

# Anatomia: An Interactive 3D Visualization Tool for Enhancing Medical Anatomy Education

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**Abstract**—Anatomy education continues to rely on cadaver dissection, which is constrained by donor shortages, costs, and limited hands-on access. Digital 3D anatomy tools offer alternatives, but most do not collaborate well across multiple users, keep upright content legible as viewers move around the table, or support hand gestures specific to anatomical interaction. This study presents Anatomia, a multi-touch tabletop application designed for around-the-table anatomy learning. It introduces a set of domain-specific hand gestures developed with medical students and instructors, a content-alignment mechanism that adjusts display orientation based on the user's position around the table, and a software-level conflict resolver that allows two users to share a single display without additional hardware. Anatomia was evaluated with medical and non-medical students under a structured two-phase protocol. Results indicate that familiar touchscreen gestures succeed on first attempts, anatomically novel gestures are learned within a single guided session, content-alignment tasks score near the ceiling, and concurrent multi-user interactions achieve a perfect task success rate with no participant rejections. Together, the findings indicate that gesture-driven collaborative 3D anatomy visualization on commodity touchscreen hardware is a viable complement to traditional dissection, especially where specialized anatomy visualization tables are not affordable.

**Keywords**—3D anatomy visualization; anatomy education; gesture interaction; multi-touch interaction; content alignment; tabletop display; collaborative learning

## I. INTRODUCTION

In the field of medical science, understanding human anatomy is fundamental for clinical knowledge and practice. For many years, anatomy education has rested on a combination of cadaver dissection, demonstrations, anatomical models, and lectures [1]. Among these, cadaver dissection has been particularly significant. It supports both anatomical knowledge and the manual dexterity, tissue-handling skills, teamwork, and professionalism that medical students require [1], [2]. Despite these benefits, cadaver dissection alone cannot easily demonstrate functional neuroanatomy, complete skeletal relationships, or the fine vascular and neural structures encountered in microsurgery [3]. Practical limitations further constrain its use: donor shortages, increasing lab costs, reduced teaching time, and health concerns related to formaldehyde exposure [4], [5], [1], [2]. These constraints are particularly tough in areas where resources are limited. Typically, in a traditional dissection lesson in medical faculties in Sri Lanka,

a group of 10-20 students are assigned to a single human cadaver to carry out the studies throughout the year. This may vary with the university location, as most of the outstation universities receive a few cadavers per year. These insights highlight that there is a need for an accessible, shared-surface visualisation tool that can support cadaver-based instruction without requiring any additional cadaveric resources.

Digital tools are increasingly used alongside these traditional methods rather than replacing them. Among the available digital approaches, three-dimensional (3D) visualization has drawn particular attention: the body is inherently three-dimensional, so the ability to explore structures from different angles, isolate systems, view cross-sections, and rotate, flip, and zoom aligns naturally with how anatomy is learned and applied. According to research, 3D visualization improves overall learning experiences, increases teaching efficiency, and can be more cost-effective compared to some traditional methods [6], [4], [2], [7].

Collaborative learning around a shared surface is not a supplementary feature in anatomy education; it is central to how the discipline is taught. Students have historically gathered around a cadaver table, pointed at structures, discussed spatial relationships, and built clinical reasoning through peer interaction. When anatomy instruction moves to a digital surface, this collaborative dimension is often the first casualty: most digital tools are designed for individual use, and those that support shared displays do not account for the cognitive costs of content appearing upside down to some users or for the input conflicts that arise when multiple hands touch the screen simultaneously. Restoring the collaborative, around-the-table dynamic on a digital surface requires addressing orientation, input conflict, and gesture design together, not as isolated features but as an integrated interaction framework.

The most widely used 3D anatomy tools today include the Anatomage Table, Anatomy 3D Atlas, and Complete Anatomy, each with different pricing and accessibility models. Across these tools, three specific gaps remain unaddressed for collaborative tabletop learning. First, none offers a gesture vocabulary tuned to anatomical tasks; all rely on generic touchscreen gestures that do not capture domain-specific actions such as organ isolation or virtual dissection. Second, none provides content-orientation adaptation for users positioned around different sides of a shared display, a significant bar-

rier to legibility. Third, none includes software-level conflict resolution for simultaneous multi-user touch input, meaning that collaborative use is unsupported.

This study presents a multi-touch tabletop application designed for around-the-table anatomy learning on commodity touchscreen hardware. The work makes three contributions. First, a domain-specific gesture vocabulary was developed through a participatory design process involving medical students and anatomy instructors. Second, a content-alignment mechanism was implemented that automatically rotates displayed content based on the user's position around the table, with a manual override for locking orientation, addressing the legibility issue that arises when text and anatomical labels are viewed at high rotation angles. Third, a software-level conflict resolver was developed that enables two users to interact with the application simultaneously without requiring specialised hardware, closing the gap between hardware-bound multi-touch systems and commodity classroom displays. Together, these three components form a reusable, open-source framework that runs on standard multi-touch hardware, making collaborative 3D anatomy visualisation accessible to institutions where dedicated anatomy visualisation tables are not affordable.

The remainder of this study is organized as follows: the background and related work section examines the impact of 3D models in anatomy education and the requirements for collaborative gesture-driven tools, with a comparison of existing digital solutions, and identifies gaps that affect user experience. The methodology section presents the application's requirements, design, implementation, and the evaluation process used to assess its effectiveness. The results section presents the evaluation results of this work, followed by the discussion and conclusion.

## II. BACKGROUND AND RELATED WORK

### A. The Role of 3D Models in Anatomy Education

Studies comparing 3D models with traditional methods for anatomy education generally support the combination of the two. Azer and Azer [8] report that incorporating 3D models into the teaching and learning process enhances the overall learning experience, increases productivity, and improves student satisfaction. Empirical comparisons point in the same direction. Yammine and Violato [7] reported that digital resources used alongside conventional techniques yield stronger learning outcomes than either approach alone.

A study by Brinke et al. [9] found that 46 undergraduate medical students at Erasmus University Medical Center who trained on 3D laparoscopic dissection models alongside lectures scored higher in both short-term and long-term anatomy assessments than peers receiving lecture-only instruction or dissection-based laparoscopic training. Murakami et al. [10] reported that 126 medical students and academic staff at the Graduate School of Medicine in Gunma University rated 3D anatomy-CT models positively, with significant improvement in radiology performance in subsequent clinical courses. A study by Müller-Stich et al. [11] compared the effectiveness of 2D CT images, static 3D-rendered liver models, and 3D models with rotational interaction (denoted 3Dr) for teaching and learning. 156 medical science students at the University of

Heidelberg, Germany, were randomly assigned to one of three groups (2D, 3D, or 3Dr) and required to respond to a series of questions based on the lessons conducted. According to the results, the students in the 3D and 3Dr conditions performed significantly better than those in the 2D group. In 2024, Sarmiento [12] conducted a quantitative study to determine differences in written and lab exam scores between physical therapy students who received gross anatomy education using the Anatomage table and those who learned gross anatomy through traditional lectures. He reported a significant positive difference in written exam scores between Anatomage users and peers taught via traditional lectures.

Taken together, these studies indicate that gains from 3D visualization are largest when the comparator is textually or two-dimensionally constrained, extend beyond short-term recall to subsequent clinical reasoning, and persist when the 3D condition includes only static rendering.

### B. The Need for Collaborative, Gesture-Driven Tools

Collaborative learning around a shared surface is central to how anatomy is taught, yet most digital tools are optimized for single-user interaction. Historically, supporting multiple users around a shared display required specialized hardware. Systems such as DiamondTouch [13] relied on antenna-embedded chairs to identify individual users via capacitive coupling. At the same time, other research has used overhead cameras to track hands using skin-color segmentation techniques [14]. These hardware-based solutions are often too expensive or complex for standard medical classrooms, particularly in resource-constrained environments where cost is a primary barrier to adoption [15]. A software-only approach to conflict resolution that works on commodity touchscreens would allow multiple students to interact simultaneously without specialized equipment.

The orientation of digital content creates an additional cognitive burden when students are positioned on opposite sides of the tabletop display. Human perception of text and objects is sensitive to rotation; for example, word recognition time is relatively stable for rotations up to 60°, but reaction times increase significantly as the orientation approaches 70–80° beyond 120°. Research indicates that at these higher angles, the brain shifts from holistic recognition to a much slower "letter-by-letter" processing method [16]. This "holistic rectification" threshold suggests that a visualization tool must automatically align its content to the user's position to remain legible and effective for learning.

Effective interaction also requires a gesture vocabulary that reflects the specific tasks of the medical domain. While standard mobile gestures like pinching and swiping are common, they often fail to capture complex anatomical actions such as organ isolation or virtual dissection. Research into the Surgery Planner system demonstrated that domain-specific interaction techniques improve usability and help maintain professional standards [17]. By using a participatory design approach, in which students and instructors help identify necessary gestures, developers can ensure alignment with users' mental models.

### C. Current Digital Solutions and Limitations

Current anatomy software generally falls into two categories: high-end hardware-bound systems and mobile-centric

applications. Neither category fully addresses the needs of collaborative, tabletop learning.

