Mixed Reality for Group-Based, Integrated Instruction of Anatomy, Pathology, and Physical Examination

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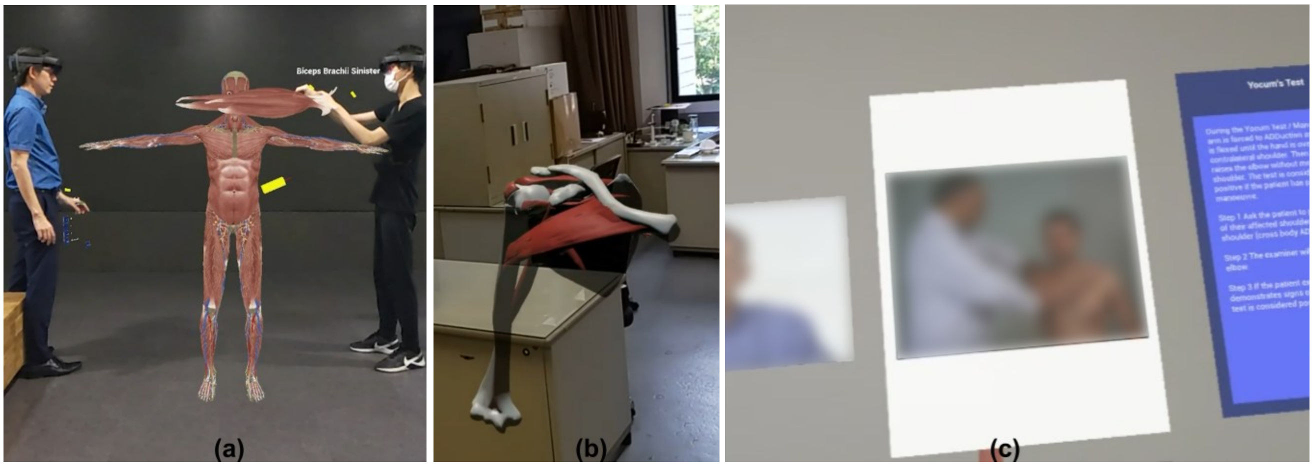

Figure 1: Collaborative MR for integrated instruction of (a) anatomy, (b) pathology (showing rotator cuff tear), and (c) physical examination (blurred due to copyright). Instructors can organize varied materials in physical space to emphasize how these three concepts interrelate.

Abstract

Anatomy is fundamental to medical education and clinical practice. Traditional instruction involves 2D atlases, dissections, and plastic models. Translating 2D images into a 3D spatial map is difficult. Dissections suffer from the cost of cadavers, formalin exposure, and emotional distress. Plastic models lack sufficient details and anatomical variation. Mixed reality (MR) addresses these issues by offering a rich, 3D environment where students can affordably and safely explore a virtual body. Anatomy instruction is typically delivered in small groups to promote active learning and knowledge sharing. Using MR for group study simplifies the body tracking burden because participants meet face-to-face, allowing both verbal and nonverbal communication while enabling them to safely move through the space. Medical curricula have integrated anatomy with clinical sciences to highlight its relevance. In clinical practice, students must link anatomy with pathology and diagnostic methods. We present a novel MR system that facilitates group-based, integrated instruction of anatomy, pathology, and physical examination. Feedback shows the system boosts learning, yet performance and learning curve need improvement.

Index terms: Mixed reality, group study, integrated instruction, anatomy, pathology, physical examination, 3D interaction.

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1 Introduction

Anatomy is the study of the human body's structures, fundamental to medical education [1], and essential for safe and accurate clinical practice [2]. Traditional anatomy instruction primarily involves 2D images in lectures and textbooks, cadaveric dissections, and plastic models [3]. Translating 2D images into 3D spatial understanding of anatomical structures is hard [3]. While dissections provide deep spatial and tactile understanding, they suffer from the scarcity and high cost of cadavers, formalin exposure, and the emotional trauma they can cause [4, 5, 6]. Plastic models lack sufficient details on the number of structures, their shapes, surfaces, and anatomical variation, the latter being crucial for disease education [7].

