Development and application of digital assistive teaching system for anatomy

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Abstract  Background  Anatomy is a required course for all medicine-related industries. In recent decades, the teaching quality and effect of anatomy have been compromised by factors including a decrease in human body specimens, dampened enthusiasm for the discipline, reduced teaching hours of anatomy, scale expansion of medical education, and obstacles in performing field autopsies and observations.  Methods  Based on China's digitalized visible human research achievements, this article extracts the boundary information of anatomic structures from tomographic images, constructs three-dimensional digital anatomical models with authentic texture information, and develops an anatomy assistive teaching system for teachers and students based on the knowledge points of anatomy, to meet the anatomy teaching requirements of different majors at various levels.  Results  This scientific, complete, and holistic system has produced over 6000 three-dimensional digital anatomical models, 5000 anatomy knowledge points, 50 anatomical operation videos, and 150 micro demonstration classes, with teaching contents for different majors and levels, such as systematic anatomy, topographic anatomy, sectional anatomy, anatomy of motion, and virtual anatomical operation table. Ranging from network terminals, desktops, touchscreen 3D displays, desktops, and projection 3D volumetric displays to augmented reality, its diversified interactive forms meet the requirements for a learning environment in different settings.  Conclusions  With multiple teaching and learning links covered, such as teaching environment, teaching resources, instructional slides, autonomous learning, and learning effect evaluation, this novel teaching system serves as a vital component and a necessary resource in anatomy teaching and functions as an important supplement to traditional anatomy teaching. Applied and promoted in most medical colleges and schools in China, this system has been recognized and approved by anatomy teachers and students, and plays a positive role in guaranteeing the effect and quality of anatomy teaching.

Keywords  Teaching anatomy; Anatomy education; Virtual reality; Simulation; Digital anatomy; Digital human
1 Introduction

As a core subject in medical education, anatomy is a required course for all medical students, medical workers, and health administrators, and it requires the longest hours in formal medical education\(^1\)\(-\)\(^4\). Gross anatomy is usually classified into systematic, topographic, and sectional anatomy based on the study means and the focus of the observed structure. A series of anatomy courses, based on the research angle and application domain, can be further derived from gross anatomy, including nursing anatomy, anatomy of motion, surface anatomy, and clinical anatomy. Except for clinical medical students, medical workers, and health administrators who only need to study one anatomy course of a similar specialty, students majoring in clinical medicine need to master systematic anatomy and topographic anatomy, whereas students of imageology-related specialties also need to acquire knowledge of sectional anatomy\(^5\). The core foundation of these anatomy courses is the morphological structure of the human body and relevant specialized knowledge, and the best way to learn such knowledge is field autopsy and observation of cadaveric specimens\(^6\).

However, scruples about body donation have led to a decrease in cadaveric specimen sources and anatomical specimens and dampened enthusiasm for this discipline has resulted in a decline in the attention paid to anatomy teaching and the quality of teachers\(^7\). Meanwhile, the emergence and development of new disciplines have reduced the number of study hours of anatomy. A series of factors have greatly affected the learning effect of anatomy, which in turn has a direct impact on the effect of clinical diagnosis and treatment\(^7\)\(-\)\(^9\). Currently, the outbreak of COVID-19 has increased the difficulty in obtaining cadaveric specimens and decreased the opportunities for face-to-face teaching, field autopsy, and observation, making anatomy study even more difficult\(^10\). Consequently, some anatomy workers continue to explore assistive teaching systems under the new situation and update the teaching mode of anatomy to improve the teaching effect\(^11\)\(-\)\(^13\).

With rich cadaveric specimen sources and ample time provided, the teaching and learning of anatomy knowledge are often based on field autopsy and observation of dissected specimens\(^14\). However, owing to the decrease in cadavers and anatomical specimens, people have begun replacing actual human body specimens with artificial models and plastinated specimens\(^15\). With advancements in computer technology, computer-based anatomy assistive teaching systems have emerged, which can simulate the morphological structure of the human body with a computer. It utilizes relevant technologies, including virtual reality and augmented reality, to reconstruct anatomy teaching scenarios, simulate anatomical operations, virtually reproduce the morphological structure of the human body, and integrates relevant anatomy knowledge to form virtual anatomy teaching systems that are conducive to teaching\(^15\)\(-\)\(^18\). The application of such systems has greatly alleviated the shortage of teaching resources and improved the effect of anatomy studies. Nevertheless, limited by data sources and technologies, these systems are still inadequate in terms of the validity of virtual anatomical models, the completeness of teaching systems, and the interactivity and operability of systems\(^19\).