The Anatomage Table is a touchscreen platform that serves as a virtual dissection table, using a library of 3D-reconstructed and prosections [18]. It allows for detailed interactive segmentation, enabling users to isolate specific muscular or neurovascular structures and view them across three section planes [18], [19]. While highly effective at simulating physical dissection, it does not provide software-based multi-user conflict resolution or adaptive content orientation. The Anatomage Table is a proprietary, non-portable hardware-software bundle with an acquisition cost that places it beyond the reach of most medical faculties in low and middle-income countries.

Anatomy 3D Atlas is an interactive virtual environment for learning about the body's various systems, including skeletal, circulatory, neurological, respiratory, digestive, and urinary systems. It supports basic 3D navigation and object manipulation, like hiding or multi-selecting organs [20]. However, it is primarily a single-user mobile tool that cannot display cross-sectional views or import medical scans such as CT or MRI data. The Anatomy 3D Atlas is subscription-based and designed for individual learning on mobile devices such as smartphones and tablets, not for shared-surface collaboration.

Complete Anatomy includes a highly detailed interactive atlas featuring over 13,000 structures and 12 systems [21]. It includes advanced features such as real-time muscle motion, nerve pathway tracing, and virtual dissection tools [22]. While it is a robust educational resource available on multiple operating systems, it is optimized for individual student use. It lacks collaborative features such as content alignment and multi-user touch handling on shared displays. When it comes to pricing, Complete Anatomy operates on a subscription model with tiered student, professional and institutional pricing [21].

Unlike educational tools, Surgery Planner was developed as a research prototype for clinical routine, specifically for planning orthopedic surgery [17]. It provides users with a comprehensive understanding of the surgical site, allowing them to draw and manipulate incision areas and explore various surgical options. While it proves the value of domain-specific gestures, it is a specialized planning tool rather than a general-purpose educational platform.

Table I highlights the specific research gaps identified among these tools. These differences mean that a direct feature comparison does not capture the full picture - features exclusive to a high-cost proprietary system may reflect its pricing tier rather than a technical advantage. Therefore this comparison intends to identify functional requirements for collaborative tabletop anatomy learning that are unmet by any single existing tool, rather than to suggest that any individual tool is deficient within its own intended context.

The unmet functional requirements identified in this literature review informed the architecture of Anatomia. Most current applications rely on generic gestures and static content that do not account for the physical position of multiple users. There is a notable lack of a reusable, open-source framework that combines domain-specific gestures with content-alignment mechanisms. Anatomia fills this gap by providing a toolkit that addresses these collaborative needs while remaining accessible on commodity touchscreen hardware.

### III. METHODOLOGY

This study followed a participatory design approach with summative task-based evaluation at the end of development. During the design phase, medical students and anatomy subject-matter experts iterated with the research team, and the application was shaped at each round to better meet learners' needs in dissection lessons. Four research questions guided the work:

- What are the suitable extended-hand gestures to interact with an anatomy visualization application?
- What are the suitable methods to address the orientation issues of the displayed content in order to enhance the user experience?
- What kind of mechanism is needed to handle the conflicts that occur when multiple users interact with the application simultaneously?
- How can a solution be provided as a framework that addresses the above-mentioned problems?

The methodology proceeded in four sequential phases: 1) problem identification and requirement gathering via the literature review and observational study of the target users; 2) solution design informed by domain expert input and a questionnaire distributed to medical students; 3) artifact development of a 3D anatomy visualization and interaction mechanism for large tabletop display systems; and 4) evaluation of the final product with medical and non-medical participants.

#### A. Domain Survey and Requirements

1) *Observational user study*: An observational study was conducted at the Faculty of Medicine, University of Wayamba, Sri Lanka, involving 75 students, 4 anatomy instructors, and 1 lecturer. At the time of the study, the faculty had only four cadavers for 150 students — approximately 1 cadaver per 38 students. Several observations were made during the study:

Most students could not clearly follow the dissection demonstrations. Only the two or three most confident students had the opportunity to perform the incision on the cadaver, leaving the rest of the group with little chance to observe the dissection. Even a small incision mistake on one cadaver could have a severe effect on all of the students allocated to that body. The same cadaver was used throughout the first academic year and was kept in glycerin rather than in freezers between classes. Smaller structures such as blood vessels, lymphatic vessels, and inner-ear organs were difficult to observe, and a few cadavers had fat layers or diseases that made certain organs hard to examine. Apart from a projector used to view some lessons with a camera, no infrastructure was available to assist in the lessons. Students reported consulting the Anatomy 3D Atlas on their personal mobile phones or laptops during dissection.

These observations established the gap that Anatomia was designed to fill: a tabletop visualization tool that supports co-located, multi-user study around a shared display without requiring additional cadaveric infrastructure.

TABLE I. COMPARISON MATRIX OF 3D ANATOMY APPLICATIONS

| Feature                  | Anatamage                                    | Anatomy 3D Atlas   | Complete Anatomy                    | Surgery Planner    | Anatomia                                       |
|--------------------------|----------------------------------------------|--------------------|-------------------------------------|--------------------|------------------------------------------------|
| Virtual dissection       | Available                                    | Available          | Available                           | Not available      | Available                                      |
| Domain-specific gestures | Not available                                | Not available      | Not available                       | Available          | Available                                      |
| X-ray & CT image viewing | Available                                    | Not available      | Available                           | Available          | Available                                      |
| Multiple 3D models       | Available                                    | Available          | Available                           | Not available      | Not available                                  |
| Details on parts         | Available                                    | Available          | Available                           | Not available      | Available                                      |
| Multi-user interaction   | Not available                                | Not available      | Not available                       | Available          | Available                                      |
| Orientation change       | Not available                                | Not available      | Not available                       | Available          | Available                                      |
| Cross-platform           | Not available                                | Available          | Available                           | Not available      | Available                                      |
| Hardware platform        | Proprietary tabletop display                 | Mobile devices     | Personal computers & mobile devices | Multi-touch table  | Commodity multi-touch display & mobile devices |
| Cost model               | High (proprietary hardware –software bundle) | Subscription-based | Subscription-based                  | Research prototype | Open-source software; commodity hardware only  |

2) *Gesture elicitation and requirements survey*: A questionnaire was administered to 20 students from the Faculty of Medicine, University of Wayamba, and 3 medical science students from the Faculty of Medicine, University of Colombo. The questionnaire captured the suitable gestures for specific interactions, desired functional requirements, and features to avoid based on prior experience with existing solutions. Video clips and images were incorporated into the questionnaire to communicate the hand gestures under discussion.

For gesture identification, participants were asked to select the most suitable gestures for each of the following operations:

- Rotate the organ in the X, Y, and Z axes
- Drag the organ in the XY plane
- Zoom the 3D model in and out
- Select an organ or menu item
- Select multiple organs of the model
- Restore/rearrange the 3D model to its default orientation
- View the organ cross-section

Participants chose the appropriate gesture from nine options, including an "Other" option that invited them to propose novel gestures, which the implementation team reviewed before adding them to the system vocabulary.

3) *Domain expert input*: According to the anatomy subject-matter expert consulted, anatomy lessons are generally conducted under separate sections of the human body, such as the head, neck, torso, upper extremities, and lower extremities, rather than by physiological system. To align with this pedagogical approach, the initial implementation of the application will focus on the human body by section rather than on systems as a whole, such as the digestive or skeletal systems.

4) *Functional and non-functional requirements*: Three main use cases were identified for the application: 1) select and view a 3D anatomical model, 2) view CT and X-ray images, and 3) interact with the 3D model through gestures. These use cases encompass sub-functionalities, including rotating and zooming the model, dragging it across the screen, viewing cross-sections, isolating and hiding organs, viewing organ details, and drawing annotations on the screen.

The application was designed to meet three key non-functional requirements: To ensure usability, it is tailored to a tabletop touch display. UI standards follow industry conventions, gestures map to real-world actions to aid memorization, with self-explanatory icons to facilitate faster learning. For accuracy, a conflict-resolution component was integrated to address conflicts arising from simultaneous multi-user interactions, and the application was designed to recognize and differentiate among hand gestures involving the same number of fingers. For performance, resource-efficient methods were adopted to implement resource-intensive functionalities, particularly when a 3D model is split into two parts.

## B. System Architecture

Anatomia was built on a layered architecture that isolates hardware, operating system, rendering, and application logic as illustrated in Fig. 1.