Computer technologies such as virtual reality (VR) can mitigate such drawbacks by providing a rich, immersive, stereoscopic 3D environment where students can interactively and repeatedly explore a virtual body safely and affordably [8]. Prior research has shown that such technologies enhance motivation, engagement, knowledge acquisition, test completion speed, and medical career aspiration [3, 8, 9].

Anatomy instruction is typically delivered in small groups to promote active learning, enable students to learn from one another, and help the group identify and correct misconceptions [10]. Supporting this teaching format in VR typically involves representing each participant with an avatar (3D virtual character), which requires complex and costly face and body tracking to convey nonverbal cues. Mixed reality (MR) is a promising alternative that simplifies the tracking requirement. In a co-located MR environment, participants meet face-to-face, allowing both verbal and nonverbal communication, while the headset's partial facial occlusion can be mitigated by using a transparent-display device like the Microsoft HoloLens. Users can also safely move through the space because physical obstacles remain visible.

Several medical school curricula have integrated anatomy with clinical sciences such as pathology [11] (the study of structural and functional changes caused by disease or injury) and clinical examination skills [12] to highlight its clinical relevance and applications, as well as to enhance critical thinking and clinical problem solving [13]. From our experience, clinical practice requires students to link (normal) anatomy with disease pathology and relevant diagnostic methods. At the Faculty of Medicine Ramathibodi Hospital, these topics are taught separately during the preclinical years (1–3), which can make it hard for some students in the early clinical years (4–5) to integrate the concepts in practice.

This paper introduces a novel MR system that facilitates group-based, integrated instruction of anatomy, pathology, and physical examination, while also supporting student-centered exploratory learning (Fig. 1). Such use of MR for integrated anatomy study in a group setting remains largely unexplored. The system mainly targets 4th- and 5th-year students to help them link concepts to clinical practice. User feedback suggested the system would improve learning, noting the benefits of a 3D human model, self-directed study, knowledge sharing, and the arrangement of varied resources to show their links. However, the system's performance and learning curve required improvement.

2 Related Work

Prior MR systems for anatomy instruction vary in formats and findings. *For individual instruction,* Maniam et al. [14] created an MR system for exploring the temporal bone in 3D, aiming to improve the understanding of the spatial relationships among its anatomical structures beyond the textbook methods. The system allowed users to rotate the model, navigate around it, view cross sections, listen to descriptions of labeled surgical landmarks, and practice cadaveric bone drilling (mastoidectomy) to investigate the anatomical relationship between superficial and deep structures, while highlighting important landmarks near a drill.

McJunkin et al. [15] developed an MR platform that provided 3D visualization of the lateral skull base, showing soft tissue, bone, and inner ear structures, to help surgical trainees build a 3D mental map of the anatomy — an essential skill for safe and efficient dissection. Users could navigate and manipulate the model to align it with a physical object, paving the way for future use in intraoperative surgical guidance.

In liver surgery, surgeons use preoperative images, such as those from magnetic resonance imaging (MRI), for clinical decision-making, surgery planning, and guidance. They typically visualize these images in 2D and mentally reconstruct a 3D view for a spatial understanding of the anatomy. Pelanis et al. [16] compared 3D liver model visualization in MR, where the user could only navigate around the model, with 2D MRI visualization for lesion identification. The MR modality statistically significantly reduced the correct identification time with no detected accuracy difference.

For group instruction, Stojanovska et al.'s MR platform [17] taught musculoskeletal anatomy through a PowerPoint-style, sequential display of 3D anatomical models mimicking the material covered in cadaveric dissection labs. Each user could walk around the models and examine them from various angles. The authors reported no superiority of MR instruction over traditional cadaveric dissection in practical exam performance, yet MR required less teaching time to cover the same content, indicating that MR may be more efficient.

Robinson et al. [18] compared group instruction in gross and microscopic respiratory anatomy delivered with a pre-dissected cadaver and glass slides examined under a light microscope to an MR approach using a 3D graphical model and PowerPoint histology slides, with labels and descriptions. The MR group matched the cadaver group on the post-test and outperformed them on the follow-up test, while also reporting higher self-perceived understanding and a more enjoyable, engaging, and easier learning experience.