Thus, based on China's digitalized visible human datasets, this article plans to adopt a 3D computer reconstruction technology to reconstruct the three-dimensional structure of the human body truthfully, and develop a digital anatomy teaching system with a complete anatomy teaching system through virtual reality and augmented reality technologies based on the characteristics and knowledge system of each anatomy course.
2 Design of digital anatomy teaching system

Digital virtual humans, that is, three-dimensional structural images of a human body reconstructed with a computerized algorithm by integrating large quantities of real cross-sectional human body data, results from combining medicine with information technology and computer technology, which provides a wealth of teaching materials for systematic anatomy, topographic anatomy, and sectional anatomy for medical education.

With the autonomous learning philosophy of "combining reality and vitality" established, it constructs a "textbook" three-dimensional digital human anatomy teaching software based on China's cross-sectional data on human body specimen, promotes the construction of digital, clean, clinical, and open autonomy laboratories, develops intelligent teaching tools, and creates an active "digital autonomy teaching system" integrating "teaching philosophy, teaching software, teaching laboratories, teaching tools, and teaching network."

2.1 Digital anatomical specimen model

2.1.1 Construction of the three-dimensional geometric model

(1) Data source

One male and female dataset was selected from China's digitalized visible human datasets\(^\text{(20)}\) as the basic data for the three-dimensional digital model—the core of the digital anatomy teaching system. Such datasets are optical images obtained by milling cadaveric specimens using the cryogenic milling technique, which has ultra-high spatial resolution and structural recognition\(^\text{(21)}\). A three-dimensional digital model of an anatomical structure with real 3D form and spatial relationship is constructed through operations on these datasets, including preprocessing of cross-sectional images, boundary segmentation and extraction of anatomical structures, and three-dimensional reconstruction.

(2) Preprocessing of cross-sectional data.

Affected by properties including collecting equipment, ambient light, and ambient temperature, images are subject to geometric deformation, excursion, color space inconsistency, etc. Therefore, preprocessing the real cross-sectional images of the human body of each layer (i.e., spatial registration and color registration) is necessary to ensure the consistency of the spatial location and color of the same anatomical structure on each layer.

(3) Extraction of anatomical structural boundaries

Anatomical structure segmentation was performed with each layer of cross-sectional images of the human body after preprocessing. The two most common methods adopted for the segmentation of anatomical structures are direct manual segmentation and interactive segmentation. Manual segmentation refers to the direct scan sampling of anatomical structures on images under the guidance of medical specialists based on experience and knowledge. Interactive segmentation refers to the segmentation of anatomical structures through automatic boundary extraction and binarization of images by a computer, with the range of gray scales determined by medical specialists.

Using manual segmentation as an example, the boundary extraction of anatomical structures is illustrated as follows: draw control points to determine the boundary of each layer of the anatomical structure, form a vector curve, and increase the density of control points properly where the change in curvature is obvious, such that the extracted boundary fits the primary structure accurately with the boundary of each anatomical structure on different levels being a closed curve.
(4) Generation of anatomical structure model

After the completion of boundary extraction, import the model generation tool, adjust information including the number of control points, and conduct surface reconstruction of each anatomical structure to obtain a three-dimensional geometric model.

Enhance the third dimension of the model data through post-processing of the generated three-dimensional model, such as smoothing and texture mapping.

2.1.2 Texture mapping

This digital anatomy teaching system processes and optimizes three-dimensional digital models from the four aspects of reference material analysis, model precision, UV layout, and texture making, to ensure the fidelity of digital anatomical specimens.

(1) Reference material analysis

Owing to the complexity of the physical structure in the making of digital specimens, rationality and validity must be considered, with information including texture, color, and reflection analyzed. In the case of the skin, the cuticle mainly reflects the part of sunlight reflected by the skin, whereas the dermis and subcutaneous tissues reflect subsurface scattering (SSS) (i.e., the SSS effect commonly referred to in computer graphics). Experiments show that approximately 96% of the light in contact with the skin is scattered by multiple layers of the skin, with only about 4% reflected. Because of the translucent property of the skin, light will be scattered multiple times on its surface, and the scattered radiation is attenuated based on its paths. Light will be diffused in the surroundings, which has a significant effect on the texture of the skin.