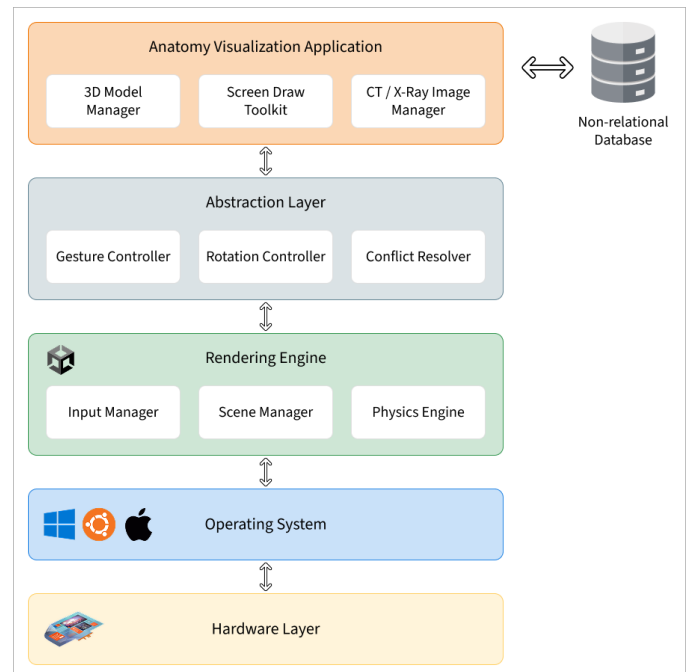


Fig. 1. System architecture diagram.

The hardware layer consists of the Displax Skin Ultra multi-touch display system, which can detect up to 100 simultaneous touch points and recognize objects. The operating system layer supports deployment on Windows, Ubuntu, and macOS. The rendering layer is powered by the Unity engine, which provides the input manager, scene manager, and physics engine. The abstraction layer contains reusable components that are loosely coupled to the anatomy visualization application: the gesture controller handles rotations, scaling, dragging, and cutting of 3D models; the rotation controller manages the rotation of UI elements to different orientations; and the conflict resolver addresses issues arising from simultaneous multi-user interaction. The application layer consists of three components: the 3D model manager, which displays user-selected 3D models and isolates relevant organs; the screen draw toolkit, which enables users to draw on the screen using single-handed gestures; and the CT/X-ray image manager, which facilitates the importing and viewing of CT and X-ray images. Organ information is stored in a MongoDB non-relational database.

### C. Implementation

Anatomia was developed using Unity 2021.3 as the development environment, chosen for its rich asset store and built-in canvas system for UI development. Blender 3.1 was used to modify the 3D models due to its comprehensive feature set and free availability. The absence of fixed relationships or a specific set of attributes for organs made a non-relational database more suitable. Therefore, MongoDB 6.0 was selected as the database for storing information about human body systems and organs. The development language was C#, and version control was managed through GitHub. The application is compatible with Windows 7 and later, macOS, and Linux operating systems.

1) *Gesture vocabulary*: The survey outcomes and domain-expert input together produced a finalized gesture vocabulary. The survey outcomes and domain-expert input together produced a finalised gesture vocabulary. The design process applied three selection principles: 1) where a clear participant majority aligned with established touchscreen conventions, that gesture was adopted directly; 2) where participants selected the same gesture for multiple operations, an alternative gesture was designed in consultation with participants and domain experts to resolve the conflict; and 3) where participants favoured the "Other" option over the predefined gestures, the most intuitive gesture from the participant-proposed suggestions was selected in consultation with domain experts.

Applying the first principle, rotation along the X, Y, and Z axes was assigned to single-finger drag, which carried the highest preference share in each case (Fig. 2a, Fig. 2b, Fig. 2c) and matches the conventional touchscreen drag-to-rotate mapping. For dragging the 3D model across the XY plane, the five-finger drag captured the majority of preferences at 39.1% (Fig. 2d). Zoom was assigned to two-finger pinch, chosen by 43.5% of participants (Fig. 2e), consistent with the established pinch-to-zoom convention. As shown in Fig. 2f, restoring the 3d model to the default anterior view was assigned to a single-finger double tap, which held the majority preference at 34.8%. These gestures required no adaptation beyond implementing the conventional mapping.

Single-finger tap was assigned to single organ or menu item selection, preferred by 82.6% of participants (Fig. 2g). The same gesture also received greater preference for selecting multiple organs (Fig. 2h). To resolve this conflict, the second principle was applied, and a two-stage gesture was designed: placing a single finger on an organ activates multi-select mode, after which subsequent single-finger taps add organs to the selection.

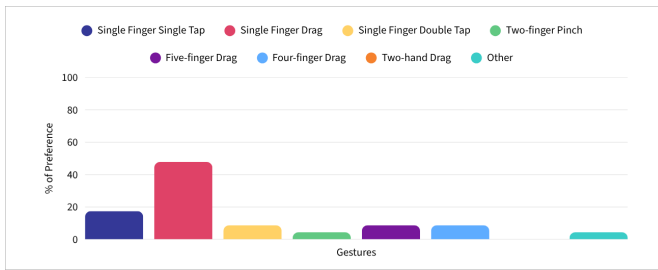
For viewing the cross-section of the model, the largest share of participants selected the "Other" option (Fig. 2i), indicating that none of the standard gestures presented in the questionnaire felt appropriate for this anatomically specific action. Participants who selected "Other" were invited to propose alternative gestures. Among the proposed suggestions, domain experts were consulted to identify the most intuitive option. The selected gesture involved the user placing all five fingers steadily on the screen while dragging a single finger across the 3D model in the area where the cross-section is to be observed. This gesture was deemed appropriate based on the input provided by the domain experts, as it mirrors the physical action of holding a specimen steady with one hand while cutting with the other, a mapping considered intuitive for students with dissection experience.

The gesture vocabulary described above represents the final iteration of the design, which was refined through formative evaluation during development. In an initial round of user testing, participants expressed difficulty remembering the specific gestures required for certain actions. They also suggested that a visual guide or tutorial on the gesture mappings could be helpful, particularly for users who are new to the system or who may not be familiar with the gestures used in the application. In response to this feedback, the gesture mappings were revised to ensure clearer differentiation between gestures sharing the same initial hand posture. A visual guide displaying the gesture vocabulary was also integrated into the application interface, providing a reference that users could consult during interaction.

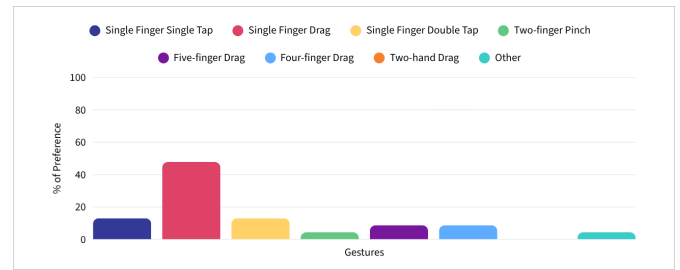
The gesture controller was implemented to handle all hand gestures for the application. It comprises a primary script that orchestrates gesture recognition, a touch controller that manages single and double taps, helper scripts for auxiliary functions, and customizable scripts for each gesture that facilitate 3D object and UI manipulation. These customizable scripts can be added to any 3D object and configured with corresponding parameters to execute a specific gesture, enabling the definition of additional gestures.

2) *Content alignment mechanism*: A radial menu at one corner of the screen indicates the user's position relative to the display. The mechanism provides auto-rotation from the menu position and a manual override that locks the orientation. Boundary parameters for auto-rotation can be reconfigured in the Unity editor without manual code changes. The threshold was set at 60°, following Koriati & Norman's finding that reading rates stay stable up to that angle [16].

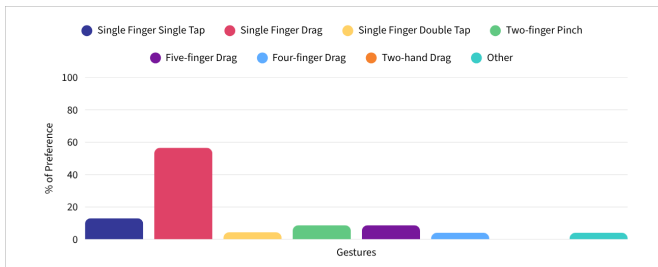
To ensure optimal content orientation, it is necessary to determine the user's position relative to the display. The proposed content alignment mechanism comprises two primary features. The first is automatic content rotation based on the user's position, achieved by leveraging the application's radial



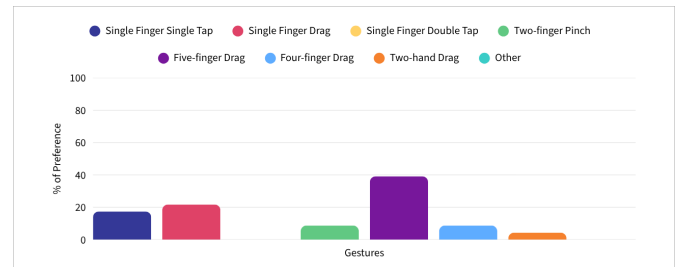
(a) Gesture preference for rotating an organ around the X-axis.



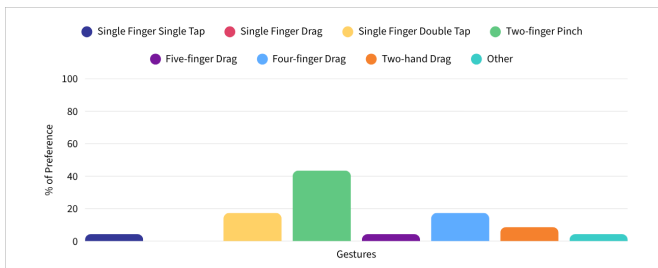
(b) Gesture preference for rotating an organ around the Y-axis.



