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INNOVATIVE TECHNOLOGIES IN ANATOMY EDUCATION AND THEIR INTEGRATION WITH ARTIFICIAL INTELLIGENCE

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Abstract. Human anatomy is a fundamental component of medical education because accurate anatomical knowledge is necessary for physical examination, medical imaging interpretation, diagnosis, and safe clinical procedures. Traditional methods, including lectures, textbooks, anatomical models, and cadaveric dissection, remain important; however, they may be limited by reduced teaching hours, insufficient cadaver availability, high maintenance costs, and difficulties in presenting complex three-dimensional relationships. Digital technologies and artificial intelligence offer new opportunities to create interactive, adaptive, and clinically oriented learning environments. This study aimed to analyze innovative technologies used in anatomy education and evaluate their relationship with artificial intelligence, including their educational advantages, limitations, and potential directions for implementation. A narrative literature review was conducted using recent scientific publications on anatomy education, artificial intelligence, virtual and augmented reality, three-dimensional visualization, virtual dissection, simulation, gamification, and intelligent tutoring systems. The findings were organized according to the principal technological approaches, their pedagogical functions, reported educational outcomes, and implementation challenges. Virtual reality, augmented reality, mixed reality, three-dimensional anatomical platforms, virtual dissection tables, mobile applications, three-dimensional printing, gamification, and online learning environments improve access to anatomical content and support interactive visualization. Artificial intelligence extends the capabilities of these technologies by enabling personalized learning, adaptive testing, automated feedback, virtual tutoring, performance analysis, content generation, and early identification of students experiencing learning difficulties. Nevertheless, current evidence does not consistently demonstrate that digital technologies are superior to all traditional teaching methods. Their effectiveness depends on instructional design, technical quality, faculty competence, and integration with conventional anatomical teaching. Artificial intelligence and innovative digital technologies should be considered complementary rather than complete replacements for traditional anatomy education. A blended educational model combining cadaveric material, teacher-guided instruction, three-dimensional visualization, clinical imaging, and AI-supported personalized learning may provide the most effective and sustainable approach.

Keywords: anatomy education, artificial intelligence, medical education, virtual reality, augmented reality, three-dimensional visualization, adaptive learning, digital anatomy.

Аннотация. Анатомия человека является фундаментальным компонентом медицинского образования, поскольку точные анатомические знания необходимы для



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проведения физикального обследования, интерпретации данных медицинской визуализации, постановки диагноза и безопасного выполнения клинических процедур. Традиционные методы, включая лекции, учебники, анатомические модели и препарирование трупного материала, сохраняют важное значение. Однако их применение может быть ограничено сокращением учебных часов, недостаточной доступностью трупного материала, высокой стоимостью его хранения и обслуживания, а также сложностями при демонстрации комплексных трёхмерных анатомических взаимоотношений. Цифровые технологии и искусственный интеллект открывают новые возможности для создания интерактивной, адаптивной и клинически ориентированной образовательной среды.

Целью данного исследования являлся анализ инновационных технологий, применяемых в преподавании анатомии, а также оценка их взаимосвязи с искусственным интеллектом, включая образовательные преимущества, ограничения и потенциальные направления внедрения.

Был проведён нарративный обзор литературы, включавший современные научные публикации по вопросам преподавания анатомии, искусственного интеллекта, виртуальной и дополненной реальности, трёхмерной визуализации, виртуального препарирования, симуляционного обучения, геймификации и интеллектуальных обучающих систем. Полученные данные были систематизированы в соответствии с основными технологическими подходами, их педагогическими функциями, описанными образовательными результатами и проблемами внедрения.

Виртуальная реальность, дополненная реальность, смешанная реальность, трёхмерные анатомические платформы, виртуальные анатомические столы, мобильные приложения, трёхмерная печать, геймификация и онлайн-образовательные среды расширяют доступ к анатомическому материалу и способствуют интерактивной визуализации. Искусственный интеллект дополнительно расширяет возможности данных технологий посредством персонализированного обучения, адаптивного тестирования, автоматизированной обратной связи, виртуального наставничества, анализа успеваемости, генерации образовательного контента и раннего выявления студентов, испытывающих трудности в обучении. Вместе с тем имеющиеся научные данные не подтверждают однозначного превосходства цифровых технологий над всеми традиционными методами обучения. Их эффективность зависит от качества педагогического дизайна, технического обеспечения, цифровой компетентности преподавателей и правильной интеграции с традиционным преподаванием анатомии.