(2) Model precision and topology

Topology is crucial for the fidelity of digital specimens. The structure, arrangement, and density of textures influence the topological relationship.

Figure 1 shows that the creation of only one map does not reflect the structure realistically. Here, we must analyze the tendinous part of muscles, the texture arrangement of the muscular part, and the hierarchical relation between these two, and distribute topological lines reasonably based on the result analysis, as shown in the blue grid in the image above. Topology must be fully considered in model making, and the high model subsequently made to bake a normal map can better support the textures of the structure and render the performance of the model more realistic and natural.

(3) UV layout

Make reasonable and good use of texture space. As shown in Figure 2a, the UV space is 4096 × 4096, which is also the size of the subsequent mapping. The texture is displayed on UV; however, the texture in Figure 2b is only approximately 1/4 of the UV space. Consequently, the texture is vague, and normal pixels cannot show the details better, which severely restricts the effect.

(4) Texture making

To achieve the ultimate effect, map information is required for the control of property values and a better simulation of the real effect.

- BaseColor map: The base color map requires the most effort, which directly displays the color information of the specimen made.
- Roughness map: The map that defines the surface roughness of different objects.

Figure 1 Texture mapping.
• Specular map: Used together with Roughness Map.
• Normal map: Use the values in texture to interfere with the normal parameters in the lighting equation, to change the lighting effect and display the subtle texture of structures better.
• Ambient occlusion map: Enhances the light attenuation resulting from ambient occlusion in reality, to give textures a better sense of reality.
• Subsurface color map: Applies in specimens with the SSS effect for better expression of permeability.

In addition, to manifest the authenticity of the effect, it must be set off by ambiance and lighting. By simulating realistic and harmonious ambient lighting information, high-dynamic-range imaging and global illumination can create a natural ambient effect and enhance the sense of reality of the specimens to be displayed.

The digital human anatomy system contains over 6000 three-dimensional digital anatomical models, which reflect the model shape and adjacent hierarchical relationship, as shown in Figure 3.

2.2 Framework of digital anatomy teaching system

The anatomy teaching content within the digital anatomy teaching system, including three-dimensional model data, knowledge points (text, images, and videos), and micro classes, is organized by the courses of systematic anatomy, topographic anatomy, sectional anatomy, and clinical anatomy. Its basic table of contents is based on systematic anatomy and enriched with other categories, including topographic, sectional, and clinical anatomy (Figure 4).

![Figure 2 UV layout.](image)

![Figure 3 Three-dimensional anatomical structure.](image)
Systematic anatomy is the basic subject for preclinical and clinical medical studies. Similarly, with the system as the unit, the digital anatomy teaching system organizes three-dimensional model data and generates a table of contents of systematic anatomy, which serves as the general program and indexes for three-dimensional model data of the entire digital human.

Relevant properties of topographic anatomy, such as the part name of the three-dimensional model and the level of hierarchy from the body surface toward the interior, and display the structure distribution, relative location, and morphology of each organ within the region from superficial to deep layers of body parts.

Add CT/MR images of the human body, corresponding to the cross-sectional images of the human body, and match the spatial location of the three-dimensional model. Corroborated by image data, cross-sectional images, and the three-dimensional model, the morphological changes and positional relations of the anatomical structures are displayed.

Add relevant data of real clinical cases and reconstruct the image data model to be bound with the three-dimensional digital anatomy model to visually display the contrast between the normal morphology of the anatomical structure and the morphology of the lesion.

The logical system of the digital anatomy teaching system is organized based on the teaching model of "teaching, learning, practice, examination, and management." In line with the teaching model above, functional, interactive, and classification systems facilitate teaching and promote autonomous learning.

The "magnet" function optimizes the teaching mode and brings convenience to autonomous learning and
review. With the "magnet" function, teachers can organize and save their courseware content, and students can study on their own or review learned courseware. In-class exercises with the in-class examination question bank promote the interaction between teaching and learning to deepen the impression of lessons. Meanwhile, with the background data record of the system, its use by teachers and students can be recorded effectively to provide reference information for the evaluation, teaching, and learning quality. In addition, the independent and mature examination system enables the fast and effective organization of the virtual specimen assessment.

3 Composition of digital anatomy teaching system

Combining anatomy experiment classes with advanced digital virtual human technology, the digital anatomy teaching system with contents of systematic anatomy, topographic anatomy, sectional anatomy, etc. offers a wealth of anatomy teaching videos and courseware for teachers and students. In the course of learning, through the contrast between virtual and real human body structures, students can master relevant knowledge quickly and accurately and prepare lessons before class or review after class.