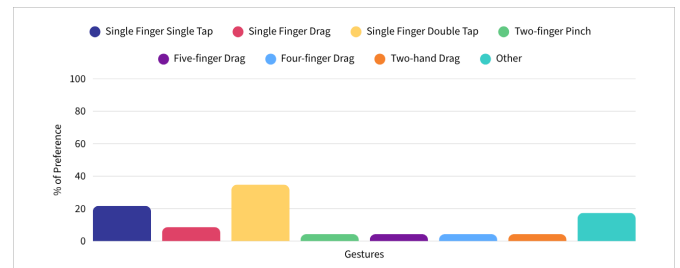
(c) Gesture preference for rotating an organ around the Z-axis.



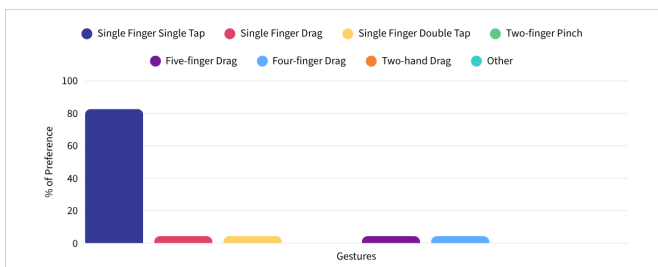
(d) Gesture preference for dragging an organ in the XY plane.



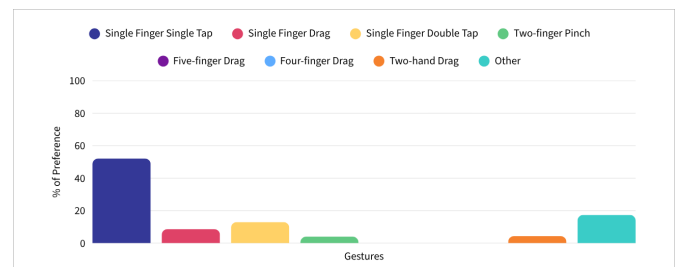
(e) Gesture preference for zooming the 3D model in/out.



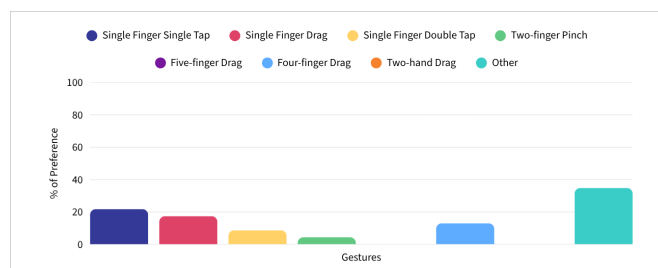
(f) Gesture preference for restoring the 3D model.



(g) Gesture preference for selecting an organ/menu item.



(h) Gesture preference for selecting multiple organs of the model.



(i) Gesture preference for viewing organ cross-section.

Fig. 2. Gesture preferences for 3D model interactions.

menu. The approach assumes that the user positions the radial menu on their side of the screen; the content on the display is then oriented accordingly. The radial menu can be moved across the screen, and all UI elements rotate accordingly. The auto-rotation boundary parameters can be easily modified in the Unity editor without requiring manual code changes. The second feature allows users to manually rotate the UI components in the X and Y planes and lock them in place to prevent auto-rotation, providing flexibility for specific viewing preferences.

3) *Multi-user conflict resolution*: Identifying users' touches distinctly on a multi-touch surface has traditionally required specialized hardware infrastructure, such as DiamondTouch's antenna-embedded chairs [17] or camera-based hand-tracking systems [14]. The focus of this project was to address multi-user interaction issues by resolving conflicts of the hand gestures of two simultaneous users at the application level, without requiring any additional hardware.

A conflict-resolution component was introduced that operates alongside an accessibility button. The conflict resolver operates as follows for two simultaneous users: 1) the screen is divided into two equal parts; 2) once a user touches the screen, the conflict resolver checks the number of touches on that particular side of the screen; 3) based on the number of touches and the behavior of those touches, the corresponding gesture is performed; and 4) if both users attempt to manipulate the 3D model at the same time, priority is given to the action performed by the user who has the radial menu or accessibility button on their side. This method is entirely implemented at the software level, with no additional hardware components required. UI dragging, 3D model rotation, and 3D model zoom-in/out actions were implemented and tested using this conflict-resolution mechanism. Other gestures can also be extended by following the same approach to provide a multi-user experience.

4) *Object dissection*: The 3D anatomy model used in the application was a combination of mesh models, and two approaches for implementing virtual dissection were investigated: mesh cutting and clipping.

The mesh cutting technique is performed with a cut gesture, in which one hand holds the model while the other draws a line. A line renderer responds to finger movement. The algorithm for separating the 3D model proceeds as follows: two empty game objects are created to represent the two sides of a given cutting plane. For each mesh model, the algorithm checks whether it intersects with the cutting plane. If it does not intersect, the model is added as a child game object to the corresponding side. If it does intersect, two dynamic mesh models are constructed (one for each side of the plane), and the position of each polygon relative to the cutting plane is computed to assign it to the appropriate side.

The clipping method, by contrast, does not divide the 3D mesh model into two separate parts. Instead, it uses a clipping plane, a custom shader, and materials created with that shader to hide or make transparent a portion of the 3D mesh. A line is drawn using the line renderer in response to finger movement; the clipping plane changes its position to the line location and orients itself to the same angle; and the user selects the part that must be removed or hidden,

which becomes transparent (Fig. 3). Because clipping requires fewer computational resources compared to mesh cutting, it was chosen as the feasible approach for the application.

5) *X-Ray/CT image viewer*: Anatomia enables users to access and interact with up to two X-ray or CT images simultaneously. Users can manipulate the images through three gestures: two-finger rotation, which allows the user to hold one finger in a fixed position on the image while moving another finger to rotate the image in any direction; two-finger zoom, which enables the user to zoom in or out by moving two fingers in opposite directions; and five-finger drag, which allows dragging the images across the screen in any direction.

6) *Other 3D object manipulation features*: Several additional features were implemented to enhance the learning experience of Anatomia.

The drawing tool lets users draw on the screen with a one-finger gesture to annotate or mark specific areas in images or 3D models. A line can be drawn by dragging one finger across the screen, and users can select from a predefined set of colors to draw around the 3D model, X-ray, and CT images.

The organ detail viewer allows users to select an organ and view a pop-up with basic information about it (Fig. 4). The hide and isolate functionality allows users to select one or more organs with a single tap or a long-tap gesture, then either isolate the selected organs (viewing only those) or hide specific organs from view. This functionality employs four stacks to manage the display state: an undo stack that stores all removed organs at each step, a redo stack that stores organs added during each undo step, an undo sequence stack that tracks the number of organs removed at each action, and a redo sequence stack that tracks the number of organs restored at each action.

The layer-wise view feature provides navigation through the multiple layers of the 3D model, with each organ placed precisely under a single layer. The Layers UI allows users to hide or restore previously hidden layers using the "Add" and "Hide" (5) options, and the "Select" option enables or disables the desired layers. The application maintains a list of layers, with two Boolean variables for each: one indicating whether the layer is entirely hidden when the "Select" option is used, and another indicating whether the layer is temporarily hidden when the "Add" or "Hide" option is used (Fig. 5).

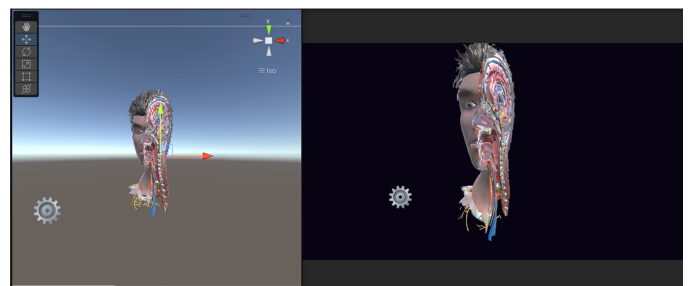


Fig. 3. Object dissection via clipping.

#### D. Evaluation

The application underwent both formative and summative evaluation. Formative evaluation was conducted iteratively throughout the development cycle to refine the interface based on user feedback. Summative evaluation assessed the user experience of the developed 3D anatomy visualization application. Two complementary analyses were carried out: a performance metrics analysis of task success and a self-reported metrics analysis comparing Anatomia with the Anatomy 3D Atlas and traditional cadaver dissection.

For the performance metrics analysis, two groups of participants were recruited: 1) 8 students from the UOC Faculty of Medicine and the Faculty of Indigenous Medicine who had prior experience with traditional cadaveric dissection, used to evaluate the application's fit for experienced anatomy learners; and 2) 5 students from non-medical backgrounds, used to evaluate usability, learnability, and collaboration support for novice users. Performance was measured using a task-success metric: the proportion of tasks each participant completed successfully out of 15 administered tasks covering hand gestures, content alignment, and multi-user interaction capabilities (6). The task list is shown in Table II; their IDs are referenced throughout the remainder of the study.