Искусственный интеллект и инновационные цифровые технологии следует рассматривать как дополнение, а не как полную замену традиционного анатомического образования. Смешанная образовательная модель, объединяющая работу с трупным материалом, обучение под руководством преподавателя, трёхмерную визуализацию, клинические методы визуализации и персонализированное обучение с поддержкой искусственного интеллекта, может стать наиболее эффективным и устойчивым подходом.

Ключевые слова: преподавание анатомии, искусственный интеллект, медицинское образование, виртуальная реальность, дополненная реальность, трёхмерная визуализация, адаптивное обучение, цифровая анатомия.

Annotatsiya. Odam anatomiyasi tibbiy ta'limning fundamental tarkibiy qismi hisoblanadi, chunki aniq anatomik bilimlar fizik tekshiruv o'tkazish, tibbiy tasvirlash natijalarini sharhlash, tashxis qo'yish va klinik muolajalarni xavfsiz bajarish uchun zarurdir. Ma'ruzalar, darsliklar, anatomik modellar va murda materiallarini disseksiya qilish kabi an'anaviy usullar muhim ahamiyatini saqlab qolmoqda. Biroq ushbu usullardan foydalanish o'quv soatlarining qisqarishi, murda materiallarining yetarli emasligi, ularni saqlash va texnik xizmat ko'rsatish xarajatlarining yuqoriligi hamda murakkab uch o'lchamli anatomik munosabatlarni namoyish etishdagi qiyinchiliklar bilan cheklanishi mumkin. Raqamli texnologiyalar va sun'iy intellekt interaktiv,



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moslashuvchan hamda klinik yo'naltirilgan ta'lim muhitini yaratish uchun yangi imkoniyatlarni taqdim etadi.

Ushbu tadqiqotning maqsadi anatomiya ta'limida qo'llanilayotgan innovatsion texnologiyalarni tahlil qilish hamda ularning sun'iy intellekt bilan o'zaro bog'liqligini, ta'limiy afzalliklarini, cheklovlarini va amaliyotga joriy etishning istiqbolli yo'nalishlarini baholashdan iborat edi.

Anatomiya ta'limi, sun'iy intellekt, virtual va kengaytirilgan reallik, uch o'lchamli vizualizatsiya, virtual disseksiya, simulyatsion ta'lim, geymifikatsiya hamda intellektual o'qitish tizimlariga oid zamonaviy ilmiy nashrlar asosida narrativ adabiyotlar sharhi o'tkazildi. Olingan ma'lumotlar asosiy texnologik yondashuvlar, ularning pedagogik vazifalari, qayd etilgan ta'lim natijalari va joriy etish jarayonidagi muammolarga muvofiq tizimlashtirildi.

Virtual reallik, kengaytirilgan reallik, aralash reallik, uch o'lchamli anatomik platformalar, virtual disseksiya stollari, mobil ilovalar, uch o'lchamli bosib chiqarish, geymifikatsiya va onlayn ta'lim muhitlari anatomik materiallardan foydalanish imkoniyatlarini kengaytiradi hamda interaktiv vizualizatsiyani qo'llab-quvvatlaydi. Sun'iy intellekt mazkur texnologiyalarning imkoniyatlarini shaxsiylashtirilgan ta'lim, moslashuvchan testlash, avtomatlashtirilgan fikr-mulohaza, virtual repetitorlik, o'zlashtirish ko'rsatkichlarini tahlil qilish, ta'lim kontentini yaratish va o'qishda qiyinchiliklarga duch kelayotgan talabalarni erta aniqlash orqali yanada kengaytiradi. Shunga qaramay, mavjud ilmiy dalillar raqamli texnologiyalarning barcha an'anaviy o'qitish usullaridan ustunligini doimiy ravishda tasdiqlamaydi. Ularning samaradorligi pedagogik dizayn, texnik sifat, professor-o'qituvchilarning malakasi va an'anaviy anatomiya ta'limi bilan to'g'ri integratsiya qilinishiga bog'liq.

