as 3D models, images, texts, and videos. This information is accessed by connected devices as illustrated in Fig. 1. This component is essential in environments seeking to address diversity (e.g., 3D models of non-conventional parts of the anatomy, personalized academic information, etc.).
- A router for establishing the local network that connects all devices participating in the metaverse learning environment.
- Generative Artificial Intelligence (genAI) models dynamically generate content, including real-time text, visuals, and interactive environments, to foster deeper engagement and creativity within metaverse scenarios. They offer a more personalized feedback system that monitors real-time performance and encourages adaptive learning based on user progress. Furthermore, these models can incorporate a gamified reward system for collaborative and multi-user experiences, promoting engagement and teamwork.

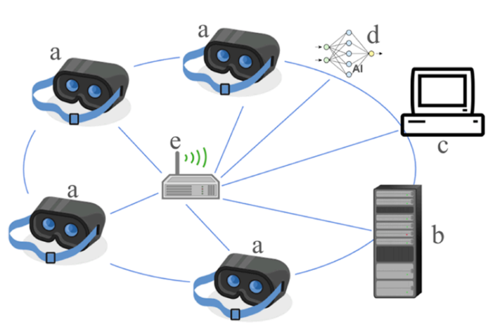

Fig. 1. A simplified diagram of metaverse technologies illustrating. (a) HMDs, (b) NAS, (c) desktop computer, (d) AI models, and (e) router. All of them interconnected via a local network (blue lines).

- Artificial Intelligence (AI) processing models enhance interaction with synthetic objects in metaverse-based anatomical education by analyzing user movement sequences. These models may be run on the desktop computer unit or directly on the HMDs.

2.4. Creation of academic content

By academic content, we refer to all materials (e.g., 3D anatomical models, images, technical texts, nomenclatures, translations, guidelines, etc.) that are incorporated into the anatomy teaching environment within the metaverse. Enhancing the diversification of anatomical education, extensive materials are required to address the broad scope of learning needs (e.g., different learning styles, various anatomical cases, diverse student profiles, scarce resources, etc.).

These materials constitute one of the most significant and highly valued aspects of the metaverse for the end-user (student and educator). However, these digitally modeled resources would not possess such considerable value without the contribution of the technologies detailed in Section 2.3. While these contents are, in essence, provided to the student for their human anatomy education and learning, their full utility, interaction, and benefits within the metaverse are realized only through the designated implementing technologies.

There are two main approaches for creating this type of academic content in teaching human anatomy in a diverse manner. The choice between these approaches depends on the learning objective that educators aim to achieve within the metaverse. The first approach involves manual modeling using specialized software or adapting existing resources found online (e.g., the Z-anatomy project, 2025). The second, conversely, entails generating anatomical academic content through AI generative models (Chheang et al., 2024, Joseph et al., 2025).

In both cases, the supervision of teachers is indispensable, as they are experts in anatomy and possess the requisite experience and knowledge to guide technical 3D modelers or to prompt AI generative models effectively (Rodriguez-Florido and Maynar, 2024).

3. Experiments

To illustrate how the metaverse addresses the challenges of anatomical education diversification identified in the Introduction, this section presents two implementations. First, we describe an experimental use-case utilizing a virtual learning environment that provides access to scarce educational resources and laboratory equipment. Second, we explore the capabilities of AI within the metaverse to support and enhance anatomical instruction. Across both cases, we highlight the role of the metaverse in fostering diversity within anatomical education.

3.1. Accessing academic resources within the metaverse

Our university currently faces two significant challenges in diversifying anatomical education. First, our students have limited access to cadavers, a critical resource that is currently unavailable in our academic labs. Second, although we aim to provide a wide range of tissue samples and high-resolution microscopes for all students, the substantial cost of this equipment and the shortage of tissues make such comprehensive access currently unfeasible. Consequently, we must mitigate this limitation in access to teaching resources, which in turn addresses the biased and limited understanding of anatomical variability that we are currently teaching.

Therefore, we have designed two virtual learning scenarios within the metaverse, both computationally and operationally efficient for transitioning from a standard virtual environment to one enriched with diversity-driven pedagogical interventions:

- A virtual dissection room accommodating up to four students simultaneously for performing dissection protocols on a 3D virtual model. Currently, we have modeled a healthy, mid-aged male, but we can include other types of anatomy (e.g., female or pathologized body, accounting for differences in body habitus, size, or specific demographic features).