This analysis was conducted in two phases to record task performance both with and without assistance. Phase 1 established the unassisted baseline for each participant, and Phase 2 established performance after brief verbal guidance. In Phase 1, each participant performed every task in Table II in sequence, without assistance from the evaluator. A think-aloud protocol was used throughout this phase to record expectations, misconceptions, and gesture-association patterns alongside task-success scores. In Phase 2, the evaluator gave brief oral instructions to any participant who had failed a task in Phase 1, and the participant then repeated the task. This phase established the level each participant could reach with minimal verbal guidance rather than independent exploration. By comparing Phase 1 and Phase 2 performance for each task, the evaluation distinguishes initial learnability from overall usability. Task success was scored on a five-level scheme as follows, with one score recorded per participant per task:

- **Score 1.0:** Participant completed the task on the first attempt without any assistance.

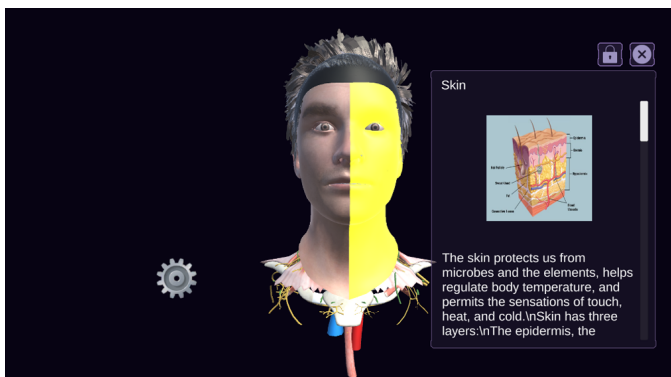


Fig. 4. View organ details.

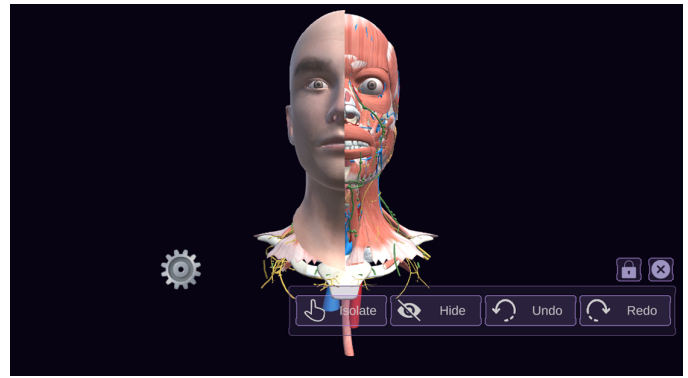


Fig. 5. View after hiding an organ/layer.

- **Score 0.75:** Participant failed the first attempt but succeeded on the second with minor verbal guidance.
- **Score 0.5:** Participant failed the first two attempts but succeeded after observing a group member perform the task.
- **Score 0.25:** Participant failed several attempts and eventually succeeded after observing a group member perform the task.
- **Score 0:** Participant failed to complete the task after more than three attempts.

Descriptive statistics were used to analyze the performance metrics ratings, including mean task-success scores across participants and the frequency distribution of each score level per task [23]. Given the ordinal nature of the task-success scores and the small sample sizes, non-parametric tests were used for all inferential analyses (Fig. 6). Between-group comparisons (medical vs. non-medical) were conducted using the Mann-Whitney U test [24], with Cliff's delta ( $\delta$ ) as the effect-size measure [25]. Cliff's delta quantifies the degree to which scores in one group tend to exceed scores in the other, ranging from  $-1$  to  $+1$ ; absolute values below  $0.147$  are interpreted as negligible, between  $0.147$ – $0.33$  as small, between  $0.33$ – $0.474$  as medium, and at or above  $0.474$  as large [26]. Within-group comparisons of familiar versus novel gestures were analysed using the Wilcoxon signed-rank test, with effect size  $r$  computed as the standardised test statistic divided by the square root of the number of pairs. All tests were two-tailed at  $\alpha = 0.05$ .

The Self-reported metrics analysis was carried out to identify users' perception of the application and their interactions [27]. This included a post-session questionnaire with 5-point Likert-scale statements (strongly disagree, disagree, neutral, agree, strongly agree) and one open-ended prompt for free-text suggestions. This questionnaire was designed specifically for this evaluation to capture comparative judgments between Anatomia, the Anatomy 3D Atlas, and traditional cadaver dissection. The questions were informed by the usability dimensions identified during the participatory design phase but should be interpreted as exploratory indicators of user perception rather than psychometrically validated measures. Each participant was allowed to interact with both applications. Then they were provided with a questionnaire that tested

TABLE II. TASKS EVALUATED IN THE PERFORMANCE METRIC ANALYSIS

| Task ID | Task                                                                         | Scenario          |
|---------|------------------------------------------------------------------------------|-------------------|
| T1      | Inspect an organ: zoom in or out of a particular organ                       | Hand gestures     |
| T2      | Rotate an organ around the X, Y, and Z axes                                  | Hand gestures     |
| T3      | Select a single organ to view its details                                    | Hand gestures     |
| T4      | Select multiple organs to isolate or hide them as a group                    | Hand gestures     |
| T5      | Restore the 3D model to its default anterior view after rotation             | Hand gestures     |
| T6      | Drag the 3D model across the XY plane                                        | Hand gestures     |
| T7      | Rotate a UI element (pop-up) manually                                        | Hand gestures     |
| T8      | Drag a UI element across the screen                                          | Hand gestures     |
| T9      | Upload an X-ray image to the X-ray viewer and perform zoom, drag, and rotate | Hand gestures     |
| T10     | Dissect the 3D model and view a cross-section                                | Hand gestures     |
| T11     | Rotate all visible UI elements to the opposite direction                     | Content alignment |
| T12     | Disable auto-rotation of a particular UI element                             | Content alignment |
| T13     | Perform two zoom actions simultaneously from opposite sides of the screen    | Multi-user        |
| T14     | Perform zoom on the 3D model and rotate the model simultaneously             | Multi-user        |
| T15     | Perform zoom on the 3D model and drag a UI element simultaneously            | Multi-user        |

whether the Anatomy application adds pedagogical value and whether it is more usable than alternative tools, such as the Anatomy 3D Atlas application and cadaver dissection. The phenomenon in which participants tend to provide responses that they believe will be perceived favorably by others is commonly known as social desirability bias [28]. To mitigate this bias, the questionnaire was anonymous, and all 13 participants completed it without being observed.

Before the summative evaluation, the Anatomy application was tested at four levels: unit testing of gesture functions using Unity Remote 5; integrated testing across the mobile device and the tabletop display system; system testing through preliminary user studies; and performance testing to ensure resource efficiency under concurrent multi-user interaction.

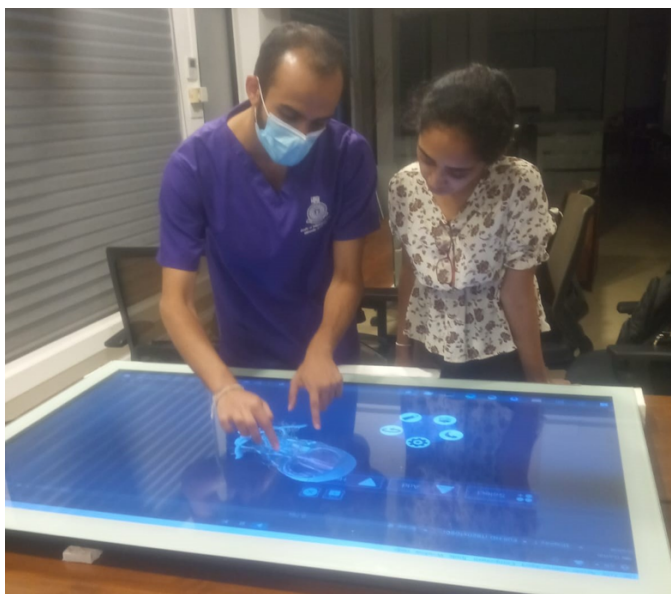


Fig. 6. Medical science students performing tasks in the summative evaluation.

## IV. RESULTS

### A. Performance Metrics Analysis Results

Medical students (Tables III and V): The 8 medical students achieved an overall median task-success score of 0.90 ( $M = 0.89$ ,  $SD = 0.04$ ) across all 15 tasks. Tasks drawing on conventional touchscreen gestures such as single-tap selection (T3,  $Mdn = 1.00$ ), single-finger drag for rotation (T2,  $Mdn = 1.00$ ), and two-finger pinch to zoom (T1,  $Mdn = 1.00$ ) received near-perfect scores, as did T8 and T9, which involve familiar gestures applied to UI elements and image upload. A Wilcoxon signed-rank test confirmed that familiar touchscreen gestures ( $Mdn = 1.00$ ) yielded significantly higher scores than the novel domain-specific gestures ( $Mdn = 0.75$ ) within this group ( $W = 0$ ,  $p = .008$ ,  $r = 0.89$ , large effect). The distribution of score levels across the medical-student group is shown in Fig. 7.

