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Review

Rethinking Human Anatomy Teaching: From Dissection to Digital Innovation and Beyond

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Abstract

Human anatomy teaching is undergoing a rapid transformation driven by digital innovation, immersive visualization, open multiscale datasets, and changing learner profiles, while donor-based dissection nevertheless remains essential for understanding human anatomical variability and tissue properties and may contribute to students' professional identity formation when supported by structured reflection. In this narrative review, we synthesize peer-reviewed literature, prioritizing contributions most relevant to current educational practice and governance. We discuss how technology-enhanced resources can extend learning before, during, and after laboratory sessions through manipulable visualization, repetition, and tighter links to imaging and data literacy. We also examine the expanding clinical, research, and innovation roles of donor-based anatomy laboratories and the associated need for explicit governance (biosafety, access control, documentation, and transparency regarding secondary uses). Ethical literacy is treated as a core learning outcome, including inclusive representation, consent and donation law awareness, and critical engagement with plastination and public display. Finally, we consider how attention fragmentation and AI-enabled tools may support personalization and feedback, yet also introduce risks such as automation bias and superficial recognition if not paired with verification and reasoning-based tasks. Overall, the future of human anatomy education lies in purposeful integration of donor-based, digital, immersive, and computational modalities within an adaptive learning ecosystem that serves learners across disciplines while maintaining robust ethical and professional standards.

Keywords: human anatomy education; donor-based anatomy laboratory; virtual reality; body donation and ethics; artificial intelligence

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1. Introduction

Human anatomy teaching is undergoing substantial transformation through the increasing availability of digital platforms, immersive visualization, and multiscale datasets. Donor-based dissection continues to provide direct exposure to human anatomical variation, tissue properties, and three-dimensional relationships [1,2], whereas interactive digital and immersive resources enable repeatable manipulation and visualization of anatomical structures [3,4]. These modalities should therefore be evaluated according to the specific learning outcomes they support rather than treated as interchangeable.

Donor-based anatomy laboratories are also used for postgraduate procedural training and technology-assisted simulation, including models designed to reproduce selected

aspects of operative workflows [5,6]. In parallel, curricular design must address distinct ethical questions using evidence appropriate to each domain: inclusive representation of sex and gender [7], consent and the permitted uses of donated bodies [8], and the preservation and public display of human remains [9].

Rather than treating these developments as separate innovations, we conceptualize them as interacting components of a human anatomy educational ecosystem (Figure 1), while recognizing that their benefits are neither equivalent nor automatic. Evidence concerning professional identity formation (PIF) illustrates the need for particular caution. In a mixed-methods study of medical students, the number of hours of observed or hands-on dissection was not significantly associated with quantitative PIF scores. However, qualitative interviews suggested that dissection may contribute to students' appreciation of humanistic values and patients' personhood [10]. These findings do not establish a causal effect, but indicate that the professional and humanistic value of donor-based learning may depend on how the experience is ethically contextualized and pedagogically structured.

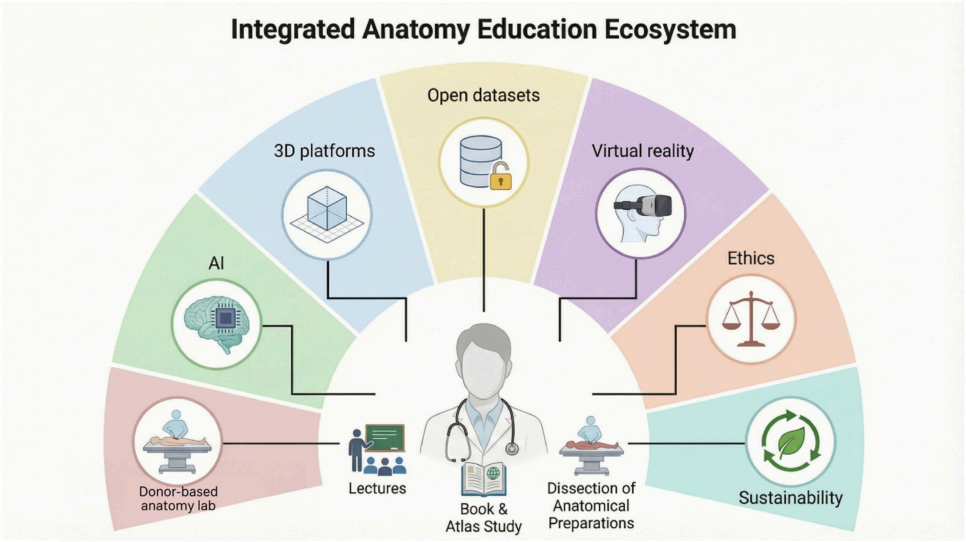


Figure 1. Infographic illustrating an integrated anatomy education ecosystem. Foundational anatomy learning (classroom teaching, atlases/resources, and donor-based experience) is extended by digital and immersive tools, open datasets, AI-supported learning, and multifunctional donor-based anatomy laboratories, all within a governance and value structure that prioritizes ethics, inclusion, and sustainability. This image was created with BioRender.

To move beyond a descriptive metaphor, we define this educational ecosystem through four operational principles: alignment with explicit learning outcomes; complementarity between donor-based, digital, and imaging-based modalities; feasibility and equitable access; and ethical governance accompanied by continuous evaluation. These principles can be assessed using predefined indicators, including performance in spatial and clinical reasoning tasks, opportunities for direct hands-on participation, accessibility across learners, adverse effects, faculty workload, cost per student, and compliance with consent and data-governance requirements. The resulting model is therefore context-dependent: a resource should be retained only when it provides demonstrable educational value without creating disproportionate ethical, organizational, or financial burdens.