- Virtual microscopes for observing digital tissue samples. At present, the model has been utilized to represent the respiratory system in standard gross anatomy. However, the platform is designed to incorporate additional tissue types, including healthy or pathologized samples acquired from high-resolution imaging equipment.

Because our group was responsible for both the design and development, we gained a comprehensive understanding of the metaverse's features and limitations. This allowed us to address emerging challenges and adapt our implementations to fit a structured classroom curriculum in healthcare education (Castro et al., 2023, Rodriguez-Florido et al., 2024a, Rodriguez-Florido et al., 2024b, Sacchini et al., 2024). In this section, we examine how the metaverse can address diversity challenges.

Regarding the virtual dissection room, we developed a series of academic activities that integrate the dissection of anatomical parts into the curriculum of several subjects in anatomical education (Table 1). This finding is noteworthy as it demonstrates the versatility of this technology and its potential for customization guided by specific learning objectives and, thereby, addresses the diversity in anatomical education (e.g. variability across populations).

For the Human Anatomy subject within the Nursing degree program, the dissection protocol we modeled focused on the layered dissection of the human head. This process extended from the skin down to the identification of the most relevant structures covered in this subject, including muscles, bones, meninges, the brain, nerves, arteries, and veins. Additionally, it encompassed the identification of other key structures, such as specific bony prominences on the inner surface of the cranial base (for example, the anterior and posterior clinoid processes, the sella turcica, or the foramen ovale and foramen rotundum), as well as nervous structures like the trigeminal nerve ganglion. In this case, the possibility exists to incorporate a non-standard component of human head anatomy (e.g., pathologized structures).

Following that, the focus shifted to the cranium, specifically its osteology, where its individual bones were identified as detachable components. Fig. 2 provides a metaverse screenshot illustrating various stages of the head's layered dissection.

For Human Anatomy II, a subject taught in the second semester of the first year of the Medicine degree program and part of the musculoskeletal system study, we found it beneficial to introduce the initial phases of the anterior thoracic wall dissection protocol. In this region, the subject covers the musculoskeletal system, superficial vascularization, and innervation of the thorax. Within this content, access was provided to several key areas: the superficial and deep fasciae, the superficial vessels and nerves, and various muscles such as the platysma, pectoralis major, pectoralis minor, serratus anterior, and subclavius. Additionally, for identification purposes, the deltoid and pectoral branches of the thoraco-acromial artery, along with the cephalic vein, were displayed. Furthermore, the content can be modified to incorporate variability across diverse populations (e.g., accounting for differences in body habitus, size, or specific demographic features).

Fig. 3 shows a view of the anterior thoracic wall dissection environment, representing a middle-aged male subject, used during teaching in the metaverse.

In Human Anatomy III, a second-year subject in the Medicine degree program, students delve into visceral systems, sense organs and nervous system. To help them grasp complex structures, we selected a challenging dissection area within the abdominal cavity. This particular region is often difficult for students to access and comprehend. During the practical session, we focused specifically on identifying and understanding the arrangement of the greater and lesser omenta, including their various parts and the pathways for accessing them. While at our medical school we lack cadavers, with this detailed approach, using the metaverse, we aim to solidify students' anatomical knowledge in a particularly demanding area.

Fig. 4 illustrates the virtual abdominal environment, representing a middle-aged male subject within the metaverse, serving as the platform for students' practical activities.

In the Human Anatomy for Biomedical Engineering subject, the teacher utilized the complete resource (i.e. a virtual middle-aged male subject of a human) to illustrate specific anatomical concepts relevant to technological development. This involved a free-form use of the resource, enabling these students to grasp concepts that extend beyond their typical curriculum in their degree program. We covered the identification of bones, joint components, muscle, fascia, body cavities, identification of organs in situ, and evisceration with identification of the different body systems. During the activity, the student received systematic guidance on the general concepts of anatomy. Using the metaverse was instrumental in addressing the challenge of presenting human anatomy as a dynamic system and conveying to bioengineering students' structural functionality, functional variations, and the implications in various medical conditions.

Fig. 5 shows a moment from the experiments conducted in our university's anatomy laboratories.

The experience sessions were organized by the teachers of each subject, with students forming groups of four and rotating through the academic content within the metaverse. Educators can monitor student activity and progress on assigned tasks from a desktop computer. This process was repeated for as many groups of four students as were present in the practical session, followed by the administration of a validated questionnaire (Rodriguez-Florido et al., 2024a) regarding their experience in the metaverse. Furthermore, a survey was conducted among educators to evaluate their experiences using this technology. This instrument was administered at the conclusion of the course.