The lower scores corresponded to the anatomically novel gestures: five-finger drag for model translation (T6,  $Mdn = 0.75$ ), single-finger double tap for default-view restoration (T5,  $Mdn = 0.75$ ), and the five-finger steady with one-finger drag for cross-section viewing (T10,  $Mdn = 0.63$ ). For T5 and T6, most participants failed on the first attempt but succeeded on the second after minimal verbal guidance. The implications of this pattern for learnability versus mental-model alignment are examined in Section V. Content-alignment tasks (T11,  $Mdn = 0.75$ ; T12,  $Mdn = 1.00$ ) and multi-user interaction tasks (T13–T15, all  $Mdn = 1.00$ ) recorded scores at or near ceiling for the medical-student group, with zero variance across participants on the multi-user tasks, indicating that the auto-rotation mechanism and the conflict resolver added no measurable usability overhead.

Non-medical students (Table IV and V): The 5 non-medical students recorded an overall median task-success score of 0.83 ( $M = 0.82$ ,  $SD = 0.04$ ), lower than the medical group. A Mann–Whitney U test on participant-level averages confirmed that this overall group difference was statistically significant ( $U = 37.0$ ,  $p = .015$ , Cliff's  $\delta = 0.85$ , large effect), consistent with a carryover advantage from prior specimen-handling experience among medical students.

A detailed breakdown of participant-level scores is shown in Fig. 8. The largest differences from the medical group

TABLE III. TASK SUCCESS METRICS OF MEDICAL STUDENTS

|      | T1   | T2  | T3  | T4   | T5   | T6   | T7   | T8  | T9  | T10  | T11  | T12 | T13 | T14 | T15 | Mean |
|------|------|-----|-----|------|------|------|------|-----|-----|------|------|-----|-----|-----|-----|------|
| P1   | 1.0  | 1.0 | 1.0 | 0.75 | 0.75 | 0.75 | 0.75 | 1.0 | 1.0 | 0.5  | 0.75 | 1.0 | 1.0 | 1.0 | 1.0 | 0.88 |
| P2   | 1.0  | 1.0 | 1.0 | 0.75 | 0.75 | 1.0  | 0.75 | 1.0 | 1.0 | 0.5  | 0.75 | 1.0 | 1.0 | 1.0 | 1.0 | 0.9  |
| P3   | 1.0  | 1.0 | 1.0 | 0.75 | 1.0  | 1.0  | 0.75 | 1.0 | 1.0 | 0.75 | 0.75 | 1.0 | 1.0 | 1.0 | 1.0 | 0.93 |
| P4   | 0.75 | 1.0 | 1.0 | 0.5  | 0.75 | 0.5  | 0.5  | 1.0 | 1.0 | 0.5  | 0.75 | 1.0 | 1.0 | 1.0 | 1.0 | 0.82 |
| P5   | 1.0  | 1.0 | 1.0 | 0.75 | 0.75 | 0.75 | 0.75 | 1.0 | 1.0 | 0.75 | 0.75 | 1.0 | 1.0 | 1.0 | 1.0 | 0.9  |
| P6   | 1.0  | 1.0 | 1.0 | 1.0  | 0.75 | 0.75 | 0.75 | 1.0 | 1.0 | 0.75 | 0.75 | 1.0 | 1.0 | 1.0 | 1.0 | 0.92 |
| P7   | 1.0  | 1.0 | 1.0 | 0.75 | 0.75 | 0.75 | 0.75 | 1.0 | 1.0 | 0.5  | 0.75 | 1.0 | 1.0 | 1.0 | 1.0 | 0.88 |
| P8   | 1.0  | 1.0 | 1.0 | 1.0  | 0.75 | 0.75 | 0.75 | 1.0 | 1.0 | 0.75 | 0.75 | 1.0 | 1.0 | 1.0 | 1.0 | 0.92 |
| Mean | 0.97 | 1.0 | 1.0 | 0.78 | 0.78 | 0.78 | 0.78 | 1.0 | 1.0 | 0.63 | 0.75 | 1.0 | 1.0 | 1.0 | 1.0 | 0.89 |

TABLE IV. TASK SUCCESS METRICS OF NON-MEDICAL STUDENTS

|      | T1   | T2   | T3   | T4   | T5   | T6   | T7   | T8   | T9   | T10 | T11  | T12 | T13 | T14 | T15 | Mean |
|------|------|------|------|------|------|------|------|------|------|-----|------|-----|-----|-----|-----|------|
| P1   | 1.0  | 1.0  | 1.0  | 0.75 | 0.75 | 0.75 | 0.75 | 1.0  | 0.75 | 0.5 | 0.75 | 1.0 | 1.0 | 1.0 | 1.0 | 0.87 |
| P2   | 0.75 | 1.0  | 0.75 | 0.5  | 0.75 | 0.5  | 0.5  | 0.75 | 0.75 | 0.5 | 0.75 | 1.0 | 1.0 | 1.0 | 1.0 | 0.77 |
| P3   | 1.0  | 0.75 | 1.0  | 0.75 | 0.75 | 0.75 | 0.5  | 1.0  | 0.75 | 0.5 | 0.75 | 1.0 | 1.0 | 1.0 | 1.0 | 0.83 |
| P4   | 0.75 | 0.75 | 0.75 | 0.5  | 0.75 | 0.75 | 0.75 | 1.0  | 0.75 | 0.5 | 0.75 | 1.0 | 1.0 | 1.0 | 1.0 | 0.8  |
| P5   | 1.0  | 1.0  | 1.0  | 0.5  | 0.75 | 0.75 | 0.75 | 1.0  | 0.75 | 0.5 | 0.75 | 1.0 | 1.0 | 1.0 | 1.0 | 0.85 |
| Mean | 0.9  | 0.9  | 0.9  | 0.6  | 0.75 | 0.7  | 0.65 | 0.95 | 0.75 | 0.5 | 0.75 | 1.0 | 1.0 | 1.0 | 1.0 | 0.82 |

TABLE V. MANN-WHITNEY U TEST RESULTS: MEDICAL VS. NON-MEDICAL STUDENTS

| Task ID | Scenario               | Med Mdn | Non-Med Mdn | U    | p       | Cliff's $\delta$ | Effect      |
|---------|------------------------|---------|-------------|------|---------|------------------|-------------|
| T1      | Familiar hand gesture  | 1.00    | 1.00        | 25.5 | 0.317   | 0.275            | Small       |
| T2      | Familiar hand gesture  | 1.00    | 1.00        | 28.0 | 0.080   | 0.400            | Medium      |
| T3      | Familiar hand gesture  | 1.00    | 1.00        | 28.0 | 0.080   | 0.400            | Medium      |
| T4      | Novel hand gesture     | 0.75    | 0.50        | 31.5 | 0.075   | 0.575            | Large       |
| T5      | Novel hand gesture     | 0.75    | 0.75        | 22.5 | 0.527   | 0.125            | Negligible  |
| T6      | Novel hand gestures    | 0.75    | 0.75        | 25.5 | 0.369   | 0.275            | Small       |
| T7      | Novel hand gesture     | 0.75    | 0.75        | 25.5 | 0.317   | 0.275            | Small       |
| T8      | Familiar hand gesture  | 1.00    | 1.00        | 24.0 | 0.268   | 0.200            | Small       |
| T9      | Familiar hand gesture  | 1.00    | 0.75        | 40.0 | < 0.001 | 1.000            | No variance |
| T10     | Novel hand gesture     | 0.62    | 0.50        | 30.0 | 0.083   | 0.500            | Large       |
| T11     | Content alignment      | 0.75    | 0.75        | 20.0 | 1.00    | 0.000            | No variance |
| T12     | Content alignment      | 1.00    | 1.00        | 20.0 | 1.00    | 0.000            | No variance |
| T13     | Multi-user interaction | 1.00    | 1.00        | 20.0 | 1.00    | 0.000            | No variance |
| T14     | Multi-user interaction | 1.00    | 1.00        | 20.0 | 1.00    | 0.000            | No variance |
| T15     | Multi-user interaction | 1.00    | 1.00        | 20.0 | 1.00    | 0.000            | No variance |
| Overall | All                    | 0.90    | 0.82        | 37.0 | .015    | 0.85             |             |

appeared on the anatomically demanding tasks: T4 (multi-organ select, Mdn = 0.50,  $\delta$  = 0.58) and T10 (cross-section viewing, Mdn = 0.50,  $\delta$  = 0.50), both showing large effect sizes. However, neither per-task comparison reached significance at  $\alpha$  = 0.05 (T4: U = 31.5, p = .075; T10: U = 30.0, p = .083), which is consistent with the limited statistical power of the sample rather than evidence of no group difference. T5 through T7 ranged from Mdn = 0.75 to Mdn = 0.65. With minimal verbal guidance during Phase 2, the non-medical participants completed most failed tasks on the next attempt. T10 recorded the lowest score in the non-medical group, with all five participants requiring peer observation before completing the task. The possible explanations for this pattern are discoverability, mental-model mismatch, or domain unfamiliarity. The pattern across both groups indicates that participants achieved task completion across the full gesture set within a single guided session, with the largest performance gaps concentrated on the anatomically novel gestures rather

than the interface mechanisms. Content-alignment and multi-user tasks showed identical median scores across both groups (T11: Mdn = 0.75; T12–T15: Mdn = 1.00), confirming that these mechanisms performed consistently regardless of domain background.