Bork et al. [9] presented an MR system that allowed multiple students to collaboratively explore 3D anatomical structures of the thorax, abdomen, and pelvis, along with their cross-sectional computed tomography (CT) images. The 3D models could be manipulated and filtered for display. A laser pointer was provided to draw immediate attention. A colored pin could be placed for longer-term attention and displayed the attached structure name. Their study found that MR significantly increased anatomy knowledge but the gain was not significantly different from that achieved with traditional learning using a textbook and plastic model. Participant feedback indicated that learning with MR was more fun, improved 3D spatial understanding and motivation, and that collaboration was useful, made learning more fruitful, and offered a means to discuss and share knowledge.

Research gap: To our knowledge, MR for integrated anatomy instruction, especially in group settings, remains largely unexplored. Veer, Phelps, and Moro [19] developed a single-user MR system for asthma education that integrated anatomy, physiology, pathology, and pharmacology to help users understand the disease and its treatment options. The system displayed 3D anatomical structures of the lungs and heart, the asthma impact on bronchioles, its triggers and management, and effective medications. Users could view structure names and dissect a model to see underlying anatomy, while the textual information was delivered via audio. The authors compared MR learning with a textbook. Both formats significantly boosted asthma knowledge, with the textbook yielding a significantly higher post-test score, yet participants rated MR as more enjoyable and useful. Retention scores did not differ significantly.

3 Design and Implementation

Our design goal is to enable instructor-led, group-based, integrated teaching of anatomy, pathology, and physical examination, while also supporting student-centered exploratory learning. Our system lets instructors arrange diverse materials in the physical space to emphasize how these three concepts interrelate in clinical practice, pose questions, and assess their comprehension. Moreover, students can review the materials independently or in groups. A supplementary video further illustrates the concepts discussed in this section.

3.1 Instructional Resources

Anatomy: Our system features a full-body human model for anatomical exploration (Fig. 1a). It comprises the integumentary, skeletal, nervous, muscular, lymphatic, cardiovascular, digestive, respiratory, and urinary systems, allowing users to interact with several distinct structures. When a user touches a structure, its Latin term appears, and the user can grasp the structure to manipulate.

Pathology: Users may select a specific body region to access related pathological data. At present, our system supports only shoulder selection, which then displays the pertinent shoulder anatomy (uninjured state, see Fig. 2). Users can then pick from three shoulder injuries to explore: acromioclavicular arthritis, biceps tendinitis, and rotator cuff tear. For each condition, our system presents three resources: a 3D model showing structural changes (Fig. 1b), a poster summarizing the injury visually, and a textbox detailing the pathology.

Physical examination: Users can also view physical examination data for a body region, though at present only the shoulder is supported. They may select from four shoulder joint examinations: a general assessment and one for each of the three injuries previously mentioned. For each examination, users can choose from a subset of topics including "Where to look?", "Where to touch?", passive movement, active movement, related tests (such as Yocum's Test, Speed's Test, and the Belly Press Test), and pertinent anatomy knowledge. For each topic, our system presents three resources: a text description, a visual poster summary, and one of the following media: a video, a 3D animation, or a 3D model.

3.2 Virtual Instruments for Learning Support

Users can manipulate the following tools to support their education.

- *Laser pointer* emits a ray to capture user attention.
- *Voodoo doll* lets users rotate the entire virtual body by mapping the doll's orientation to that of the virtual body [20].
- *Magic bar* creates an invisible cut plane that produces a cross-sectional visualization (Fig. 3a) by rendering any surface part falling on one side of the plane transparent.
- *Magic wand* has an invisible sphere at its tip that renders any surface part falling within the sphere transparent, thereby revealing the body's internal structures (Fig. 3b).
- *Control panel* lets users toggle the visibility of an anatomical system, access pathological and examination data, and change the grasp technique (Sec. 3.3).