All sessions integrated both traditional (physical) methodologies and those utilizing the metaverse.

Concerning virtual microscopes within the metaverse, students can interact with a digital microscope that is superimposed in their physical space, using handheld controllers to observe samples of various airway healthy tissues (Figs. 6b, 6c, and 6d). Besides, they may visualize the anatomical system of the airway, which includes scaled and superimposed microscopic images of the corresponding tissues. This helps them learn the relationship between a microscopic view and its anatomical position (Fig. 6a). The teacher can monitor student activity and progress on assigned tasks from a desktop computer. Furthermore, other types of tissues (e.g., pathologized) or more advanced microscopic images, despite current resource limitations, can be included for teaching lessons.

In this case, while no questionnaire was administered to students, the practical validation of the technology by educators confirmed that it was an evidently valuable tool for addressing the proposed challenges.

Table 1
Academic subjects and their content selected for inclusion in metaverse experiments.

Subject	Degree	Year	Credits	Students	Academic Content In Metaverse
Human Anatomy	Nursing	1º	6	131	Head Dissection
Human Anatomy II	Medicine	1º	6	169	Superficial Thorax Dissection
Human Anatomy III	Medicine	2º	9	150	Partial Abdomen Dissection
Human Anatomy for Biomedical Eng.	Biomedical Eng.	2º	6	45	Freehand Human Dissection

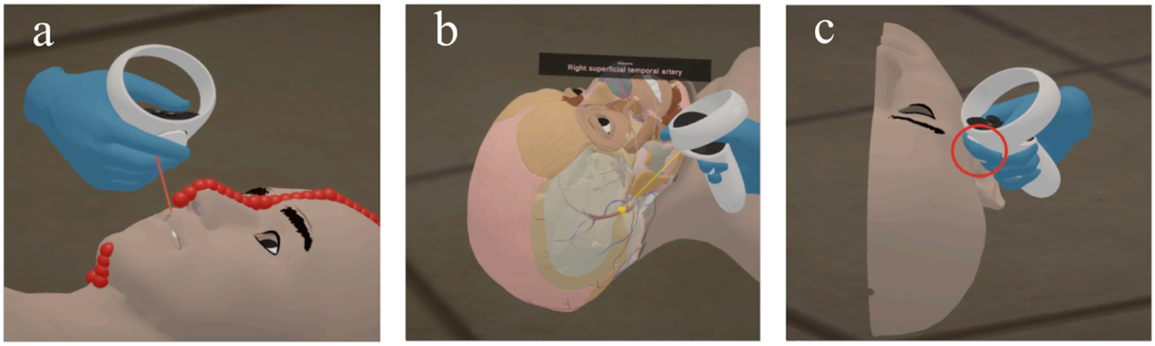

Fig. 2. A metaverse screenshot illustrating various stages of the head's layered dissection. Handheld controllers enable students to perform three core interactions: (a) cutting, (b) selecting or pointing, and (c) grasping anatomical structures.

Fig. 3. Anterior thoracic wall dissection in the metaverse. Note the handheld controller interacting with a selected anatomical tissue.

Fig. 4. Virtual abdominal environment within the metaverse, illustrating the controller's pointing functionality for anatomical identification.

3.2. Including artificial intelligence in the metaverse

Here, we explore the versatility of AI within the metaverse to support student interaction and its ability to include specific content that assists students with diverse needs (e.g., students with physical impairments, those who are color-blind, deaf, or foreign language speakers).

Regarding student interaction in virtual educational scenarios within the metaverse, Arias-Ruiz-Esquide et al. (2025a, 2025b) have found that the metaverse has inherent limitations stemming from its underlying technology. While some of these limitations can be addressed by adapting the technology for health science students (Rodriguez-Florido and Maynar, 2024), more complex issues arise in the accuracy and naturalness of basic interactions. For example, the manipulation or selection of a virtual human body part (see Fig. 7) often presents a significant discrepancy between the metaverse and reality (Arias-Ruiz-Esquide et al., 2025a). AI can help regularize this limitation, which is primarily caused by HMD handheld controllers. This issue impacts students' perception and the accuracy of their task performance (see Fig. 8) and can sometimes be frustrating (Arias-Ruiz-Esquide et al., 2025a).

Fig. 5. Student engagement during the metaverse-based anatomical experiments. The photograph shows the practical application of the tool in a higher education environment.