#### B. Self-Reported Metrics Analysis Results

The post-session questionnaire aimed to capture participants' comparative judgments of Anatomy relative to the Anatomy 3D application and traditional lessons. Fig. 9–10 present the bar-chart distributions for the six reported items, and the remaining items are summarised at the end of this subsection. All response frequencies are reported as a numerator over 13 participants ( $N=13$ ).

In the questionnaire-based comparison, participants consistently rated Anatomy favorably over both traditional dissection lessons and the Anatomy 3D Atlas. On the user-friendliness

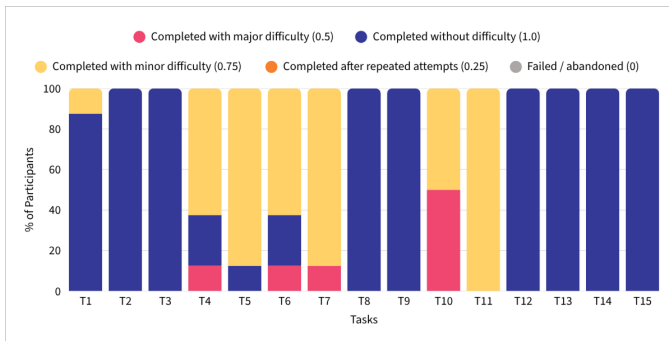


Fig. 7. Task success rates of medical students.

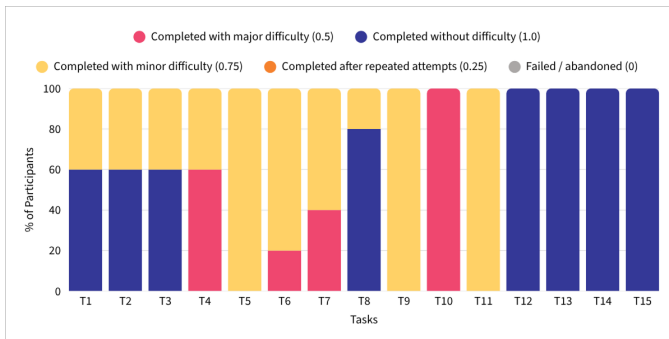


Fig. 8. Task success rates of non-medical students.

of *Anatomia* over *Anatomy 3D Atlas*, all 13 participants (8 strongly agree, 5 agree; 100.0% total agreement) endorsed *Anatomia*, as shown in Fig. 9a. On around-the-table alignment, again 13 out of 13 (6 strongly agree, 7 agree; 100.0% agreement) voted for *Anatomia* (Fig. 9b). Regarding menu design, all participants (9 strongly agree, 4 agree; 100.0% agreement) endorsed the radial menu over the *Atlas* fixed menus (Fig. 9c). *Anatomia*'s ability to allow multi-user interaction was also endorsed unanimously (8 strongly agree, 5 agree; 100.0% agreement, as shown in Fig. 9d). This complements the performance-metric findings in Section IV-A, where tasks involving multi-user interaction reached 1.00 across all 13 participants.

When comparing the *Anatomia* application to cadaver-based dissection, regarding reusability, all 13 participants (9 strongly agree, 4 agree; 100.0% agreement) endorsed *Anatomia* as superior to traditional dissection (Fig. 10a). On collaboration, 10 of 13 (5 strongly agree, 5 agree; 76.9% agreement) endorsed *Anatomia*, with 2 of 13 remaining neutral and 1 of 13 strongly disagreeing (Fig. 10b). The gap between reusability and collaboration aligns with the cadaver-access constraints recorded at the University of Wayamba during the observational study (150 medical students shared 4 cadavers across the academic year): reusability addresses a constraint that participants experience universally, whereas the collaboration axis compares *Anatomia*'s deliberate two-user protocol against the unstructured peer interaction that already happens at a single cadaver station.

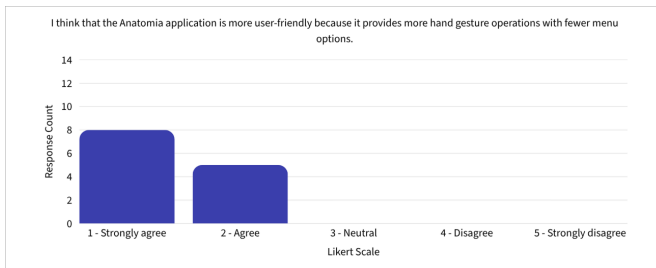
## V. DISCUSSION

The summative evaluation supports each of the three design contributions outlined in Section III: the gesture vocabulary is learnable, the content alignment mechanism scores highly on usability, and the software-level conflict resolver works in the context of two concurrent user interactions without introducing qualitative friction. The overall group difference between medical students (Mdn = 0.90) and non-medical students (Mdn = 0.82) was statistically significant ( $U = 37.0$ ,  $p = .015$ , Cliff's  $\delta = 0.85$ ), and the self-reported comparison items reached 100.0% or 76.9% agreement, providing evidence behind that conclusion.

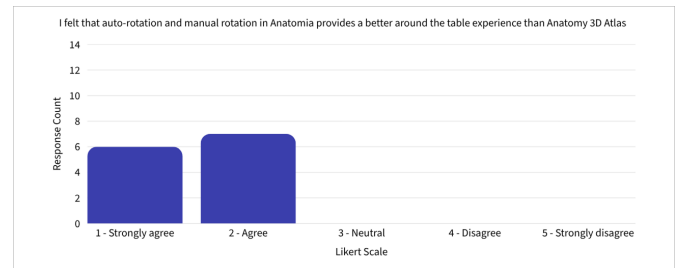
The three basic hand-gesture tasks—single-finger tap for selection, single-finger drag for rotation, and two-finger pinch for zoom—recorded first-attempt task-success averages of 0.97, 1.00, and 1.00 in the medical-student group (Table III) and equivalent values in the non-medical group (Table IV). The anatomically novel gestures recorded lower first-attempt scores: T4 (multi-organ select) averaged 0.6 in the non-medical group; T5 (default-view recall), T6 (five-finger drag), and T7 (manual UI rotation) ranged from 0.65 to 0.75; and T10 (cross-section viewing) recorded the lowest single-task score, 0.5, in the non-medical group, meaning that participants succeeded only after observing a peer perform the gesture. Because the composite scoring scale does not separate discoverability from mental-model alignment, this result is open to two interpretations: the gesture may be learnable but not independently discoverable from the interface cues alone, or participants' prior expectations of how cross-sectional viewing should work may have been incompatible with the five-finger steady plus one-finger drag design. The fact that medical students also scored below ceiling on T10 (Mdn = 0.63) suggests that discoverability is the primary barrier, though the current instrument cannot confirm this distinction. For the remaining gesture tasks, content-alignment tasks, and multi-user tasks, effect sizes were small or negligible, indicating that the group difference does not reflect a structural usability gap. Both groups converged on task completion after a single round of verbal guidance.

These findings establish that the gesture vocabulary is learnable within a single guided session, but they do not speak to long-term retention. Learnability and retention are distinct constructs: a gesture that is easy to acquire during an introduction may still be difficult to recall after a period of disuse, particularly if it lacks a strong mnemonic mapping to a familiar physical action. The novel gestures in *Anatomia*, such as the five-finger steady plus one-finger drag for cross-sectional viewing, are designed to mirror anatomical actions, which may support longer-term recall, but this remains an empirical question. A follow-up evaluation conducted after two to four weeks without practice would be necessary to determine whether the proposed interaction techniques are retained or whether periodic reinforcement is needed.

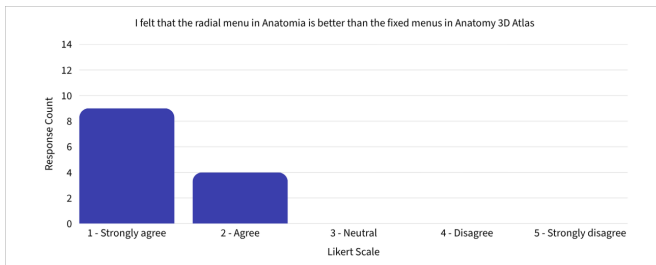
Koriat and Norman showed that reading time remains stable through rotations up to 60° and degrades substantially beyond 120° of in-plane rotation, where the visual system shifts from holistic to letter-by-letter processing [16]. Existing commercial systems reviewed in I did not address this dimension. The dual approach adopted in *Anatomia* pairs automatic rotation from the radial-menu position with manual rotation



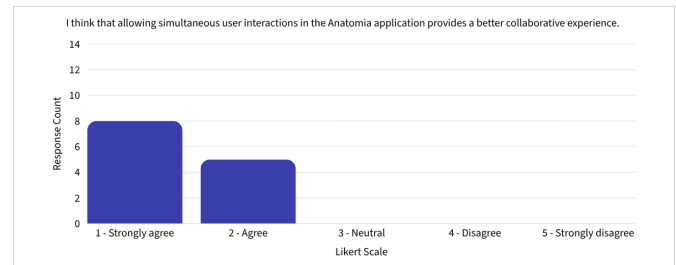
(a) Anatomy 3D Atlas vs. Anatomia application's hand gestures.