3.3 3D Interaction Techniques

We introduce techniques designed to enhance anatomical exploration that overcome the interaction constraints of cadaver and plastic model teaching.

Copying and deleting: The instructor can create multiple copies of an anatomical structure, letting several students examine their copies concurrently instead of taking turns. To make a copy, a user grasps the structure with one hand and then touches the back of that hand with the index finger of the other hand (Fig. 4a). The user repeats the same action on a copy to delete it.

Scaling: Users can enlarge a structure to inspect fine details — a desirable feature noted by Bork et al. [9]. By grasping the structure with both hands and pulling them apart, the user enlarges it. Bringing the hands together shrinks it.

Reeling: If walking is inconvenient, users can send a structure to a desired location by translating it along a pointing direction (fishing-reel metaphor [21]). The user first grasps the structure, then pushes a widget next to that hand with the index finger of the other hand (Fig. 4b) to reel the structure back and forth (depending on the push direction) along the pointing direction of the first hand.

Users can grasp an anatomical structure using one of three distinct object selection (grasp) techniques, allowing them to match the method to their preferred interaction style or the activity at hand. Once selected, the object attaches to the hand, allowing it to be translated, rotated, or scaled.

Hand selection: The user selects an object by touching it with the thumb tip and the index fingertip [22]. A highlight appears on the object when either finger contacts it, serving as a selection cue. The highlight fades once both fingers touch the object, indicating selection completion. This method is intuitive because it mirrors how we interact with everyday objects. The user can only select objects within arm's reach unless navigation is used, which slows the selection process [21].

Gaze selection: The user selects an object by looking at it and then makes a pinch gesture — touching the thumb tip with the index fingertip [23]. An invisible ray is projected from the head in the gaze direction to highlight the first intersected object (Fig. 5a). This highlight, serving as a selection cue, disappears once the pinch gesture is made, signaling selection completion. In general, pointing-based selection methods like this are faster than hand selection methods because they involve less physical movement [24]. This method also allows selecting distant objects with less dependence on navigation and should prove helpful when the target is partially occluded, leaving only a small visible area that would be hard to reach with a hand unless the occluding object is removed (the gaze ray may more easily intersect the small visible portion).

Figure 2: Pertinent shoulder structures in the uninjured state during pathological data access. Students can compare this to an injured state (Fig. 1b) to study structural changes.

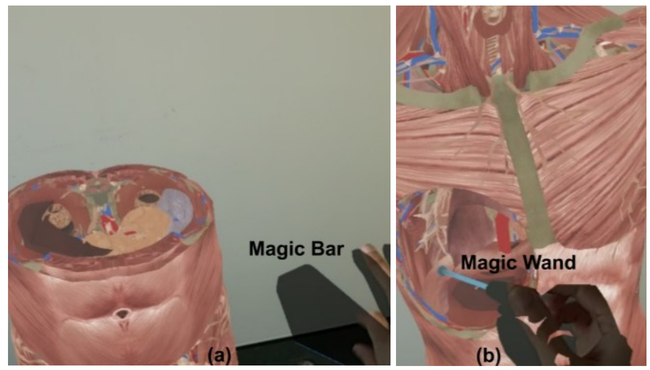

Figure 3: Learning support instruments: (a) the magic bar creates a cross-sectional view, (b) the magic wand displays the body's internal structures.

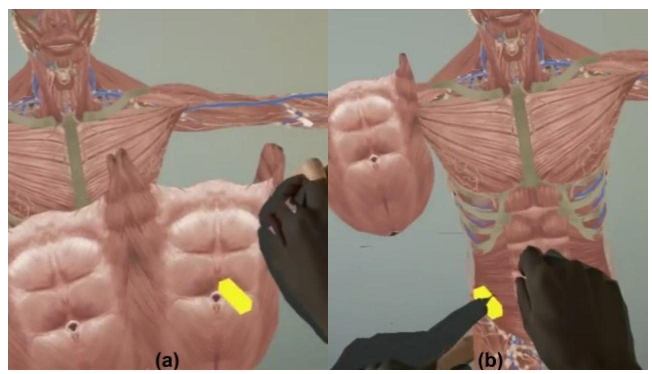

Figure 4: Interaction enhancing anatomical exploration: (a) creating a replica for concurrent inspection, (b) reeling a structure by pushing the yellow widget to move it closer or farther away.