Additionally, AI's ability to generate content through generative models has been shown to be helpful for creating academic content in anatomy (Chheang et al., 2024, Joseph et al., 2025). To explore this capability further, one of our experiments involves creating a metaverse environment where students can simulate a clinical visit by interacting vocally with virtual characters powered by genAI (e.g., ChatGPT). This scenario is illustrated in Fig. 9.

This evaluation suggests that AI represents a versatile and cost-effective technical resource for metaverse applications. Within virtual environments, such as those detailed in Section 3.1, AI can mitigate technological limitations during tissue dissection while potentially enriching the learning experience through AI-driven agents. These preliminary findings indicate that integrating such AI tools into the metaverse could offer a scalable means of addressing diversification challenges in anatomical education.

4. Results

In our first experimental case study (Section 3.1) we describe a common pedagogical intervention within the metaverse that we have established in our School of Healthcare Sciences (Rodriguez-Florido et al., 2024b).

In this work, we present a re-analysis of those findings derived from our practical application of the metaverse. This new study is the first to

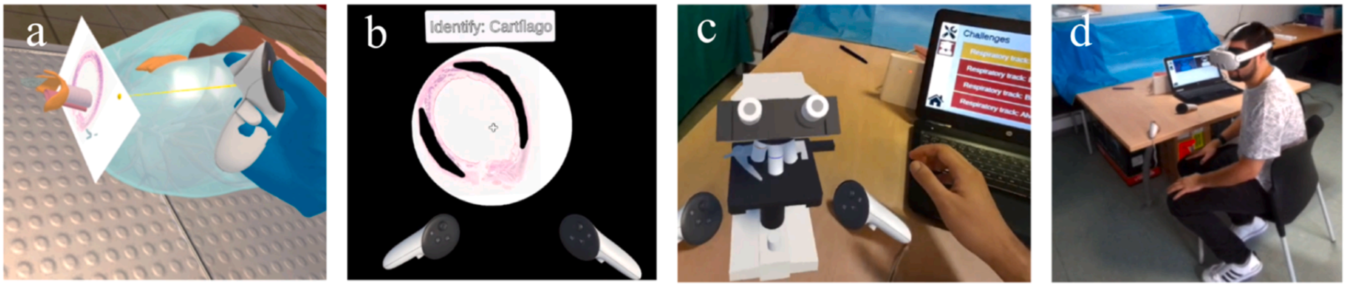

Fig. 6. Virtual scenario within metaverse in VR and AR modes. (a) VR mode view which displays the human respiratory system accompanied by a scaled and superimposed microscopic tissue image (b) Microscopic image presented to the student as part of an academic task when viewed through the virtual microscope (c) Virtual microscope superimposed on the physical surroundings (AR mode) (d) A group member utilizing an HMD to visualize the virtual microscope in AR mode, as depicted in Fig. 6c.

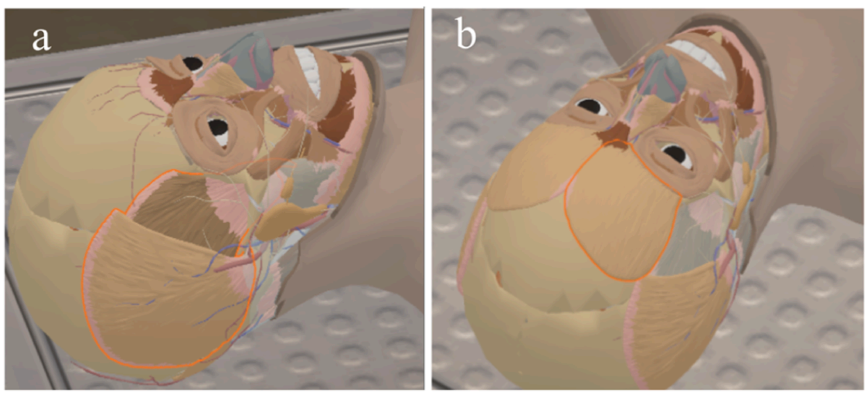

Fig. 7. Illustration of overlying structures complicating isolated muscle selection. (a) The occipitofrontal temporal muscle shown with associated neurovascular structures. (b) The frontalis muscle presented in isolation for comparative clarity.