Sun'iy intellekt va innovatsion raqamli texnologiyalar an'anaviy anatomiya ta'limining to'liq o'rnini bosuvchi vositalar sifatida emas, balki uni to'ldiruvchi yondashuv sifatida qaralishi lozim. Murda materiallari, o'qituvchi rahbarligidagi ta'lim, uch o'lchamli vizualizatsiya, klinik tasvirlash usullari va sun'iy intellekt yordamidagi shaxsiylashtirilgan ta'limni birlashtiruvchi aralash ta'lim modeli eng samarali va barqaror yondashuv bo'lishi mumkin.

Kalit so'zlar: anatomiya ta'limi, sun'iy intellekt, tibbiy ta'lim, virtual reallik, kengaytirilgan reallik, uch o'lchamli vizualizatsiya, moslashuvchan ta'lim, raqamli anatomiya.

Introduction

Anatomy is one of the foundational disciplines in medical and health professions education. A detailed understanding of the structure, position, and relationships of organs, vessels, nerves, muscles, and fascial spaces is essential for clinical examination, interpretation of radiological images, surgical planning, and the prevention of procedural complications. Therefore, deficiencies in anatomical knowledge may negatively influence subsequent clinical training and patient safety.

For centuries, anatomy was taught primarily through cadaveric dissection, lectures, atlases, and physical models. Cadaveric dissection provides direct observation of real human structures, anatomical variation, tissue texture, and spatial relationships. It also contributes to the development of professional behavior, teamwork, and respect for the human body. Consequently, dissection remains an important element of anatomical education.

Nevertheless, contemporary medical education faces several difficulties. Anatomy teaching hours have been reduced in many integrated curricula, while student numbers have increased. Institutions may experience shortages of donated bodies, laboratory space, qualified teachers, and financial resources. Conventional two-dimensional images may also be insufficient for students who have difficulty mentally reconstructing complex three-dimensional structures.

The rapid development of digital educational technologies has introduced new approaches to addressing these challenges. Virtual and augmented reality, interactive three-dimensional models, virtual dissection tables, three-dimensional printing, mobile applications, digital imaging archives,



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simulation, and gamified learning platforms can present anatomical information in dynamic and clinically relevant formats. Recent reviews describe the transition of anatomical teaching from a predominantly dissection-based model toward a blended system that combines traditional and digital methods.

Artificial intelligence has further expanded the possibilities of digital education. AI systems can analyze student performance, generate questions and explanations, recommend individualized learning materials, provide immediate feedback, and support interactive dialogue. A recent systematic review of AI in anatomy education identified applications involving virtual simulations, adaptive feedback, personalized learning pathways, gamification, and automated educational support.

However, the introduction of new technology does not automatically guarantee improved learning. Digital tools may increase engagement while producing limited or inconsistent improvements in objective examination results. They may also generate inaccurate information, increase dependence on technology, create inequalities in access, and reduce direct interaction with teachers or anatomical specimens. Therefore, these technologies should be evaluated from pedagogical, ethical, and practical perspectives.

The aim of this study was to analyze the principal innovative technologies used in teaching anatomy and examine how their integration with artificial intelligence may improve visualization, personalization, assessment, and clinical application of anatomical knowledge.

Materials and Methods

This study was designed as a narrative review of the scientific literature.

Publications addressing the following areas were considered:

- conventional and technology-enhanced anatomy education;
- virtual reality, augmented reality, and mixed reality;
- interactive three-dimensional anatomical visualization;
- virtual dissection tables and digital cadavers;
- three-dimensional printing;
- mobile and web-based learning platforms;
- gamification and simulation;
- artificial intelligence and machine learning in medical education;
- large language models and intelligent tutoring systems;
- adaptive assessment and automated feedback.

Scientific publications were analyzed according to four principal dimensions:

1. the function of the technology in anatomy teaching;
2. its potential influence on engagement, spatial understanding, and knowledge acquisition;
3. its relationship with artificial intelligence;
4. its educational, ethical, technical, and institutional limitations.

The review focused primarily on undergraduate medical and health professions education. Because this research synthesized previously published evidence and did not involve human participants, patient data, or biological specimens, ethical approval was not required.