Gaze-assisted hand selection: The user first moves the hand to highlight nearby objects, marking them as selection candidates, and then uses the gaze selection method to disambiguate (select) the target. The target is highlighted in a different color (red) to distinguish it from the other candidates (Fig. 5b). All highlights vanish once the selection succeeds. This method aims to combine the naturalness of the hand selection method with the gaze selection's ability to potentially resolve occlusion.

3.4 Implementation Notes

Users wear a Microsoft Hololens 2 — a standalone MR headset featuring two 1440 × 936 displays that refresh at 60 Hz. The see-through lenses provide a 52° diagonal FOV of stereoscopic 3D images. It includes 6-DoF head tracking, full-articulation hand tracking, eye tracking, a Qualcomm Kryo 2.96 GHz processor, 4 GB RAM, a Qualcomm Adreno 630 GPU, and Wi-Fi 5.

We adapted the VR anatomy atlas project [8], developed in Unreal engine, to the MR platform and added multiuser collaboration, pathology and physical examination modules, gaze and gaze-assisted hand selection, copying, scaling, and reeling.

We used the full-body human model that came with the original VR project and built the pathological shoulder models and physical examination animations in Blender. For our proof-of-concept system, we collected the video, poster, and textual content used in the pathology and physical examination modules from websites, medical journals, and a textbook, and verified their accuracy.

We support multiuser collaboration on the anatomical, pathological, and physical examination content by synchronizing the states of these items in the real world, e.g., their positions, orientations, scales, and highlighting, across all Hololens devices. This lets, for example, one user pick up a structure and hand it to another. We use a client-server model in which one client acts as the server and use a reliable UDP protocol to transmit data. When a client changes an object's state (e.g., moves it), it sends the update to the server, which then broadcasts it to all other clients. We also synchronize user states so that each user's visual representation is shared with the others, allowing, e.g., the reeling widget (Fig. 4b) next to one user's hand to be visible to the rest.

For interaction, each fingertip has an invisible sphere that detects touch. An object is considered touched when this sphere collides with the object's collision shape. Additionally, each palm has an invisible sphere that highlights nearby colliding objects for the gaze-assisted hand selection. The Hololens estimates a gaze ray that is typically within 1.5° of the visual angle around a view target. The magic bar and wand (transparencies) were implemented by setting the opacity mask of surface materials in the Unreal engine.

4 User Feedback and Observation

We gathered feedback from eight users about their experiences with our MR system during 30- to 40-minute sessions. This study aimed to highlight strengths, avoid major issues, and gain early design insights. For this purpose, a small number of participants is adequate [25]. The users were four medical experts and four extended reality (XR) experts, each of whom explored the system freely alongside another participant from the same expert group, with a 10-minute tutorial included (there were four sessions in total, each featuring two experts). We asked the medical users to focus on instructional elements and the XR users to examine technical aspects. We report the overall findings.

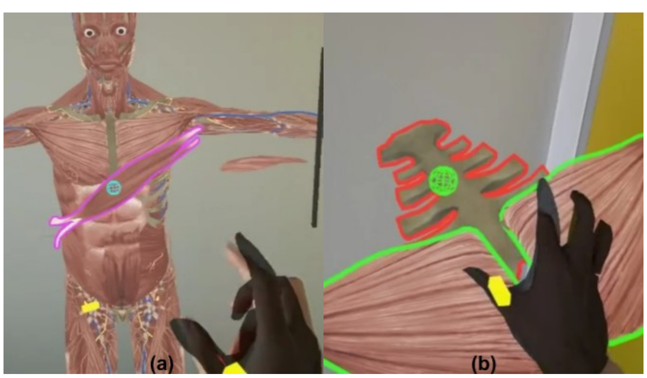

Figure 5: Selection methods: (a) gaze selection picks an object by looking at it and pinching, (b) gaze-assisted hand selection highlights objects near the hand and uses gaze selection to pick the target. In both cases, the spheres show where gaze rays hit objects.