To enhance the learning experience, virtual reality/augmented reality (VR/AR) anatomy products are provided, and online teaching products are set up for convenient use during and after class. Out of the laboratories, the anatomy teaching system can be accessed anytime in places with network coverage, such as offices, libraries, and dormitories.

3.1 Digital human anatomy system

Mainly applied in the teaching of anatomy-related subjects, this product closely follows the teaching program, with its content integrated and arranged in the teaching order. The software comprises six modules, including "systematic anatomy," "topographic anatomy," "sectional anatomy," "clinical cases," "anatomy micro-classes," and "autonomous learning" as shown in Figure 5. With a wealth of teaching resources including human anatomical models, cross-sectional images, clinical cases, micro-class videos, pictures, and cartoons, the software supports digital teaching and autonomous learning before, during, and after the class. The resources in the system are complete and rich, including over 6000 three-dimensional
digital anatomical models, over 5000 anatomy knowledge points, over 50 anatomical operation videos, and over 150 micro demonstration classes.

Teachers can make teaching courseware with a digital human presetting bit through the courseware-making module, and place it in the main interface in the form of "magnet." In the teaching process, teachers can invoke the preset three-dimensional human body structure quickly with the "magnet" function. The system is designed with a variety of fast and convenient functions for in-class demonstration, analysis, and explanation of courseware, including background switch, annotation, transparency, staining, stripping, search, pronunciation, paintbrush, and 3D display, as shown in Figure 6.

Basic anatomy is supplemented by additional disciplinary knowledge. Images of histological sections were added to relevant "magnets" in the "systematic anatomy" and "topographic anatomy" modules, corresponding to the anatomical structure in "magnets" and with annotation on key structure, for the convenience of students observing the gross morphology and micromorphology of the same structure, as shown in Figure 7.

The "clinical cases" module contains over 80 real clinical cases, which are classified into eight categories: nervous system, five sense organs, abdomen, skeletal muscle, neck, alimentary canal, chest, and pelvic cavity. Each clinical case includes multiple real, computed tomography (CT) or magnetic resonance imaging (MRI), case description, three-dimensional data reconstructed based on clinical images, and three-dimensional data on the corresponding normal human body structure. The case model data and the normal human body structure model data are contrasted on a one-to-one basis, as shown in Figure 8.

### 3.2 Digital human virtual dissecting table

The product includes two datasets: male and female. Through methods such as section cutting, three-dimensional display, touch screen interaction, landscape, and vertical screen, it can display the anatomical structure of any section, system, part, and layer, and can be associated with the corresponding microscopic
histological structure.

The system can quickly display high-definition sections, complete surgical operations such as cutting and endoscopy (as shown in Figure 9), alleviate the shortage of specimens in medical teaching, help medical students and doctors with macroscopic and microscopic multi-layered cognition of stereoscopic structures, and meet the demands of medical teaching, clinical practice, and popular science education.
3.3 Digital human VR anatomy teaching system

In medical teaching, a lot of time is spent during lessons to explain anatomical knowledge, such as the structure and morphology of each human body part and their adjacent relationships. Verbal expressions and simple model displays alone could not establish a systematic framework of the human body in the minds of students and making them understand and memorize textbook content.

The digital human VR anatomy teaching system applies VR technology in the teaching of anatomy knowledge, and expresses anatomical structures vividly, stereoscopically, and systematically through an immersive experience and refined human body structure data, which allows students to study human anatomy in an immersive environment, as shown in Figure 10.

![Scene of digital human VR anatomy teaching system.](image)

With a cooperative multiplayer mode designed for medical teaching, the digital human VR anatomy teaching system simulates the classroom scene and synchronizes the teacher side to the associated student side to ensure consistent class content such as models and knowledge points in VR scenes. Information on the student side is fed back to the teacher side, to promote communication and interaction between students and teachers, and help teachers to grasp the progress of the available students.

A cognitive test module was added to the digital human VR anatomy teaching system to arouse the enthusiasm and initiative of students and deepen medical knowledge, including the morphology, spatial location, and adjacent relationship of the anatomical structure by enabling a manual combination of anatomical structure test modes, thus improving the teaching quality.