Results

Virtual reality in anatomy education

Virtual reality creates a computer-generated environment in which learners can interact with digital anatomical structures. Using a headset, desktop system, or immersive laboratory, students may rotate, enlarge, separate, hide, or reconstruct anatomical structures.

VR is particularly useful for teaching regions with complex spatial relationships, such as the brain, skull base, middle ear, pelvis, mediastinum, and retroperitoneal space. It enables repeated



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exploration without damaging a specimen and allows students to review structures outside scheduled laboratory hours.

Technology-enhanced neuroanatomy education has been associated with increased motivation, confidence, perceived understanding, and spatial comprehension. However, improvements in objective academic outcomes have not been consistent across all studies.

AI can improve VR platforms by tracking learner behavior, time spent on structures, repeated errors, and task completion patterns. Based on these data, an AI system may automatically adjust the difficulty of the activity, provide additional explanations, or recommend targeted revision.

For example, when a student repeatedly confuses the branches of the external carotid artery, the system may highlight these vessels, generate a simplified pathway, offer a clinical case, and subsequently administer a focused test.

Augmented and mixed reality

Augmented reality overlays digital anatomical objects onto the real environment through smartphones, tablets, projection systems, or head-mounted displays. Mixed reality enables more advanced interaction between virtual models and physical space.

Students may observe a three-dimensional heart positioned on a desk, project internal organs over a mannequin, or visualize muscles and vessels over the surface of a standardized patient. These approaches help connect theoretical anatomy with surface anatomy, physical examination, and clinical procedures.

A systematic review comparing augmented reality with other anatomy-teaching methods found considerable heterogeneity among studies. Most reported no statistically significant difference in learning outcomes, although AR showed potential as an engaging complementary tool.

A more recent systematic review of mixed-reality technology concluded that VR and AR are generally as effective as traditional teaching and may serve as useful supplementary methods, with some studies reporting higher academic scores.

AI-enhanced AR may recognize physical objects, anatomical landmarks, or learner gestures. Computer vision can help align digital structures with a mannequin or body surface. AI may also identify whether a student has correctly located a pulse point, muscle attachment, injection site, or surface projection of an internal organ.

Three-dimensional anatomical visualization

Interactive three-dimensional anatomical software allows students to study structures layer by layer. Unlike static textbook images, these platforms permit rotation, transparency adjustment, isolation of individual organs, and visualization from different anatomical planes.

Three-dimensional visualization is especially useful for students who have difficulty understanding depth and orientation from two-dimensional diagrams. It may also support integration with computed tomography, magnetic resonance imaging, ultrasound, and surgical anatomy.

AI can personalize the use of three-dimensional models. A learning platform may identify weak areas from previous assessments and automatically construct a revision session. Students with difficulty in musculoskeletal anatomy may receive additional bone landmarks, muscle attachments, functional animations, and clinical cases.

Multimodal AI systems may also connect textual descriptions with images and models. A student could ask the system to demonstrate the course of the facial nerve, compare its intracranial and extracranial segments, and explain the clinical consequences of injury at different levels.

Virtual dissection tables and digital cadavers

Virtual dissection tables display high-resolution three-dimensional reconstructions of the human body. Students can perform digital cuts in different planes, isolate organs, examine cross-sectional anatomy, and compare normal structures with pathological conditions.



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These systems are particularly valuable for radiological anatomy because they allow direct comparison between anatomical structures and CT or MRI sections. They are reusable, clean, and suitable for large-group demonstrations.

Artificial intelligence may support automatic structure recognition, labeling, segmentation, and clinical correlation. An AI-supported table could automatically identify a structure selected by the student, show its blood supply and innervation, display associated radiological images, and generate a short formative test.

Nevertheless, virtual dissection does not reproduce all features of cadaveric work. Students cannot fully experience tissue resistance, natural variation, dissection technique, or the emotional and professional aspects associated with donor-based learning. Therefore, digital dissection should complement rather than automatically eliminate cadaveric teaching.

Three-dimensional printing

Three-dimensional printing converts digital anatomical data into physical models. Models can represent bones, organs, vessels, congenital abnormalities, tumors, and patient-specific surgical anatomy.