This narrative review used a structured literature-search strategy. PubMed and Scopus were searched using combinations of terms related to human anatomy education, donor-based teaching and dissection, digital and three-dimensional resources, virtual and augmented reality, ethics and inclusion, plastination, professional identity formation, ar-

tificial intelligence, sustainability, and anatomy-laboratory infrastructure, as detailed in Table 1.

Table 1. Structured PubMed and Scopus search strategy and raw results.

Search Domain	Thematic Terms Combined with the Anatomy-Education Search Block	PubMed	Scopus
Donor-based anatomy and dissection	"body donation"; "cadaveric dissection"; "cadaver dissection"; "human dissection"; "cadaver laboratory"; prosection	225	317
Digital and immersive technologies	"digital anatomy"; "virtual anatomy"; "3D model(s)"; "3D printing"; "three-dimensional model(s)"; "virtual dissection"; "virtual reality"; "augmented reality"; "mixed reality"; Anatomage	271	512
Ethics, inclusion, and professional identity formation	"body donation"; "informed consent"; "anatomical ethics"; "ethical use"; inclusivity; "inclusive anatomy"; "sex and gender"; "gender diversity"; plastination; plastinated; "public display"; "professional identity"; "professional identity formation"	113	182
Artificial intelligence and cognition	"artificial intelligence"; "generative AI"; ChatGPT; "large language model(s)"; "automation bias"; "cognitive load"; "task switching"; "media multitasking"; attention; gamification; "game-based learning"	106	200
Sustainability and anatomy laboratories	sustainability; sustainable; "environmental sustainability"; formaldehyde; embalming; "anatomy laboratory"; "cadaver laboratory"; "dissection room"; "laboratory design"; "surgical simulation"; "clinical simulation"; infrastructure; interdisciplinary	133	205
Database-specific raw results		848	1416
Selection flow: 2264 raw database records → 1308 unique database records after duplicate removal → integration of 2 supplementary sources → 83 full-text sources assessed → 56 sources included			

Note. The structured database searches covered publications from 2010 up to September 2026. Within each thematic block, terms were combined using OR; each thematic block was then combined using AND with the common search block ("human anatomy education" OR "anatomy education" OR "anatomy teaching" OR "anatomy curriculum"). Raw results overlapped across databases and thematic domains. Two earlier seminal papers, published in 2002 and 2006, have also been included. Although not part of 1308 unique records identified through database searches, they constituted two of the 56 sources included in the final narrative synthesis.

The structured database searches covered publications from 2010 up to September 2026, a period selected to capture the rapid expansion of digital, immersive, and AI-supported approaches, together with recent developments in ethics, governance, and sustainability in human anatomy education. Two earlier key sources, published between 2002 and 2009, were also included as necessary for the historical and conceptual context of the review.

Peer-reviewed publications and authoritative institutional or regulatory sources were included when they were directly relevant to human anatomy education, had methodological, pedagogical, ethical or regulatory significance, or contributed to current educational practice and governance. Sources were excluded when they lacked a substantive connection to human anatomy education, addressed clinical or technological applications without a relevant educational component, provided insufficient information for assessment, or did not add distinct evidence to the narrative synthesis.

The PubMed and Scopus searches yielded 1308 unique records after duplicate removal. Following title and abstract screening and the integration of supplementary sources, 83 full-text sources were assessed for eligibility, and 56 were included in the final narrative synthesis.

We first examine technology-enhanced learning, focusing on contemporary 3D platforms, immersive modalities, and the growing role of open, multiscale datasets as resources for both visualization and inquiry. We then discuss how donor-based anatomy laboratories are expanding beyond their traditional teaching function to become hubs for clinical training, morphological research, and interdisciplinary innovation. In parallel, we address

inclusion and ethics as central components of modern anatomy curricula, with particular attention to how human bodies are represented and used in education, and to the ongoing debate surrounding plastination and its role in public exhibitions. Finally, we consider how changing student cognition intersects with the opportunities and risks introduced by artificial intelligence, shaping attention, learning strategies, and the nature of anatomical expertise.

Overall, the aim is not to replace donor-based dissection but to embed it within a broader educational ecosystem that equips learners to navigate the scientific, technological, and ethical challenges of contemporary biomedical science.

2. Human Anatomy: An Operational Definition for Teachers, Health Care Professionals and Scientists

According to the Italian Ministry of University and Research, human anatomy addresses the "morphological organization and structure of the human body" across macroscopic, dissectoral, microscopic, ultrastructural, and molecular levels, including development, individual variation, functional and clinical implications, and imaging-based methods. Its areas of interest include Human Anatomy, Clinical Anatomy, Topographical Anatomy, Surgical Anatomy, Radiological Anatomy, and Neuroanatomy [11] (authors' translation).

Human anatomy therefore comprises the multilevel study of human morphology in both clinical practice and research, with a continuous exchange between the teaching and dissection room and multiple clinical domains.

Human anatomy therefore provides an essential foundation for medical, health-professions, and biomedical disciplines concerned with the human body.

In many degree programs, human anatomy provides students with their first structured encounter with the patient and the body as a whole. This formative experience encourages an empathetic, responsible, and ethical relationship with the human body that may shape students throughout their professional lives.

Professional identity formation (PIF) is the process through which students internalize the values, responsibilities, and behaviors of their future profession. In human anatomy education, engagement with a donor may encourage reflection on personhood, mortality, empathy, respect, and professional responsibility. However, this effect is not automatic: Ong et al. found no significant association between time spent in dissection and quantitative PIF scores, although their qualitative findings suggested greater appreciation of humanistic values and patients' personhood [10]. Structured reflection activities may therefore help students recognize and articulate these professional values, making PIF an explicit learning outcome rather than leaving it solely to the hidden curriculum [12].