3.4 Digital human AR anatomy system

This system is characterized by "depth perception," "panoramic view," and "vivid simulation." By wearing a pair of 3D glasses, the user can operate the system interactively with a special control pen. The system can be operated freely with six degrees of freedom. Users can observe the human body structure from all directions and observe the inside of the organs by controlling the camera to obtain an immersive 3D experience. Different operations were enabled through buttons on the control pen. The images can be viewed by other observers through an external screen, as shown in Figure 11 and Figure 12.

Combined with realistic scenes, the system improves on the conventional teaching method of verbal
expression supplemented by static and 2D pictures by providing students with a stereoscopic and vivid sensual experience. By promoting students' participation and stimulating their interest in learning, the immersive interactive experience improves the teaching efficiency and learning to achieve the purpose of virtual simulation teaching.

### 3.5 Online edition of digital human anatomy system

The digital human anatomy system is installed on the campus network server, as shown in Figure 13, for teachers and students of the school to log in with usernames and passwords. The system is downloaded only when it is needed to prevent the problem of network bandwidth limitation, maximize operating speed, and support simultaneous login of the largest possible number of users.

![Figure 11 Stereoscopic effect of digital human AR anatomy system](image1)

![Figure 12 Scene effect of digital human AR anatomy system.](image2)

### 3.6 Digital human anatomy examination system

Examination is an important link for adjustment in anatomy teaching, with multiple functions including testing, feedback, supervision, motivation, and guidance. It reflects the effect of teaching, effectively reinforces the content of courses, and serves as an important means of cultivating students' comprehensive abilities. Through examination, teachers can adjust the application of teaching methods, add or delete teaching content, and influence students' learning and thinking methods. Therefore, examination reform is an important aspect of teaching reform.

Through the digital acquisition of real specimens using a computer, the digital human anatomy examination system realizes network-based paperless examination. System management is simpler and more efficient with a massive collection of quality exercises and specimens and a wealth of innovative functions, thus helping teachers to set, compose, mark, and perform statistics of examination papers, and encourage students to learn independently with this system.
Conventionally, anatomy examination mainly takes the forms of "real specimen examination," "picture/PPT-based static examination," and "multimedia examination." Limited by objective conditions, these forms of examination often cannot reflect students' mastery of specimens objectively and are plagued by many drawbacks. The digital human anatomy examination system provides a new tool for digital anatomy examination. It makes examination more scientific, objective, standardized, and convenient while saving teaching resources, optimizing resource allocation, and improving teaching efficiency, and is of great importance to the development of digital anatomy teaching.

4 Application of digital anatomy teaching system

4.1 Comprehensive anatomy teaching laboratory

It realizes intelligent management and remote control of the laboratory and improves laboratory management through the smart laboratory management system and various intelligent control and management systems. It provides all-round equipment for environment creation, air treatment, digital teaching, specialized anatomy teaching resources, optimizes teaching methods, combines reality and virtuality, improves teaching quality, and aid teachers in the informatization reform of teaching. It offers medical schools an integrated solution to anatomy teaching, performs stepwise construction based on the specific conditions and needs of each school, and gradually creates a world-class new mode of anatomy experiment teaching by improving the overall teaching environment of laboratories.

After polishing and optimizing varied anatomy laboratories and digital teaching equipment, quality teaching resources become simple and easy to use and can be perfectly integrated into anatomy teaching to improve the efficiency of teaching and learning. Learning exchange among teachers and students is
promoted through a variety of interactive modes. Interactive teaching can be realized between laboratories, and the supervision of the learning process and learning effect is reinforced through exercises and the examination system, thus providing a ubiquitous learning mode.

### 4.1.1 Virtual anatomy teaching laboratory

The virtual anatomy teaching laboratory comprises a "digital human anatomy teaching system," "digital human VR anatomy teaching system," "digital human AR anatomy teaching system," and "digital human virtual dissecting table," with an integrated decoration design adopted (Shown in Figure 14).

![Figure 14 Virtual anatomy teaching laboratory.](image)

Through interactive experience enabled by technologies such as VR, AR, 3D projection, and virtual anatomy, it realizes unprecedented anatomy learning effect with immersive observation and operation as if the user is personally on the scene and creates even more realistic and future-oriented teaching scenes for medical anatomy teaching.

### 4.1.2 Intelligent anatomy experiment teaching center

Composed of "comprehensive creation of laboratory environment," "smart comprehensive air management system," "digital teaching facilities" and "intelligent laboratory management system," the intelligent anatomy experiment teaching center is designed and constructed in strict conformance with the construction specifications for digital anatomy laboratories (shown in Figure 15).