Printed structures are useful when cadaveric specimens are unavailable or when rare anatomical abnormalities need to be demonstrated. They can be enlarged, sectioned, color-coded, and reused. They are also suitable for tactile learning and may support students with certain visual or learning difficulties.

AI may assist in the segmentation of medical images, correction of digital models, identification of clinically important structures, and preparation of patient-specific printing files. Machine-learning algorithms can reduce the time required to separate organs, vessels, bones, and pathological lesions from imaging data.

The principal limitations include equipment costs, material expenses, production time, and the need for technical expertise. Simplified models may also fail to demonstrate small structures or realistic tissue properties.

Mobile applications and online learning platforms

Mobile applications make anatomical content available at any time and place. They may include atlases, three-dimensional models, quizzes, flashcards, videos, pronunciation tools, and clinical cases.

Online platforms support blended learning, flipped classrooms, remote instruction, and self-directed study. Lecture content can be reviewed before class, allowing classroom time to be used for discussion, imaging interpretation, problem-solving, and clinical application.

AI transforms a conventional online platform into an adaptive learning environment. Instead of presenting every student with identical content, the system can analyze performance and select materials according to individual needs.

A student who answers basic questions correctly may receive clinically integrated tasks, while a student with persistent errors may receive simpler explanations, additional illustrations, and spaced repetition. AI may also identify students at risk of academic difficulty and inform educators before major examinations.

Intelligent tutoring and conversational AI

Large language models and AI chatbots can provide explanations, generate questions, construct clinical cases, summarize topics, and simulate interactive tutoring. Students can ask follow-up questions and receive immediate responses outside regular teaching hours.

AI tutors may be particularly valuable for active recall. A chatbot can ask a sequence of questions about the brachial plexus, evaluate the answers, explain errors, and adapt the next question according to performance.

Recent evidence suggests that large language models have improved substantially in answering anatomy-related questions. However, performance varies across models and anatomical



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regions, and not all questions are answered accurately. Therefore, AI tools should remain supplementary resources under academic supervision.

The educational value of conversational AI depends on the quality of prompts, source material, and validation. Students should be taught to verify AI-generated explanations using accepted atlases, textbooks, peer-reviewed sources, and instructor guidance.

AI-supported assessment

Traditional anatomy assessment often includes written examinations, spot tests, oral examinations, image identification, and practical laboratory evaluation. AI can assist in generating question banks, selecting items by difficulty, analyzing distractor quality, and providing immediate formative feedback.

Computer vision may also support identification tasks involving images, models, or radiological scans. An AI system may compare a student's selected structure with the correct answer and explain the surrounding anatomical relationships.

Machine-learning algorithms can analyze patterns of errors across a class. Educators may discover that many students misunderstand a particular anatomical region and subsequently modify teaching methods.

Nevertheless, automated assessment must be carefully validated. AI-generated questions may be ambiguous, factually incorrect, or misaligned with curriculum outcomes. Final academic decisions should not be made solely by non-transparent algorithms.

Gamification

Gamification applies elements such as points, levels, challenges, competitions, badges, and progress indicators to learning activities. In anatomy education, students may complete timed structure-identification tasks, virtual dissections, or team-based clinical challenges.

AI can adapt game difficulty to the learner's performance. It can also generate individualized challenges and maintain an appropriate balance between difficulty and achievement.

Gamification may increase motivation and participation, but excessive competition can create anxiety or encourage superficial memorization. Educational objectives must remain more important than points or entertainment.

Discussion

The results of this review indicate that innovative technologies can improve the flexibility, accessibility, visualization, and interactivity of anatomy education. Their greatest contribution may be the ability to demonstrate complex three-dimensional structures repeatedly and from multiple perspectives.

However, technology itself is not a teaching method. The educational value of a digital tool depends on how it is connected to learning objectives, assessment, clinical relevance, and teacher guidance. A visually impressive application may have limited value when it lacks structured tasks or encourages passive observation.

Current research supports the use of extended-reality technologies as complementary learning methods, but evidence of clear superiority over conventional teaching remains inconsistent. This suggests that institutions should avoid replacing effective traditional methods solely because a newer technology is available.