3. Anatomy in Undergraduate Medical Education

Digital platforms have expanded the ways in which students engage with anatomical structures, and contemporary curricula increasingly integrate virtual resources for exploration, preparation, and consolidation [13]. Online instructional anatomy videos and self-guided, video-based prosection modules allow students to revisit anatomical demonstrations outside scheduled laboratory sessions and are used particularly for practical-class preparation and revision [14,15]. However, their educational benefits are not uniform: video-based resources may support anatomical understanding without necessarily improving performance across the entire cohort or promoting critical reflection. They should therefore complement, rather than replace, active and hands-on learning [14,15].

The online availability of a resource does not establish its ethical provenance. Before using dissection videos or donor-derived images, including content hosted on open platforms such as YouTube, educators should verify the source of the material, the scope

of donor consent, and authorization for recording and online distribution. Resources for which appropriate consent cannot be verified should not be incorporated into teaching; secure institutional platforms with restrictions on downloading and redistribution should be preferred [16,17].

Even in technology-rich curricula, classroom teaching remains a cornerstone of anatomy education, but its format is evolving (Figure 2). Traditional lectures are increasingly complemented by flipped-classroom models, short case-based segments, and structured in-class questioning that promotes active retrieval and integration with imaging and clinical reasoning. In this context, digital resources are most effective when they are intentionally sequenced around core teaching moments pre-class preparation, in-class application, and post-class consolidation rather than treated as optional add-ons.



Figure 2. Representative image of a traditional university lecture hall used for human anatomy teaching. This conventional setting can support evolving formats, including flipped-classroom preparation, case-based teaching, and structured in-class questioning.

Alongside high-technology resources, low-tech embodied strategies remain valuable: "living/surface anatomy" activities (e.g., surface landmarking and guided palpation) and brief learner-generated sketching can promote active encoding and help link systematic, topographic, and surface anatomy to clinically meaningful landmarks [18].

3.1. Digital Anatomy Platforms

Interactive 3D digital tools allow learners to manipulate anatomical structures and explore spatial and functional relationships from multiple viewpoints. Their educational value, however, is not uniform across learners. In a controlled study, active interaction with the Antepulsio platform improved long-term retention relative to passive viewing only among students with higher visuospatial working memory [3]. Similarly, a cross-sectional and randomized study found that lower spatial ability was associated with poorer anatomy performance and that color-coded artistic 3D models produced better post-test scores than photorealistic models [19]. These findings suggest that digital 3D resources should be integrated with appropriate instructional scaffolding and deliberate visual design, rather than assumed to compensate automatically for differences in spatial ability.

In parallel, 3D printing provides portable and reproducible models that can be handled outside the anatomy laboratory and used for self-directed learning, peer teaching, and assessment. These models are particularly useful for anatomical regions that are spatially complex, difficult to dissect, or not repeatedly accessible within limited laboratory time. Systematic reviews and meta-analyses indicate potential benefits for anatomical understanding and learner satisfaction, particularly when printed models are integrated with, rather than substituted for, traditional resources [20–22]. However, educational effectiveness varies with model design and study methodology. Production time and cost can be substantial, while segmentation errors, limited resolution, unrealistic colors or textures,

and the absence of genuine tissue properties may reduce anatomical fidelity. Material consumption and plastic waste should also be considered. Institutions should therefore select and validate models according to specific learning outcomes and ensure appropriate consent and governance when printing files are derived from donor imaging data.

3.2. Virtual Dissection Table

Virtual dissection tables (e.g., the Anatomage Table, Asclepius Virtual Dissection Table, Surglasses Virtual Dissection Table, Virtual Anatomy Table, Digital Anatomy, 3D Anatomix, and Sectra Table for medical education) have gained attention because they mirror the logic of layer-by-layer dissection while enabling rapid resetting, repetition, and cross-sectional exploration. Their ability to display anatomy in radiological planes supports early integration of imaging literacy. Reported uses include structured pre-lab preparation, targeted post-lab consolidation, and case-based integration using CT (computed tomography) and MRI (magnetic resonance imaging) datasets [23]. These commercial examples are illustrative rather than exhaustive because multiple vendors provide comparable functionality.

However, tactile learning is inherently absent, and over-reliance on virtual dissection may lead students to underestimate the complexity of real human tissue (e.g., adhesions, pathological changes, interindividual variations or irregularities) [24]. These limitations reinforce the value of virtual tools as complements rather than replacements for donor learning (Figure 3).

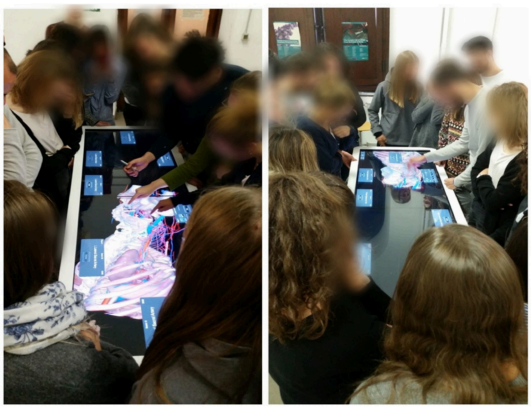


Figure 3. Representative image of a virtual anatomy table supporting interactive, repeatable exploration and imaging-oriented visualization. Although useful for layered and cross-sectional learning, virtual tables do not provide tactile feedback and may underrepresent tissue properties, pathological changes, and interindividual variation.

3.3. Virtual and Augmented Reality

Virtual reality (VR) provides immersive 3D environments, whereas augmented reality (AR) superimposes digital anatomical information onto the physical environment. Both modalities can support interactive exploration of spatial relationships in human anatomy, but their educational value varies according to hardware configuration, interface design, anatomical content, learner characteristics, and the comparator used. In a 2025 systematic review of 15 studies of VR-based anatomy education in health sciences and allied health, only four of the eight studies evaluating knowledge acquisition or retention reported statistically significant improvements following VR adoption. Most studies were conducted at a single institution, only one-third used random allocation, and differences in hardware and comparison methods limited generalization [25]. Similarly, in a randomized study of 59 participants learning skull anatomy, assessment scores did not differ significantly between VR, AR, and tablet-based instruction; VR users also reported headaches, dizziness,

and blurred vision more frequently [26]. Engagement and satisfaction should therefore not be treated as proxies for improved anatomical knowledge.