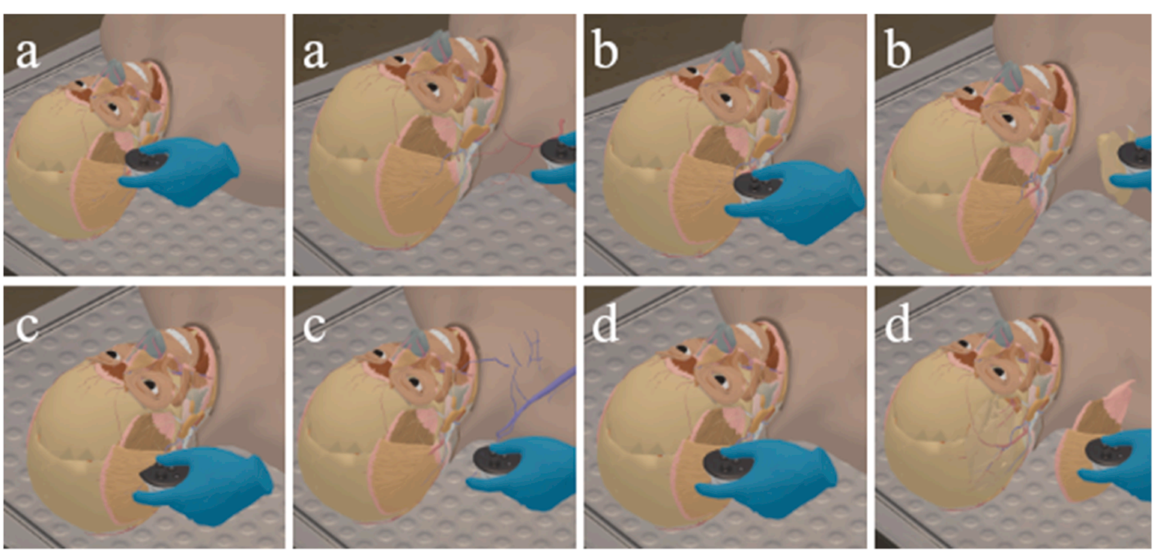

Fig. 8. Examples of errors and successful attempts by students when grasping the occipitofrontal temporal muscle within the metaverse. In (a), notice the failure by selecting an artery, in (b) they select the temporal bone, in (c) a vein, and in (d), that is a less cluttered area, the target is successfully extracted.

analyze these results through an inclusive and diverse lens and yields new results for addressing the anatomical education diversity challenges discussed in the Introduction.

To contextualize these new results, it is necessary to recapitulate the experimental details and key findings of our previous work, particularly as the cited study was published in a language other than English.

The validation of the collaborative virtual dissection room was conducted by 240 students (122 individuals in Human Anatomy, 61 in Human Anatomy II, and 57 in Human Anatomy III). We employed a validated questionnaire to gather data (Rodriguez-Florido et al., 2024a). Responses were rated on a 1–5 scale for assessing several intrinsic metaverse topics (presence, immersion, concentration, handling the environment, emotional response, technological enthusiasm, and general assessment) and, additionally, on a Yes/No basis for other feeling

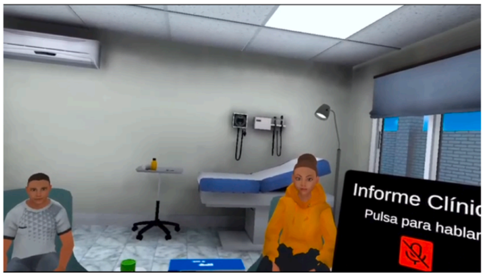

Fig. 9. Illustrative view of the metaverse environment where generative AI has been included. Notably, the virtual characters displayed are AI-driven agents designed to be interactive and to generate verbose feedback upon user engagement.

aspects (e.g., capturing attention, familiarity, and adverse effects).

To facilitate the interpretation of these topics, the data are presented in a boxplot (Fig. 10), depicting the average values for each subscale measured on a 5-point Likert scale.

Participants rated the pedagogical tool favorably across all scales, suggesting it is perceived as both functional for learning and effective for accessing scarce materials, such as cadavers and laboratory equipment. Building upon these findings, the data also indicates that students value the metaverse for its capacity to represent varied anatomical scenarios, such as pathological cases and diverse demographic features, that are often underrepresented in traditional curricula.

Regarding the binary (Yes/No) questions pertaining to the "capturing attention" and "familiarity" scales, our results indicated that, on average, 90.0% of healthcare students affirmed that the quality of the metaverse scene facilitated their attention. Furthermore, concerning their prior experience, 96.0% of healthcare students stated they are not regular users of metaverse environments, and 98.3% of students indicated they do not own virtual reality or immersive systems. These results also suggest that students' receptiveness and sustained focus within the metaverse, despite their lack of traditional familiarity with such technology, highlight a transformative opportunity. Educators can leverage this inherent engagement to transcend standard curricula and introduce more diverse, complex anatomical scenarios, aligned with the objectives of our work.