The most suitable approach is likely to be blended anatomy education. Cadaveric dissection can demonstrate real variation and tissue relationships. Three-dimensional software can clarify difficult spatial concepts. Virtual dissection tables can strengthen cross-sectional and radiological anatomy. AR can connect internal structures with the living body. Three-dimensional printing can provide access to rare or patient-specific anatomy. AI can personalize learning and provide continuous formative support.

Artificial intelligence has the potential to transform anatomy education in four major ways.



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First, it can personalize learning. Students differ in prior knowledge, spatial ability, pace, and preferred learning method. Adaptive systems can provide targeted instruction rather than identical content for all learners.

Second, AI can provide immediate feedback. Rapid correction prevents persistent misconceptions and supports self-directed learning.

Third, AI can assist educators. It may reduce time spent on routine question generation, initial feedback, learning analytics, and content organization. Systematic reviews of AI in medical education describe applications in exam-question generation, tutoring, clinical simulations, assessment, and performance analysis.

Fourth, AI can connect anatomy with clinical practice. It can generate cases requiring students to apply anatomical knowledge to trauma, neurological deficits, imaging findings, or surgical complications.

Despite these advantages, several risks must be considered. Generative AI can produce convincing but inaccurate answers. Students may become dependent on generated summaries and avoid deeper study. Algorithms may contain bias, and commercial systems may collect personal learning data. Differences in infrastructure can increase educational inequality.

A recent review of AI in anatomy education emphasized the need to balance technological innovation with human interaction, ethical oversight, and traditional methods. Broader medical education frameworks similarly recommend aligning AI tools with learning theory, defined educational outcomes, transparency, and human supervision.

Faculty development is therefore essential. Anatomy teachers do not need to become software engineers, but they should understand the capabilities and limitations of AI, evaluate generated content, design effective prompts, protect student data, and determine when technology improves learning.

Students also need AI literacy. They should understand that fluent language does not guarantee scientific accuracy. They must learn to compare AI responses with authoritative sources and identify uncertainty or contradiction.

Institutions implementing AI-supported anatomy education should establish clear policies concerning data protection, academic integrity, acceptable use, assessment, and validation of educational content.

Practical Model for Implementation

A practical AI-integrated anatomy curriculum may include the following stages.

Before class, students review short videos, digital atlases, and AI-generated diagnostic quizzes. The platform identifies areas requiring additional preparation.

During class, the teacher presents key concepts and uses three-dimensional models, cadaveric specimens, radiological images, or AR applications. Students solve clinically oriented problems in groups.

During laboratory sessions, cadaveric dissection or prosection is combined with virtual dissection and imaging. AI tools provide structure labels, additional explanations, and formative questions.

After class, students complete personalized revision tasks. The AI system uses spaced repetition and adjusts question difficulty according to individual performance.

Educators review class-level analytics, identify common misconceptions, and modify subsequent instruction. Final assessment remains supervised and aligned with validated curriculum standards.

Limitations

This article was based on a narrative review and did not perform a statistical meta-analysis. The included technologies differ considerably in design, cost, educational content, student population, and assessment methods.



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Many studies evaluate short-term knowledge acquisition or student satisfaction rather than long-term retention, clinical performance, or patient outcomes. Evidence concerning fully AI-integrated anatomy curricula is still developing.

Rapid changes in artificial intelligence may also cause specific platforms and findings to become outdated. Continuous evaluation is therefore necessary.

Conclusion

Innovative technologies have significantly expanded the methods available for teaching human anatomy. Virtual reality, augmented reality, mixed reality, three-dimensional visualization, virtual dissection, three-dimensional printing, mobile applications, online platforms, gamification, and simulation can improve access to anatomical material and support spatial understanding.

Artificial intelligence strengthens these methods through adaptive learning, automated feedback, intelligent tutoring, content generation, learning analytics, and individualized assessment. It can help students identify weaknesses, practice actively, and connect anatomical knowledge with clinical cases.

However, AI-generated information may be inaccurate, and digital technologies do not consistently produce better learning outcomes than well-designed traditional teaching. They cannot fully replace the educational value of teachers, cadaveric material, direct laboratory experience, and human interaction.

The most appropriate strategy is a blended model in which innovative technologies and artificial intelligence complement established anatomy-teaching methods. Successful integration requires clear educational objectives, faculty training, validated content, equal access, ethical standards, and continuous evaluation of learning outcomes.

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