Implementation feasibility also changes substantially with cohort size. In a course involving 292 first-year medical students, limited equipment and curricular time required students to rotate around the virtual dissection table in groups of 10–15 for brief instructor-led demonstrations, without performing their own virtual dissections [27]. This illustrates how technology intended for active exploration may become predominantly demonstrative when student throughput is not considered. Institutions should therefore evaluate total cost of ownership rather than purchase price alone, including hardware, software licenses, upgrades, replacement cycles, network capacity, reliable power supply and charging, secure storage, cleaning of shared headsets, technical support, and faculty training [25,28]. Large-scale adoption should be preceded by pilot testing and accompanied by non-immersive alternatives, monitoring of equitable access and adverse effects, and evaluation of objective learning outcomes and cost per student.

3.4. Large-Scale Anatomical and Neurobiological Data

One of the most transformative trends in anatomy education is the availability of large, open-access datasets that go far beyond traditional anatomical representations. For example, EBRAINS, developed as part of the European Human Brain Project, provides high-resolution structural and functional brain atlases, multimodal datasets integrating MRI, histology, electrophysiology, and connectomics, interactive 3D viewers that allow navigation across different levels of organization, and educational modules that enable instructors to design investigation-based learning experiences [29,30]. EBRAINS allows students to explore how macroscopic structures relate to cellular distributions, connectivity patterns, and computational models. This provides a more integrated understanding of brain organization than classical dissection alone, which often remains confined to macroscopic relationships.

Similarly, the Allen Institute for Brain Science hosts a suite of datasets, including gene expression atlases and detailed cell type typologies that allow students to visualize the nervous system at microscopic scales. Recent courses have demonstrated how connectomics data can be incorporated into neuroscience education to promote data literacy and strengthen conceptual understanding. These infrastructures position anatomy as a multi-scale discipline, linking structure and function in ways that align with modern biomedical research and clinical innovation [31]. More broadly, open anatomical resources exist beyond neuroscience. For example, the U.S. National Library of Medicine's Visible Human Project provides publicly available cross-sectional cryosection, CT, and MR image datasets from a male and a female donor, which can be used to teach regional and cross-sectional anatomy and to link gross anatomy to radiological planes [32]. Because the datasets are fully standardized and can be revisited repeatedly, they support case-based exploration of thoracic, abdominal, and musculoskeletal regions and help learners practice spatial navigation across planes and levels of detail.

Importantly, these modalities can help students connect systematic, topographic, and surface anatomy within a single learning pathway, linking structure identification to spatial navigation, imaging planes, and clinically meaningful landmarks. As digital tools extend learning beyond the laboratory, they also change expectations for what the laboratory itself should provide. The next section therefore shifts from curricular tools to the donor-based anatomy laboratory as an educational and research infrastructure, highlighting how its role has expanded and what this means for training, governance, and collaboration.

4. Functional Roles of the Donor-Based Anatomy Laboratory (Clinical Education, Morphological Research, and Interdisciplinary Innovation)

Donor-based anatomy laboratories have evolved far beyond their traditional role as spaces for student dissection. In contemporary biomedical education and research, the anatomy laboratory functions as a complex environment where anatomists, clinicians, biomedical engineers, and technology developers collaborate (Figure 4). This interdisciplinary dynamic reflects the changing expectations of both anatomy and surgery, as well as the increasing integration of new technological tools into training and research [5]. While the clinical role of donor-based anatomy laboratories is widely recognized, particularly in the training of residents and surgeons in complex procedures, their importance for anatomists is equally significant but less often emphasized. Anatomists use donor-based anatomy laboratories not only to educate but also to generate new morphological knowledge, validate anatomical models, and maintain the scientific expertise necessary to interpret variation, pathology, and surgical relevance [33].

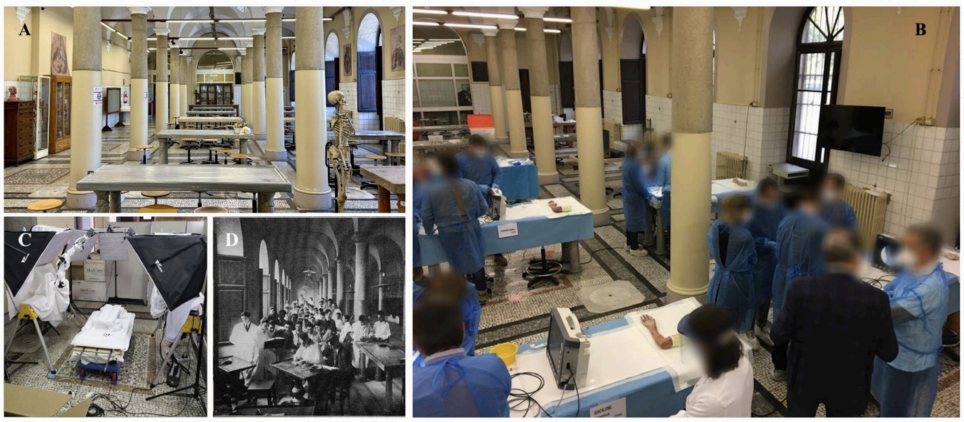


Figure 4. (**A**–**C**) Representative images showing the dissection room with workstations using donor material to support hands-on learning of anatomical variability; (**D**) representative image showing the dissection room at the beginning of the 20th century.