Concerning the scale of "adverse effects", the majority of healthcare students reported no issues with the technology: 67.9% reported no dizziness, 89.2% indicated they did not experience headaches, 72.2% reported no visual fatigue, 85.6% stated they did not sweat more than usual, and 88.8% confirmed they did not suffer from vertigo in the metaverse. In the event that a student experienced discomfort, established protocols ensured an immediate cessation of the immersive experience and a transition to alternative academic activities using traditional resources.

However, in the context of the diversification of anatomical education, the minority of students who did experience these adverse effects should be considered.

In addition to these student-centered findings, it is essential to examine educators' perceptions. As a contribution to this work, we address this gap by developing a survey (included as supplementary material). The survey encompassed several thematic areas: educators' expertise in anatomy instruction, traditional pedagogical methods, prior experience with immersive technologies, and their interest in utilizing the metaverse for instruction. Furthermore, it assessed the usability of the platform, the participants' technical confidence, and the perceived utility of the resource. It was designed to capture qualitative insights into the usability and user experience of the desktop-integrated software component described in Section 2.3 (Campbell, 2024). Rather than performing a formal hypothesis-driven quantitative analysis, we conducted an exploratory poll to gauge educators' perceptions after they had gained practical experience with the platform. Administering the survey at the conclusion of the course ensured that participants could provide feedback based on a complete cycle of teaching within the metaverse environment.

We conducted this survey with six educators, one for each subject listed in Table 1. Our findings indicated a willingness to adopt these virtual environments as a new pedagogical resource for teaching anatomy, thereby contributing to the diversification of anatomical education. Although our survey was limited to six participants, our primary intention was not to obtain a quantitative or statistical result, but rather to gain an overview of usability, user experience, and the acceptance of this technology among teachers (Campbell, 2024). A favorable perception of the technology is a prerequisite for its potential adoption and use in diversifying anatomical education.

In our second experiment (Section 3.2), concerning the exploration of AI within metaverse, we have found that AI models enhance the detection of students' decisions and their interaction with the virtual pieces of the human anatomy (e.g. Figs. 7 and 8) (Arias-Ruiz-Esquide et al., 2025b). This improves both student confidence in the learning resource and a teacher's ability to rely on it for assessing academic

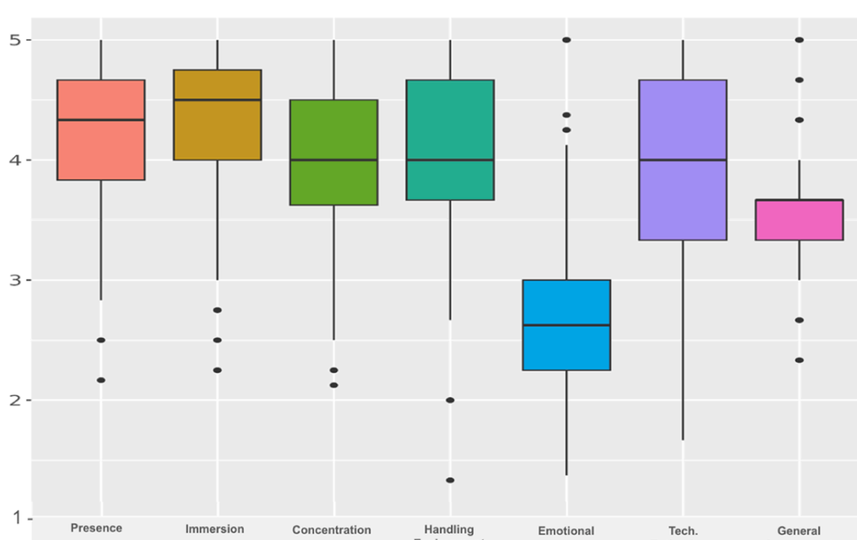

Fig. 10. Boxplot depicting the average values for each subscale, with scores ranging from 1 to 5. Note that for questions within the "emotional" topic, lower values on the scale indicate a more favorable evaluation. The isolated black dots represent singular values derived from the observations.

activities. In the context of inclusive anatomical education, the integration of AI within the metaverse facilitates participation for students with physical impairments who may require additional assistance.