A perfect laboratory environment optimizes the way laboratories are used, creates world-class intelligent anatomy experiment teaching conditions, improves the school image and teaching effect, and promotes the implementation of new ideas and new methods of anatomy teaching and teaching reforms.

### 4.1.3 Anatomy autonomous learning laboratory

This solution comprises digital teaching systems including "digital human anatomy teaching system," "high definition tomographic 3D printing model" and "imaging clinical diagnosis and surgical planning system (Shown in Figure 16)."

Based on clinician anatomy training and the teaching programs of human sectional anatomy for five-year and eight-year clinical medicine majors, a high-definition tomographic 3D printing model is
contrasted and combined with reconstruction cases of medical CT and MRI images. Supported by sectional anatomy micro-classes and teaching facilities such as film viewers, it realizes personalized demands for cross-sectional imaging teaching and autonomous learning.

4.2 Teaching application

Based on the teaching needs, the content of the virtual anatomy teaching system is integrated and arranged in the teaching order closely following the syllabus. The digital human anatomy model can be exported quickly and conveniently, and a wealth of quality teaching resources are provided using means such as "magnet," section images, micro-class videos, pictures, and cartoons, which greatly facilitate digital teaching and autonomous learning before, during, and after lessons.
As a result of combining medicine with information and computer technologies, this system integrates and reconstructs a large quantity of real human body cross-sectional data into three-dimensional structure images of the human body through a computer algorithm. It provides a wealth of teaching materials of systematic, topographic, and sectional anatomy, transforms the conventional teaching mode of anatomy, and breaks the fetters in conventional anatomy teaching. With rich teaching resources, teaching can be conducted in a three-dimensional, vivid, and interactive manner, which greatly increases students' learning interest.

4.3 Popularization and application

Over 200 medical schools in 28 provinces, cities, and autonomous regions have purchased the China Digital Human Anatomy Teaching System, and over 30 schools have established digital anatomy laboratories, all applied in the teaching of human anatomy for medical students. Thenceforth, we have received eight certificates of application, with the total number of training teachers and benefited students being 213 and 123042, respectively. To date, the digital human system has been installed in five Grade A Class III hospitals. In addition, the system has been applied in Baotou, Hulun Buir, and Shan Xian Science and Technology Museum.

5 Discussion

5.1 Scientificity of digital anatomical specimen and restoration degree of morphological characteristics

Anatomy is a science that studies the morphological structure of a normal human body and its laws, and the cognition of anatomical knowledge should also be accurate and error-free. In recent years, the misunderstanding of certain anatomical knowledge by medical students and the lack of anatomical knowledge of inexperienced surgeons have led to some clinical medical malpractices that could have been avoided[22,23]. In addition to learning attitude, the misunderstanding or inadequate cognition of certain anatomical knowledge is, to a greater extent, the consequence of insufficient anatomy teaching resources, or the morphological structure of the human body observed is inaccurate[22,23]. The virtual anatomical models in the digital or electronic anatomy teaching system were constructed in a virtual environment using digital tools. Some models in the virtual anatomy teaching system are constructed based on anatomy experts' cognition of the morphological structure of the human body, and the morphological structure and spatial relationship of these models can hardly be described accurately and scientifically, especially for some complex structures[21,24-27]. To some extent, these inaccurate virtual models may lead to cognitive errors among medical students.

The models in digital anatomy teaching are three-dimensional digital models constructed through technical means, including image segmentation, computer-aided 3D reconstruction, and texture mapping based on continuous thin-layer tomographic images of the real human body. Owing to the high precision of the original tomographic data, the reconstructed 3D digital models can truly represent the morphological structure of the human body and its 3D spatial relationship, which ensures the scientificity of anatomical structures in the digital anatomy system and the high degree of restoration of morphological characteristics.

For some thin vessels and small nerves as well as structures unidentifiable on tomographic images, their spatial location and approximate size are determined strictly based on their identifiable reference structures on tomographic images, with corresponding 3D models generated in the 3D modeling method. The
generated models are then approved by anatomy experts; hence, their authenticity and scientificity are guaranteed.

5.2 Systematicness and completeness of digital anatomy teaching system

The goal of anatomy teaching is for medical students to gain insight into the morphological, location, and spatial relationship of body structures. As the difficulty in understanding their spatial characteristics is increased by the complexity of these structures, medical students have to recognize and understand anatomical structures from different angles to gain a comprehensive understanding of knowledge on both systematic and topographic levels [29].