4.1. The Donor-Based Anatomy Laboratory as a Clinical Training Environment

Donor-based anatomy laboratories remain essential for surgical training and skill acquisition. Donor tissue provides unparalleled realism that cannot be replicated by digital or synthetic models. It offers tactile feedback, natural anatomical variability, and exposure to the complexities of human morphology, such as adhesions, vascular anomalies, congenital variants, and pathological alterations. Unlike idealized digital or synthetic models, donor material reflects clinically relevant variation in body composition, age-related changes, and pathology [34]. These features are critical for residents learning procedures in neurosurgery, orthopedics, otolaryngology, and minimally invasive surgery. Modern anatomy laboratories often incorporate intraoperative imaging, navigation systems, endoscopic towers, robotic surgery consoles, and augmented reality overlays to simulate operative workflow more accurately [35,36]. These integrations help learners bridge anatomical knowledge with procedural performance and clinical reasoning.

4.2. The Donor-Based Anatomy Laboratory as a Morphological Research Hub for Anatomists

For anatomists, donor-based anatomy laboratories maintain a central role that extends significantly beyond teaching. Anatomists use these laboratories as a scientific environment where new knowledge about human structure continues to be produced. Despite the rise of digital anatomy, direct study of human donor material remains indispensable.

First, work with donor material reveals the breadth of anatomical variability, including arterial branching patterns, muscular asymmetries, and atypical nerve courses, which is often underrepresented in idealized textbook anatomy yet is essential for research and clinical translation [6]. Second, anatomists contribute to clinical practice by providing detailed morphological interpretations that support surgical planning, anatomical corridor analysis, and the preclinical evaluation of novel techniques; these insights cannot be fully reproduced by computational models alone. Finally, donor-based anatomy laboratories support the training and continuing professional development of anatomists: advanced dissection skills, prosection expertise, and the ability to interpret meaningful variation require prolonged hands-on exposure and support the discipline's methodological rigor [37].

4.3. The Donor-Based Anatomy Laboratory as an Interdisciplinary Learning Environment

Laboratory environments using donor material enable iterative testing of prototype instruments, robotic systems, imaging devices, and procedural approaches before clinical deployment. Anatomical expertise is crucial for identifying limits and opportunities not evident from digital models alone [35]. Programs such as the simulation center in Poitiers demonstrate how anatomy, surgery, and engineering can converge to enhance training and accelerate innovation, including through advanced dynamic perfusion models. In this setting, "perfusion" does not simply refer to the one-time vascular injection of fixative used in standard embalming; rather, the donated body is connected to a pump-based system that continuously circulates a temperature-controlled, colored fluid through the vascular network to simulate physiologic flow and flow-dependent procedural conditions. This enables more realistic rehearsal of surgical contexts, including bleeding-related scenarios, time pressure, and team-based workflows, while still maintaining a controlled training environment [6].

Within this evolving context, the modern donor-based anatomy laboratory supports diverse activities, including anatomy learning, surgical training, development of clinical approaches, device testing, and morphological research. This multifunctionality strengthens the educational and scientific impact of anatomy departments and ensures that the discipline remains relevant in an era of increasing biomedical complexity. This expansion also requires explicit governance: clear protocols for donor stewardship, biosafety, access control, and documentation of procedures performed on donors, as well as transparency regarding secondary uses (research, device testing, or commercial collaborations). When these elements are articulated as part of the curriculum, learners can connect technical competence with professional responsibility and respect for the donor [8,17].

These expanded roles define what a modern donor-based anatomy laboratory must support. The next section translates these functional requirements into spatial, technological, biosafety, and operational design principles.

5. Physical and Operational Design Principles (Architectural Flexibility, Digital Infrastructure, and Simulation-Compatible Layout)

Accordingly, this section focuses on how architectural flexibility, integrated digital infrastructure, and simulation-compatible layouts can support these activities within a single environment [6,29].

5.1. Redesigning the Architecture of the Dissection Room

A multifunctional dissection room begins with architectural flexibility and robust biosafety. Traditionally, the arrangement of fixed dissection tables, ventilation systems, and storage limited how the space could be used. New designs emphasize modular and reconfigurable layouts with movable tables, flexible lighting, and adaptable workstation

clusters, allowing the same space to support undergraduate and advanced dissection, surgical simulation, and digital anatomy sessions [38].

Environmental controls remain essential. Foundational prerequisites for safe hybrid use include ventilation and filtration systems with negative pressure or forced air exchange where required; appropriate temperature and humidity control; safe chemical handling and storage; formaldehyde-exposure mitigation; and clear workflows that separate "clean" (digital) and "wet" (donor) zones to protect both people and equipment.

Integrated digital infrastructure can support deliberate transitions between donor-based anatomy, digital models, and clinical imaging. Darras et al. integrated six CT-based virtual dissection sessions into a donor-based course involving 292 first-year medical students. Most survey respondents perceived improvements in their understanding of donor-based anatomy and clinical anatomy, although the study assessed perceptions rather than objective knowledge or skills; limited equipment and curricular time also restricted students' direct interaction with the virtual dissection table [27]. Accordingly, we propose that a multifunctional anatomy laboratory should not be defined by a fixed equipment checklist. Connectivity, shared displays, secure access to radiological datasets and, where educationally justified, VR/AR or telepresence facilities should be selected according to learning outcomes, cohort size, staff expertise, technical support, data-governance capacity, and local cost-value analysis [27,28]. AI-assisted tools constitute a separate pedagogical and governance layer and should be evaluated for specific learning tasks rather than used to justify the physical infrastructure.

Beyond physical infrastructure, implementation depends on operational design: scheduling that separates wet-lab and clean-lab activities, staff competencies that span anatomy, simulation, and digital support, and assessment strategies that explicitly integrate outcomes across modalities (for example, requiring learners to move from imaging to donor identification and then to clinical reasoning). In this way, the room itself becomes a learning interface that enables learners to connect representations, evidence, and hands-on experience [5,38].