(b) Anatomy 3D Atlas vs. Anatomia in terms of content alignment.

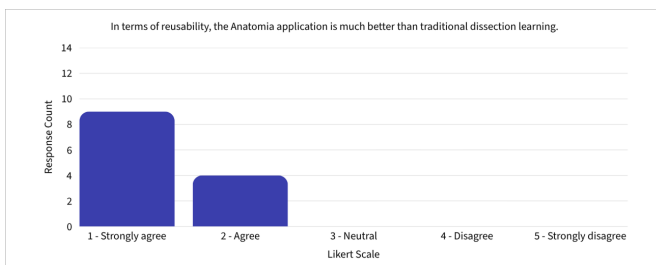


(c) Anatomy 3D Atlas vs. Anatomia in terms of fixed menu options.

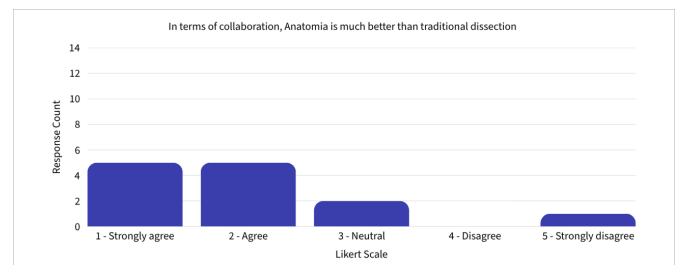


(d) Anatomy 3D Atlas vs. Anatomia in terms of multi-user interaction.

Fig. 9. Comparison of anatomia application against anatomy 3D atlas.



(a) Traditional lessons vs. Anatomia application in terms of reusability.



(b) Traditional lessons vs. Anatomia application in terms of collaboration.

Fig. 10. Comparison of anatomia application against traditional dissection lessons.

and locking. The alignment task set (T11–T12) recorded a median score of 0.88 in both groups, with zero between-group variance (Cliff's  $\delta = 0.00$ ), indicating that the mechanism adds little cognitive overhead while removing the legibility issue of fixed orientation. The identical performance across groups suggests that content alignment is intuitive irrespective of anatomical background.

The self-reported metric questionnaire reinforces this finding: both statements—"auto/manual rotation provides a better around-the-table experience than the fixed orientation of the Anatomy 3D Atlas," and "the radial menu is better than fixed menus"—received 100% agreement, with zero neutral or disagreeing responses. This is consistent with the underlying reading-time penalty: participants who have experienced the legibility drop on a fixed-orientation app perceive the rotation mechanism as an unambiguous improvement.

Prior multi-user identification mechanisms on shared surfaces require hardware [17], [14] that is not widely available in teaching classrooms. The University of Wayamba's anatomical

resources had 4 cadavers for 150 medical students during the academic year of the observational study, resulting in an approximately 38:1 student-to-cadaver ratio, which makes capital investment in specialized hardware a binding adoption constraint. The conflict resolver in Anatomia runs at the software level. Multi-user task success reached a perfect 1.00 (Mdn = 1.00, zero variance) across both participant groups, with no between-group difference (Cliff's  $\delta = 0.00$ ). The corresponding self-reported item received 13 of 13 endorsements (100.0% agreement). The convergence of ceiling-level task success and unanimous subjective endorsement across participants with different domain backgrounds provides consistent evidence that the conflict-resolution mechanism does not impose a usability penalty.

This study has several limitations. The participant sample comprised 13 individuals (8 medical, 5 non-medical) drawn from two faculties of a Sri Lankan university, which constrains the generalisability of the results to other populations, educational systems, and cultural contexts. Given these sample sizes, the non-parametric tests employed have sufficient power

to detect only large effects. The per-task Mann–Whitney U comparisons did not reach significance at  $\alpha = 0.05$ , even where effect-size estimates indicated large group differences (e.g., T4: Cliff's  $\delta = 0.58$ ; T10:  $\delta = 0.50$ ). These non-significant per-task results should be interpreted as inconclusive rather than as evidence of no difference between groups. Replication with a larger and more demographically diverse cohort would be necessary to detect small and medium effects and to establish external validity. Recent cross-cultural studies have raised the standard required for the methodology used in usability investigations of interactive educational applications. Criollo-C et al. [29] assessed a mobile augmented reality application designed to provide training on PC hardware in three countries using the IBM Computer System Usability Questionnaire (CSUQ), a well-established tool that has proven psychometric properties. Their study highlights the value of employing validated measurement instruments and of using samples that are geographically diverse when evaluating educational technology.

The summative evaluation benchmarked Anatomia against the Anatomy 3D Atlas and traditional cadaver dissection, but not against the Anatomage Table, which Table I identifies as the closest existing tabletop competitor. The Anatomage Table's acquisition cost made a controlled academic comparison impractical within the study's resource constraints. A controlled comparison against the Anatomage Table would provide a more balanced evaluation of Anatomia's contributions.

Anatomia's current implementation includes a single 3D model covering only the head region, whereas all three commercial competitors support multiple 3D models spanning the full body, a capability that Anatomia does not yet offer. This limits the evaluation's ecological validity: gesture challenges specific to larger or more complex anatomical regions are not represented in the current task set. The system architecture was designed to accommodate additional models through the 3D Model Manager component, but the feasibility of maintaining acceptable frame rates and interaction responsiveness as model complexity and polygon counts increase has not been empirically verified. Future work should assess how the framework scales to more detailed 3D models, larger anatomical datasets, and varying hardware configurations.

Finally, this study measured interaction quality, usability, and learnability, not learning outcomes. Whether the interaction-level gains documented here translate into measurable improvements in anatomical knowledge over a curriculum term remains open. A longitudinal study comparing learning outcomes between traditional dissection and Anatomia-augmented instruction would be necessary to establish the pedagogical impact of the tool.

From these limitations, there are several avenues for future research. The anatomical model library could be extended from the head area to the entire body in order to check the framework's scalability with regard to more complicated structures. The two-user limit of the conflict resolver might be increased by incorporating a third-party user-identification pipeline at the application level, which could in turn allow three or more users to use the system at the same time on larger display surfaces. A formal computational-performance benchmark covering a range of hardware configurations would define the boundaries for deployment. Longitudinal classroom

studies that compare Anatomia-augmented instruction with traditional dissection using standardised anatomy assessments would determine whether the usability and interaction benefits reported here lead to better learning outcomes. Lastly, future evaluations of Anatomia could adopt a standardised usability instrument with established reliability. The use of such instruments with a larger and more diverse group of participants, preferably in several different institutions and educational settings, would improve generalisability and enable internal-consistency reporting, cross-study comparison, and more confident interpretation of subjective responses.

## VI. CONCLUSION

This study presents Anatomia, a 3D anatomy visualization application for tabletop display systems that addresses three limitations common to current 3D anatomy visualization tools: the lack of domain-specific gestures, the lack of adaptive content orientation, and the lack of multi-user support on shared surfaces. The summative evaluation conducted with experienced and novice users confirms that all three contributions work together without trading off one for another. The domain-specific gestures defined in the participatory design achieved their highest task performance with minimal guidance within a single session. Basic touchscreen gestures (single-tap, single-finger drag, two-finger pinch) succeeded on the first attempt for both participant groups, and the novel gestures succeeded after a single round of verbal guidance, with the cross-section gesture the only task whose non-medical group required a second observation. The content-alignment mechanism, which pairs automatic rotation driven by radial-menu position with manual rotation and locking, received a median usability score of 0.88 on the alignment task set, with identical performance across medical and non-medical groups (Cliff's  $\delta = 0.00$ ) and 100.0% participant endorsement on the post-session questionnaire. Both performance and self-reported metrics indicate that the mechanism removes the reading-time penalty associated with fixed orientation on shared surfaces without introducing a perceptible usability tax. The software-level conflict resolver achieved a perfect task-success score of 100.0% in two-user interactions (Mdn = 1.00, zero variance across all 13 participants) and 100.0% participant endorsement. It is the first mechanism to support two-user multi-touch interaction without antenna-embedded furniture or external cameras in the domain of medical anatomy education, which is the principal contribution of this work in terms of classroom viability. Three concrete extensions follow from this work. The anatomical model layer can be expanded from the head region to the rest of the body. The conflict resolver's two-user limit can be lifted by integrating a third-party user-identification pipeline. Finally, a longitudinal study comparing learning outcomes between traditional dissection and Anatomia-augmented instruction would be necessary to confirm that the interaction-level gains documented here translate into measurable learning gains over a curriculum term.

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#### DECLARATION ON GENERATIVE AI

Generative AI tools were used to assist with language refinement and clarity during the preparation of this manuscript. All technical content, data collection and analysis, and conclusions were developed and verified by the authors. Generative AI was not used to generate, fabricate, or alter any experimental data, nor to produce original research claims. The authors take full responsibility for the accuracy, originality, and integrity of the work, and confirm that the manuscript reflects their own intellectual contributions throughout.

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