Additionally, consistent with a recent study (Yusuf et al., 2025), our exploratory experiments indicate that using genAI enables real-time data processing and the dynamic generation of virtual content within the metaverse. This technology's capability suggests significant potential for smart, interactive integration within the metaverse, specifically by providing real-time translations, guidelines, and supportive resources to integrate diverse student populations effectively into the classroom learning process.

5. Discussion and conclusions

The metaverse and its underlying technology are currently unfamiliar concepts and novel instructional instruments for a significant portion of the anatomical teaching community. Consequently, this novelty may elicit skepticism or professional resistance, and precipitate extensive questioning when the technology is presented as a solution to existing classroom challenges.

In this paper, our central argument is that the metaverse represents an effective platform for diversifying human anatomy instruction. This study re-analyzes our previous experimental results through the framework of inclusive education to expand upon our earlier conclusions. This work may significantly benefit the anatomical teaching community by informing them about this emerging area, encouraging its adoption, and proposing concrete strategies for tackling the challenges of diversification. While much work remains, we think that the inclusion of a paper presenting the metaverse framework, along with scientifically validated experiences and an approach to the challenges raised in our contribution, will be highly valuable for the educational community.

Our results not only affirm the acceptance of metaverse technology among healthcare students, but also mitigate mentioned challenges related to scarce educational resources (e.g., cadavers and laboratory materials) and offering the potential to integrate diverse anatomical scenarios (e.g., female bodies, pathologies, or variations in habitus and demographic features). Additionally, by presenting human anatomy as a dynamic system and emphasizing structural functionality, the metaverse bridges the gap between anatomical study and the technical interests of non-healthcare students (e.g. bioengineering).

However, it is important to emphasize that the metaverse is not intended to replace the use of cadavers or real equipment (e.g., microscopes) in a student's education. Instead, it is designed to provide access when these resources are limited. Furthermore, the metaverse complements these traditional tools and could even serve as a way to identify students who demonstrate a greater aptitude for handling such limited resources.

Regarding the use of this specific technology within the metaverse (e.g., immersive devices) in our study of healthcare students, our results indicate that metaverse technology is an effective medium for engaging students and disseminating anatomical knowledge. This finding is significant because it supports the application of metaverse technology to facilitate the integration of diverse student populations, such as those with language barriers, cultural differences or disabilities, thereby diversifying anatomical education through customizable features like guidance prompts and scaffolding.

However, the data also revealed that a minority of students experienced adverse effects, a finding that warrants careful consideration within the context of diversifying anatomical education. Specifically, this suggests the potential for metaverse technology to inadvertently become a source of exclusion. Consequently, this possibility necessitates further investigation.

Concerning anatomical educators, the findings indicate a readiness to adopt this technological resource as a novel pedagogical tool complementary to conventional teaching methods. They recognize its potential to mitigate educational bias (e.g., through access to diverse anatomical models in virtual dissection rooms) and view it as an effective supplement for enhancing student engagement in human anatomy knowledge. Thus, given the educators' openness to adopting this technology for accessing scarce pedagogical resources and integrating it with conventional anatomical teaching methods, they are likely to incorporate the metaverse to enhance diversification in anatomical education. This alignment is crucial, as educators are the primary drivers of curriculum development and resource integration; their acceptance is therefore essential for the effective implementation and sustained validation of our pedagogical proposal.

Pertaining to the integration of AI into the metaverse, our experimental and previous findings allow for an expanded interpretation. AI technology can be seamlessly implemented without technical issues, and it aims to establish a novel and highly diversified approach to anatomical education. The incorporation of AI models minimizes the constraints of technology, correcting inaccuracies resulting from the inherent imprecision of immersive devices (e.g., Fig. 8). This predictive capability also allows the system to anticipate student actions and intervene, thereby compensating for interactions where the core technology may fail. Thus, the metaverse offers robust functionality for educators while ensuring a seamless experience for students and it is also designed to facilitate participation for those with physical impairments who may require additional assistance.

Furthermore, genAI services can also be integrated to interact in real time within the metaverse and generate personalized content. This capability suggests key functions (e.g., real-time translations of anatomical text, personalized tutoring, and adaptive audio or text support for students with specific needs) that guide and support students in a diverse anatomical education environment. Specifically, although further research in this domain is warranted, AI-driven agents (e.g., see Fig. 9) can interact intelligently and dynamically with students, providing personalized tutoring support in specific contexts or to further diversify anatomical education.