5.2. Implementation Barriers and Institutional Readiness

Implementation may be limited by initial and recurring costs, infrastructure, technical support, faculty readiness and acceptance, unequal student access, and accreditation requirements. Limited equipment and large cohorts may also transform interactive technologies into predominantly demonstrative resources [27]. Before adoption, institutions should define educational outcomes, assess institutional readiness, and estimate total cost per student, including training, maintenance, licensing, and replacement [28]. New tools should be piloted and evaluated in terms of learning outcomes, accessibility, faculty workload, and cost, while non-digital alternatives should remain available.

6. Inclusion and Ethical Considerations in Current Anatomy Education

The evolution of anatomical education is not only technological; it is also profoundly ethical and cultural. As anatomy integrates digital tools, embraces diversity, and redefines its pedagogical environments, the discipline must continually reassess how human bodies are represented and how donated bodies are used, handled, and contextualized. Three domains have become particularly important: the representation of human diversity, the ethical stewardship of donated bodies, and the controversies surrounding plastination and public anatomical exhibitions. These themes inform not only the moral responsibilities of educators but also how students interpret the meaning of the human body in medical practice [8,39].

6.1. Human Diversity in Anatomical Teaching

Traditional anatomical resources have disproportionately represented young, male, light-skinned bodies. An analysis of 5001 images from 11 commonly used anatomy atlases and textbooks found that 81.2% of images with a codable skin tone depicted light skin and 61.6% of sex-coded images depicted males [40]. Digital platforms can broaden representation by providing selectable models with different phenotypic characteristics. However, these options remain curated and should not be equated with the breadth of interindividual anatomical variation encountered in donor-based courses. Standardized digital models may not adequately represent unexpected variants, pathological changes, or differences in tissue relationships. Digital resources should therefore complement donor-based learning, and educators should critically evaluate their representation of sex, age, body size, skin tone, and anatomical variation [24]. In addition, the increasing visibility of transgender and gender-diverse anatomies highlights the need to teach anatomical variations associated with gender-affirming procedures, intersex conditions, and hormonal influences [39,41]. This inclusivity is not merely sociocultural; it is also pedagogical [39]. Understanding variability enhances diagnostic accuracy, improves patient communication, and supports more equitable clinical care.

6.2. Ethical Considerations and Body Donation Law

Body donation remains the foundation of anatomical education. Yet modern anatomy programs increasingly recognize that interacting with donated bodies is not only a technical exercise but also an opportunity for ethical reflection and empathy. Students who reflect on the donor's identity, altruism, and contribution may develop greater empathy and a deeper understanding of professional responsibility [8].

In addition to individual consent and professional conduct, body donation is shaped by legal frameworks that determine who can donate, how consent is documented, which institutions are authorized to receive bodies, and how remains may be used for teaching, research, or surgical training.

In Italy, the current framework and related professional guidance emphasize transparent procedures, institutional accountability, and alignment between consent and permitted educational or research uses [8]. A brief comparative perspective further clarifies why local policy matters: across countries, consent models, permitted duration of retention, rules for transfer between institutions, and oversight mechanisms can differ substantially. Recognizing this variability helps learners understand that ethical best practice requires not only legal compliance but often a higher professional standard grounded in respect and public trust [8].

In practical curricular terms, educators can make the legal dimension visible by explaining donation pathways to students, clarifying how consent limits permissible uses (e.g., public display vs. academic teaching), and incorporating donor stewardship activities (memorial ceremonies, reflective writing, and explicit discussion of professional responsibilities) into the learning experience. Consistent with this approach, ethical stewardship requires clear and transparent consent, especially when donated bodies may be used for research, device testing, or surgical training beyond teaching. It also requires respectful handling from initial reception to final disposition and safeguards to ensure that commercial partnerships do not compromise dignity or transparency [17]. Explicit attention to the legal basis of donation strengthens public trust and clarifies boundaries between education, research, and innovation activities performed in donor-based anatomy laboratories [8].

6.3. Digital Use of Donor Material and Consent

The digital use of donor-derived material requires specific consent and governance and should not be subsumed under a generic authorization for "educational use." Creating photographs, videos, radiological datasets, surface scans, or 3D files changes the temporal and spatial boundaries of the original donation: unlike physical specimens, digital representations can be duplicated, transferred, repurposed, and retained after the final disposition of the donor's remains. Consent documentation should therefore specify whether digital images or data may be acquired, their intended purposes, permitted users, storage and security arrangements, duration of retention, interinstitutional sharing, publication, public accessibility, and possible commercial use. De-identification reduces privacy risks but does not replace appropriate authorization. Current recommendations also favor secure, password-protected institutional platforms, discourage indefinite retention, and require oversight of image acquisition, use, transfer, and destruction [16,17]. Where existing consent refers only broadly to educational use, institutions should not assume that it authorizes digitization or perpetual online dissemination; if appropriate consent cannot be verified, the material should not be digitized or shared.

6.4. Plastination

Plastination, introduced by Gunther von Hagens in the late 1970s, preserves anatomical specimens by replacing water and lipids with polymers. The resulting preparations are dry, durable, and suitable for repeated handling in ordinary classrooms, small-group sessions, revision stations, and assessment settings, thereby extending access to human anatomical material beyond the laboratory [42,43]. Plastinates can preserve carefully dissected spatial relationships and tissue sections over many years, making them particularly useful for regional, cross-sectional, and neuroanatomical teaching and for integration with clinical imaging. Their repeated use may also reduce the need to handle wet-preserved specimens during routine teaching and consequently limit students' exposure to preservation fluids. Nevertheless, plastination should not be described as chemical-free: specimen production remains technically demanding and requires specialized facilities, solvents, polymers, time, and expertise. Moreover, plastinates are relatively rigid, cannot be re-dissected, and do not reproduce tissue texture or mobility. They should therefore complement rather than replace donor-based dissection. Importantly, the available educational evidence remains limited and has not demonstrated the superiority of plastination over traditional dissection [42,43].