This scientific, complete, and holistic system has produced over 6000 three-dimensional digital anatomical models, over 5000 anatomy knowledge points, over 50 anatomical operation videos, and over 150 micro demonstration classes, with teaching contents for different majors and levels, such as systematic anatomy, topographic anatomy, sectional anatomy, anatomy of motion, and virtual anatomical operation table. Ranging from network terminals, desktops, touchscreen 3D displays, and projection 3D volumetric displays to AR, its diversified interactive forms meet the requirements for a learning environment in different settings.

5.3 Diversity of virtual anatomy in digital anatomy teaching systems

Students of anatomy mainly include clinical medical students, non-clinical medical students, medical workers, special industry practitioners, and relearners of anatomy. Students of different majors have varied learning needs and goals. For instance, clinical medical students require a comprehensive and in-depth grasp of human anatomy, which involves the study of systematic anatomy, topographic anatomy, and even sectional anatomy; students majoring in nursing, laboratory medicine, and preventive medicine often focus on the study of systematic anatomy; students majoring in sports emphasize the sport anatomy; and relearners of anatomy; in particular, surgeons pursuing advanced studies need to master more refined anatomical knowledge, especially details of topographic anatomy.

With different anatomy demands and teaching goals fully taken into consideration, the digital anatomy assistive teaching system has constructed targeted anatomy-assistive teaching systems, including systematic anatomy, topographic anatomy, nursing anatomy, and sport anatomy assistive teaching systems. The digital models in each digital anatomy assistive teaching system come from the same digital anatomical specimen model base. In different anatomy assistive teaching systems, the arrangement of teaching content and the virtual anatomical operation of 3D digital models are based on the respective features and requirements of each course, to fully embody the teaching characteristics of the course and achieve a good teaching effect.

When the different needs of users and the requirements at various stages are considered, except for the navigation framework of each anatomy course system, quick navigation "magnets" are arranged for the teaching and learning of common anatomy knowledge of all anatomy courses; cartoons and video resources to display special structures and functions and anatomical resources in an outline form for review and memory reinforcement are made, and a series of anatomy-assistive teaching tools are designed, including an examination system for anatomical specimen structure identification and anatomy knowledge test. By integrating the teaching and learning of anatomy, the assistive teaching system of each anatomy course satisfies the teaching and learning demands of medical students and anatomy teachers at various levels [29].
5.4 Diversity and practicability of the teaching mode

5.4.1 Virtual anatomy teaching environment

In addition to the efforts of students and the teaching level of teachers, the learning effect of anatomy is directly correlated with the anatomy learning environment and teaching resources. A good learning environment can dissipate fears for cadaveric specimens to a great degree and even increase interest in anatomy studies\cite{30}.

The popularization of digital technology and the rapid development of virtual simulation experiment teaching in this modern era, the fast growth of "5G," "IoT" and "smart technologies" will certainly bring about new waves of digital learning reforms.

Constructing as "intelligent, digital and professional," the "smart anatomy experiment teaching center" comprised "specimen processing and display" and a variety of "anatomy laboratories," "clinical anatomy training centers" and "intelligent control management systems."

In the course of anatomy teaching, covering systematic anatomy, topographic anatomy, sectional anatomy, and clinical anatomy, it creates a ubiquitous novel mode of autonomous learning and contributes to the reform of anatomy teaching in various medical schools.

Although cadaver specimens are considered to be the best teaching model, some alternative teaching resources and models have been applied in teaching owing to the shortage of specimens. The digital human anatomy teaching system is derived from the real human body data, with a detailed and real structure, similar to the real specimen in visual appearance, integrated anatomy knowledge system, and conforms to the anatomy teaching syllabus of all professional levels, which is a powerful supplement to the anatomy teaching resources and innovative teaching mode. It satisfies various needs of anatomy teaching including "learning, teaching, practice, examination and management," and effectively solves problems in anatomy teaching, such as inadequate cadaver sources, a shortage of specimen supply, monotonous teaching resources, obstacles to autonomous learning and difficulties in implementing autonomy exercises and examinations.

5.4.2 Implementation of virtual anatomy teaching

Based on questionnaire surveys and certificates of application\cite{31}, the digital anatomy teaching system has received unanimous praise of teachers and students and improved the teaching effect of human anatomy courses\cite{32-38}. The reasons for this improvement are summarized as follows:

(1) The autonomous learning environment offered by the digital human system innovates the conventional anatomy teaching mode and promotes the transformation from passive learning to autonomous learning.