In conclusion, our research indicates that the metaverse offers several key advantages for approaching diversity in anatomical education:

- It addresses the needs of those who lack the necessary material resources in their educational institutions (e.g., cadavers and laboratory equipment).
- It enables remote connection for both students and teachers, facilitates the incorporation of specific virtual models for enhancing the anatomical diversity (e.g., female bodies, pathologies, or variations in habitus and demographic features).
- It efficiently supports AI models for minimizing the limitations of the immersive technology in real time and also facilitates participation for those with physical impairments who may require additional assistance.
- It monitors and measures all student activity within its digital environment, enabling educators to conduct assessments that are responsive to the diverse circumstances of each student.

In addition, while the integration of AI requires further investigation, our preliminary observations within the metaverse potentially suggest that:

- It is capable of supporting translation into different languages and allows for the use of guidance material for students with specific needs (e.g., deaf or colorblind individuals).
- It is capable of providing unlimited accessibility for students with physical restrictions or mobility issues (e.g., wheelchair users or students recovering from injuries).
- It is capable of including genAI for automating some key functions (e.g., real-time translations of anatomical text, personalized content, and adaptive audio or text support for students with specific needs) or for including AI-driven agents for tutoring within the metaverse.

Limitations of this work and future directions

While this work establishes a foundational framework for diversifying anatomical education, presents new approaches, and paves the way for tackling some of the diversification challenges outlined in the Introduction, we acknowledge that this study does not yet incorporate a dedicated quantitative evaluation to validate those interventions in this area. To address this, future research will statistically measure the efficacy of the environment by tracking shifts in student “Sense of Belonging” (Dias-Broens et al., 2024), the mitigation of attainment gaps across demographic groups, and objective performance on anatomical assessments.

This subsequent research will explore three interventions:

- Intervention 1: Examine the role of the metaverse in fostering inclusivity within a diverse student population. Our institution’s multicultural setting includes a student body of European, African, and South Asian descent.
- Intervention 2: Examine the integration of the diverse academic and linguistic backgrounds of Erasmus+ mobility students. Our university hosts a significant number of European exchange students annually.
- Intervention 3: Investigate whether the metaverse acts as an exclusionary pedagogical resource.

It is essential to evaluate whether the metaverse inadvertently excludes certain students due to adverse effects or the integration of genAI assets to augment existing academic content (e.g., features like contextual overlays, real-time visualization of anatomical variations, and AI-driven agents for tutoring within the metaverse).

In both Interventions 1 and 2, students will interact with virtual models representing ethnic anatomical variations and engage with AI agents to request diverse phenotype models or adaptive translations. We will evaluate specific engagement metrics, such as the correlation between personalized feature use and learning outcomes. Evaluation will also include the frequency of AI agent utilization, longitudinal “Sense of Belonging” questionnaires to measure perceived inclusion, and comparative assessments to identify attainment gaps and ensure mastery of diverse phenotypes while removing language barriers.

Intervention 3 will be examined in detail, evaluating longitudinal “Sense of Belonging” questionnaires to determine if students who experience adverse effects, or those who rely on genAI for support, perceive an academic gap between themselves and their peers or feel a diminished sense of academic self-efficacy.

Furthermore, we intend to evaluate the implementation of remote access for students and instructors beyond the university’s internal network. This expansion will allow the platform to serve geographically distant learners and educational centers, fostering global knowledge exchange. While this supports the widespread dissemination of educational resources, it necessitates a robust framework for data security and privacy. Additionally, proactive ethical oversight is imperative when leveraging genAI for content production; these models must be closely monitored to prevent outputs that reflect cultural or religious insensitivities.

Since the current curriculum is already in progress, the experimental validation is scheduled for the next academic year. The proposed timeline guarantees feedback based on a complete cycle of teaching. The interim period is dedicated to the iterative design and technical refinement of virtual assets, questionnaires, and other research materials under the direct supervision of anatomy educators. This deliberate timeline ensures that the resulting quantitative data is underpinned by a mature, educator-validated technological ecosystem.

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CRediT authorship contribution statement

Castro P. L.: Writing – review & editing, Investigation. **Rodriguez-Florido Miguel Angel:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Resources, Methodology, Investigation, Conceptualization. **C. Sosa:** Writing – review & editing, Investigation. **S. Sacchini:** Writing – review & editing, Investigation. **J. A. Ramírez:** Writing – review & editing, Investigation. **C.P. Krasucki:** Writing – review & editing, Investigation. **L. Pérez:** Writing – review & editing, Investigation. **Suárez-Santana C. M.:** Writing – review & editing, Investigation.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.aanat.2026.152832.

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