At the same time, plastination has acquired a public-facing dimension through exhibitions that have generated sustained ethical debate. Public displays frequently present plastinated individuals in theatrical or dynamic poses, which may shift the interpretive frame from scientific education toward spectacle and entertainment. The central concerns raised in the literature include the commercialization of human remains, uncertainty regarding the provenance of bodies and the robustness of consent processes, the potential erosion of dignity when bodies are staged for display, and the possibility of cultural or religious insensitivity in how human remains are represented [9,43]. Importantly, these controversies have implications for academic institutions as well: even when plastination is used for legitimate educational purposes, anatomy programs must consider how the technique is framed, explained, and governed to preserve public trust and maintain an ethic of respect for the "donor as teacher".

For academic anatomy programs, plastinated specimens should be used in accordance with clear ethical standards and for explicitly defined educational purposes. This requires appropriate contextualization, transparent documentation of provenance and consent, respectful handling, and avoidance of sensationalist presentation. These safeguards are

essential to distinguish the educational use of plastination within universities from its more controversial use in public exhibitions [44].

7. Contemporary Digital Learning Environments

Contemporary health-professions students learn in an environment in which digital resources and artificial intelligence tools are increasingly available, but their knowledge, curricular exposure, and perceived preparedness remain heterogeneous. In a 2023 survey of 4596 medical, dental, and veterinary students from 192 faculties in 48 countries, respondents generally expressed positive attitudes towards AI and a desire for further education about AI; nevertheless, 75.3% reported little or no knowledge of AI, 76.3% reported no AI-related curricular activities, and perceived preparedness varied across geographical regions [45]. Although these findings are based on self-reported data and are not specific to anatomy education, they caution against treating contemporary students as a homogeneous "digital generation" with a single cognitive profile or learning preference. For human anatomy education, a more appropriate response is to assess learners' actual digital and AI literacy and provide structured support while preserving the sustained spatial reasoning, conceptual integration, and critical evaluation required by the discipline.

7.1. Cognitive and Pedagogical Considerations

7.1.1. Attention, Task Switching, and Cognitive Load

Attention should not be treated as a fixed or generation-specific capacity. In particular, the literature does not support a universal 8-s attention span or a fixed 10–15-min limit after which students cease to attend during a lecture [46]. A better-supported concern is academic media multitasking. A recent meta-analysis of 11 correlational studies identified a small negative association between academic media multitasking and academic achievement, although substantial heterogeneity across studies limits causal inference and generalizability [47]. Educational design should therefore reduce avoidable task switching and digital distraction without assuming that all students have intrinsically shortened attention spans.

These considerations are particularly relevant to human anatomy, where learners may need to coordinate textbook illustrations, interactive three-dimensional models, radiological images, and donor-based structures. Poorly aligned representations can generate split attention and extraneous cognitive load because students must mentally reconcile information presented in different formats or locations. In a small study involving 12 senior medical students during donor-based dissection, the superimposition of donor-specific radiological images through mixed reality was associated with greater EEG-derived engagement and lower cognitive-load indices than viewing the same images on a tablet [48]. The small sample and absence of direct learning-outcome measures make these findings preliminary, but they illustrate why coherence and integration may be more important than merely shortening instructional content. Anatomy educators should therefore sequence representations explicitly, minimize irrelevant interface elements, and incorporate active learning and retrieval opportunities while preserving conceptual depth.

7.1.2. The Role of Play and Gamified Learning

Carefully designed interactive questioning, low-stakes competition, and team-based challenges can serve a dual purpose in contemporary anatomy teaching. First, they function as "attention resets" by periodically interrupting passive reception and re-engaging learners at predictable intervals. Second, they make the retrieval process explicit, prompting students to actively reconstruct knowledge rather than simply re-read or rewatch material. From a cognitive perspective, interpolated testing during lectures has been associated

with reduced mind wandering and improved subsequent learning compared with uninterrupted study, suggesting that brief moments of integrated assessment can support both engagement and retention [49].

In anatomy, this logic can be implemented through short quiz cycles integrated into lectures (e.g., a clinical vignette followed by targeted structure–function questions), rapid "spot and explain" prompts that require students to justify spatial relationships rather than merely name structures, and team-based challenges that distribute cognitive load and encourage peer instruction. Digital visualization tools can further support these approaches by enabling timed identification tasks, guided navigation to a target region, or collaborative annotation of key landmarks. In the laboratory, structured "challenge rounds" can be used to reinforce procedural workflows such as orienting to planes, tracing neurovascular pathways, or interpreting cross-sectional anatomy while keeping the emphasis on reasoning and integration rather than just speed.

However, the educational value of gamified elements depends on design quality. Activities should remain explicitly aligned with learning outcomes, include mechanisms for feedback and correction, and be calibrated to avoid unintended consequences such as performance anxiety, exclusion of less competitive students, or a shift toward superficial recognition at the expense of deeper anatomical understanding. In practice, the most productive format is often low-risk and collaborative: competition against a standard (or a previous performance benchmark) rather than against colleagues, repeated attempts, and prompts that require explanation of relationships, variation, and clinical implications. When designed in this way, gamification functions not as a motivational add-on but as a structured strategy for retrieval, explanation, collaboration, and durable anatomical learning [49]. These cognitive and pedagogical considerations provide the basis for evaluating AI-supported learning, in which the central issue is not only engagement but also the reliability and verification of generated information.