(2) The three-dimensional, vivid, and highly interactive system greatly improves the learning interest of students.

(3) Three-dimensional anatomical structures cultivate the ability of spatial thinking among students.

(4) Innovative experimentation with a digital human system helps students develop innovation and entrepreneurship abilities.

(5) The Chinese and foreign pronunciation system teaches students the correct pronunciation of terms.

(6) Teachers are provided with a wealth of teaching resources.

5.4.3 Recognition of digital anatomy teaching systems

Developed with data on the Chinese people and modern means of informatization, the digital human anatomy system is original, standardized, advanced, and autonomous. Applied in anatomy teaching by over
220 medical colleges and universities in China, it has improved teaching quality and set the trend for the teaching reform of human anatomy and even the informatization of medical education\cite{32-38}.

Compared with other similar products, in the data source, the content of products and product experience interactions have prominent advantages\cite{39}.

1. Real and detailed data sources

The Chinese digital human anatomy system is the only digital human anatomy product based on the 3D reconstruction of continuous optical sections. Compared with other similar applications, it has significant advantages in terms of authenticity and accuracy, and the product has passed the appraisal of the expert committee of the Chinese Society of Anatomy.

2. Complete product knowledge system

The model structure was real, and over 6000 lifelike three-dimensional digital anatomical models were produced. The models were real, and the rendering effect was not significantly different from that of the real specimen. The integrated anatomical knowledge covers many courses, such as systematic and local anatomy, which are suitable for the teaching of clinical and non-clinical medicine.

3. Flexible and immersive interaction experience

The digital human system integrates a variety of interactive equipment and teaching environments, which can give full play to the teaching purpose and teaching effect of digital anatomy teaching systems. These can better reflect the value of digital anatomy teaching resources and teaching models than other related systems.

6 Conclusion

Chinese digitalized visible human datasets are optical images obtained by milling cadaveric specimens with the cryogenic milling technique, which have ultra-high spatial resolution and structural recognition\cite{25}. The digital human structure model is meticulous and real, and the rendering effect is not significantly different from that of a real specimen, with a sense of reality and immersion. The integrated anatomy knowledge covers many courses, such as systematic and local anatomy, which is suitable for the teaching of clinical and non-clinical medicine. In the digital human anatomy teaching system, through the integration of three-dimensional anatomical structure model, anatomical model knowledge points, sections, tomography images, CT/MRI images, micro-class videos and other resources based on the requirements of teaching arrangements, the modules of systematic anatomy, sectional anatomy, local anatomy, clinical cases, and micro-class anatomy are constructed, which are encapsulated into VR anatomy system, AR anatomy system, digital human anatomy system, digital human anatomy examination system and other products based on the requirements of interactive experience.

The integration of digital human systems, various interactive equipment, and teaching environments can fully enhance the teaching purpose and teaching effect of digital anatomy teaching systems. These can better reflect the value of digital anatomy teaching resources and teaching models than other related systems. With the improvement of interactive equipment, it is expected to replace most of the anatomy teaching content.

The development of digital and information technology continues to promote the innovation and progress of anatomy teaching in medical colleges and universities. With the update of teaching philosophy, the perfection of digital teaching resources and accelerated reformation of anatomy teaching ideas, information, and network construction has been deepened and popularized, with teaching tools being
innovated continuously. In the course of anatomy teaching, the digital human anatomy system effectively solves problems including inadequate cadaver sources and a shortage of specimen supply, contributes to the reform of anatomy teaching in various medical colleges and universities, and improves the overall teaching environment of laboratories and school images. Applied in most Chinese medical schools, this system has been affirmed and recognized by anatomy teachers and students, and plays a vital role in guaranteeing the effect of the quality of anatomy teaching.

Limitation of the study

Although the digital human anatomy system developed in this study is close to real anatomy teaching in terms of knowledge dissemination, perception performance of anatomical models, and anatomical operation experience, it has the potential to replace traditional anatomy teaching modes. With the help of good VR interactive equipment, the digital human anatomy teaching system can teach most anatomy courses, which cannot yet fully meet the teaching needs of clinical professional medical students who have relatively high requirements for anatomical skills training. It is best to combine field anatomy teaching with this system.

Declaration of competing interest

We declare that we have no conflict of interest.

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