The medical users considered the educational features valuable and felt that incorporating the system into their curriculum would enhance student learning. They especially appreciated the ability to interact with a full-body 3D human model, the freedom afforded by the independent learning mode, the chance to exchange knowledge with peers, the wide range of pathology and physical examination materials, and the ability to organize these materials in 3D to highlight their interconnections. They reported that the gesture used for the copying interaction (Sec. 3.3) felt unfriendly.

The XR users reported that the gaze-assisted hand selection worked better than the other methods. With the hand selection method, they noted that Hololens hand tracking was noisy, occasionally causing an object to be released unintentionally or a grasp to fail. In the gaze selection method, they said they tended to keep the thumb tip and index fingertip close together, which sometimes led to accidental object selections because of hand motion or tracking noise. For the gaze-assisted hand selection, they explained that using the palm to pick candidates helped them focus on the hand and encouraged them to spread the two fingertips apart, thereby lowering the chance of unintended selections. Moreover, they found that the pinch gesture was less susceptible to tracking noise than the grasp heuristics employed in the hand selection method, making it a more reliable way to select objects.

The frame rate usually fell between 20 and 30 fps. However, it dropped sharply during computationally intensive moments, such as when users interacted with voodoo dolls, which caused several structures to rotate and triggered many update transmissions, bringing the rate down to about 4 fps and sometimes causing network disconnections that disrupted the collaborative session. These disconnections may be explained by the server's inability to process the update packets quickly enough, leading to buffer overflow and client-side timeouts when acknowledgements were missing or too late. In our system, the server also functions as a client, handling visual and audio rendering and processing user input. Both medical and XR users required guidance to operate the system, yet the XR users adapted more quickly.

5 Conclusion and Future Work

To the best of our knowledge, our MR system introduces the following novel concepts: integrated instruction of anatomy, pathology, and physical examination in group settings, anatomical exploration that overcomes the interaction constraints of cadaver and plastic model teaching, and the gaze-assisted hand selection technique designed to improve grasping of an anatomical structure.

Medical and XR experts tested our system. They reported that it would enhance learning, citing advantages such as a 3D human model, self-directed study, knowledge sharing, and an organization of diverse resources that illustrate their interconnections. Nonetheless, the system's performance and learning curve need improvement. The XR experts noted that the gaze-assisted hand selection outperformed the two conventional selection methods.

In future work, we will enhance server performance by adopting a dedicated server model. In this model, the server functions solely as a server, omitting graphics, sound, and input to operate more efficiently. Instead of using a Hololens as the server, we will employ a dedicated PC to run it. To increase the client's frame rate and input responsiveness, we will split our software into two main threads: one for graphics rendering and another for input processing and networking. We will ease the learning curve by adding a hand-attached menu that lets users choose copying, scaling, and reeling, instead of depending solely on gesture-based controls.

To provide a more comprehensive education, we will expand the pathological and physical examination data beyond the shoulder to include additional anatomical regions. We will formally evaluate how well our system helps medical students integrate anatomy, pathology, and physical examination for clinical practice. We will compare students trained with our system to those taught through a conventional method that uses lectures, a standard plastic model lacking pathology, and peer-based physical examination simulation, judging them by test scores and subjective feedback. We will also explore the design space of the gaze-assisted hand selection in depth.

Inspired by Borst, Lipari, and Woodworth's work [26], we aim to examine the use of depth camera recordings of an instructor in teacher-directed sessions. While prerecorded instructors cannot answer questions or correct misconceptions, they let students pause and replay the instruction [26], provide extra learning time independent of instructor availability, may encourage more active participation in group discussions when no live instructor is present, free instructors for other duties, and reduce coordination and equipment requirements. We are particularly interested in determining which interactions best support learning with a prerecorded instructor. As artificial intelligence advances rapidly, the logical next step is to investigate an autonomous instructor.

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