7.2. Artificial Intelligence in Human Anatomy Education

7.2.1. Opportunities and Risks of AI-Supported Learning

Artificial intelligence (AI) is becoming increasingly common in learning environments, including human anatomy education. Its integration offers powerful opportunities but also raises profound questions about cognition, autonomy, and the future of expertise.

AI-driven tools can generate personalized learning pathways based on student performance; label anatomical structures in imaging datasets; create adaptive quizzes that identify conceptual weaknesses; support automated tutoring systems that explain complex anatomical relationships; and assist with 3D reconstruction from radiological data [50–52].

These technologies may improve learning efficiency and support higher-level activities. However, overdependence on AI may weaken spatial reasoning, error detection, and conceptual integration. Automation bias occurs when learners accept algorithmic outputs even when they are incorrect. In anatomy education, this may involve accepting an AI-generated label that misidentifies a nerve or vessel, or relying on an automated segmentation that omits an anatomical variant, without checking the result against validated atlases, imaging, or donor material. Superficial recognition may occur when a student can select a named structure in a labeled image but cannot trace its course, explain its spatial relationships, recognize anatomical variation, or predict its clinical implications [51,52]. The central educational safeguard is therefore verification: AI output should initiate, rather than conclude, anatomical reasoning.

7.2.2. Practical Integration, Assessment, and Faculty Development

AI should be introduced through bounded and verifiable learning tasks rather than unrestricted answer generation. Before laboratory sessions, students may use institutionally approved generative AI to generate practice questions or explain spatial relationships, but they should verify each output against validated atlases, imaging datasets, or donor material and document any errors. In imaging-based activities, learners can compare AI-assisted labels or segmentations with manual identification and explain discrepancies. Assessment can include "identify, verify, and correct" exercises based on deliberately flawed AI outputs, requiring students to justify anatomical relationships, variability, and clinical relevance. Unsupervised generative AI should not be used as the sole assessor or source of feedback.

Faculty development should address task selection, interpretation of uncertainty, privacy, copyright, and donor-data governance. Programs should define permitted uses, provide equitable access to approved tools, prohibit the unauthorized uploading of patient or donor material, and pilot AI activities before wider implementation. Evaluation should consider knowledge, reasoning, error detection, accessibility, faculty workload, and cost, rather than learner satisfaction alone [16,17,45].

Overall, AI should function as a supervised and verifiable aid to anatomical reasoning, not as a substitute for direct observation, validated resources, or expert judgment. Its adoption should also account for the environmental and economic consequences discussed in the following section.

8. Sustainability Challenges

Human anatomy laboratories entail environmental and economic costs. Establishing a dissection facility in compliance with occupational safety and biosafety regulations requires resource-intensive infrastructure, including forced air exchange, air conditioning, appropriate cleaning systems, and safe freezers [53]. Technology-enhanced facilities may also require high-resolution audiovisual systems for recording, transmission, and remote observation.

Anatomy laboratories also rely on preservation chemicals and disposable materials (including plastic waste and 3D-printing materials) [54,55]. Green laboratory practices should include optimizing reagent volumes, adopting less hazardous alternatives, properly segregating waste, and reducing or reusing consumables whenever possible. Institutions using donor material must also ensure the legally compliant management and final disposition of human remains. These processes have environmental and economic implications alongside their ethical and regulatory requirements.

Digital anatomy is not environmentally or economically neutral. Audiovisual systems, virtual dissection tables, and computers are subject to hardware obsolescence, software discontinuation, recurrent licensing, maintenance, and upgrade costs. Their life-cycle impact also includes manufacturing, energy consumption, and electronic waste.

AI systems and data-intensive platforms used in anatomy have environmental costs related to computational demands, cloud storage, and repeated model use [56]. As anatomy becomes more technologically driven, educators should weigh pedagogical benefits against ecological impacts and consider strategies for sustainable use.

In this context, shared interdepartmental laboratories or anatomy centers may provide a more sustainable organizational model by pooling facilities, equipment, expertise, and maintenance costs. These centers may involve anatomists, surgeons from different specialties, technical staff, and bioethicists, as well as companies interested in testing new instruments within an appropriate ethical framework. Sustainability should therefore

be treated as an institutional design criterion rather than as a secondary consequence of technological adoption.

9. Concluding Remarks

Human anatomy education is undergoing a profound transformation. Donor-based dissection remains foundational for appreciating human variability, tissue properties, and the embodied realities of the human body; however, it now functions within a more extensive educational ecosystem enriched by digital visualization, immersive technologies, open and multiscale datasets, and AI-enabled tools. Rather than competing with dissection, these modalities can extend learning before, during, and after laboratory sessions by supporting repeated exposure, personalized support, and new forms of inquiry that bridge macroscopic structure with imaging, data science, and contemporary biomedical research.

At the same time, the expansion of anatomical education must be matched by a parallel expansion of ethical literacy. Donor dignity, transparent consent, and careful stewardship of human remains are not peripheral concerns but central curricular responsibilities, particularly as donor-based anatomy laboratories increasingly support research, device development, and procedure-oriented training. Similarly, improving the representation of human diversity in anatomical resources and engaging critically with controversial practices such as the public display of plastinated bodies help ensure that anatomy remains grounded in respect, equity, and public trust.

The multifunctional dissection room embodies this integrated vision. Conceptually, it is not merely a place for tissue-based teaching but a flexible infrastructure in which learners can connect dissection with imaging, digital and immersive visualization, interdisciplinary collaboration, and structured forms of active learning. Practically, it creates a shared environment in which students, anatomists, clinicians, and innovators can work together while maintaining clear governance and professional standards. In this model, the future of anatomy education is defined not by the replacement of traditional methods but by their purposeful integration with new tools, data, and pedagogical strategies. By embracing adaptability, inclusivity, and ethical depth, anatomy education can prepare learners across disciplines to navigate the cognitive, technological, and cultural complexities of contemporary biomedical science and practice.

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