Computers & Graphics 85 (2019) 74–84

Contents lists available at ScienceDirect

Computers & Graphics

journal homepage: www.elsevier.com/locate/cag

Special Section on SVR 2019

Anatomy Studio: A tool for virtual dissection through augmented 3D reconstruction

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ARTICLE INFO

Article history:
Received 15 May 2019
Revised 25 September 2019
Accepted 30 September 2019
Available online 4 October 2019

Keywords:
Mixed reality
Tablet
Collaboration
Medical image segmentation
3D reconstruction

ABSTRACT

3D reconstruction from anatomical slices allows anatomists to create three dimensional depictions of real structures by tracing organs from sequences of cryosections. However, conventional user interfaces rely on single-user experiences and mouse-based input to create content for education or training purposes. In this work, we present Anatomy Studio, a collaborative Mixed Reality tool for virtual dissection that combines tablets with styli and see-through head-mounted displays to assist anatomists by easing manual tracing and exploring cryosection images. We contribute novel interaction techniques intended to promote spatial understanding and expedite manual segmentation. By using mid-air interactions and interactive surfaces, anatomists can easily access any cryosection and edit contours, while following other user's contributions. A user study including experienced anatomists and medical professionals, conducted in real working sessions, demonstrates that Anatomy Studio is appropriate and useful for 3D reconstruction. Results indicate that Anatomy Studio encourages closely-coupled collaborations and group discussion, to achieve deeper insights.

1. Introduction

The *de facto* source of teaching material for anatomical education is cadaver dissection. Classical anatomy dissection is conducted within a specialized room where anatomists produce unique anatomical *œuvres* for medical training and research. However, once dissected, the results become irreversible since the surrounding structures are damaged for underlining the target structure. Furthermore, there is a global shortage of cadavers in medical schools for training students and surgeons. To alleviate this problem, anatomists and students rely on a wide variety tools for 3D reconstruction from anatomical slices (3DRAS). These tools suit several purposes: promote novel educational methods [1–3], allow statistical analysis of anatomical variability [4], and support clinical practice to optimize decisions [5]. It should be noted that 3DRAS tools are a complementary medium to live dissection, not their replacement [6–9].

3DRAS make possible the virtual dissection resulting in accurate and interactive 3D anatomical models. Due to its digital nature, 3DRAS promotes new ways to share anatomical knowledge and, more importantly, produces accurate subject-specific models that can be used to analyze a specific structure, its functionality and relationships with neighbouring structures [9]. Yet, current 3DRAS solutions, besides being expensive, rely on flat displays and ill-suited mouse-based user interfaces tailored for single-user interaction. Indeed, when relying on conventional virtual dissection tools, experts have to browse through large sequences of cryosections (2D slices) using slice-by-slice navigation tools to reach and identify relevant details. Moreover, they are required to manually segment their geometric *locus* to reveal relationships among neighbouring organs. However, these are tedious, error-prone and cumbersome tasks that make content creation a major hurdle to successful deployment of applications of digital anatomy including, education, training, surgical planning, among others.

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https://doi.org/10.1016/j.cag.2019.09.006

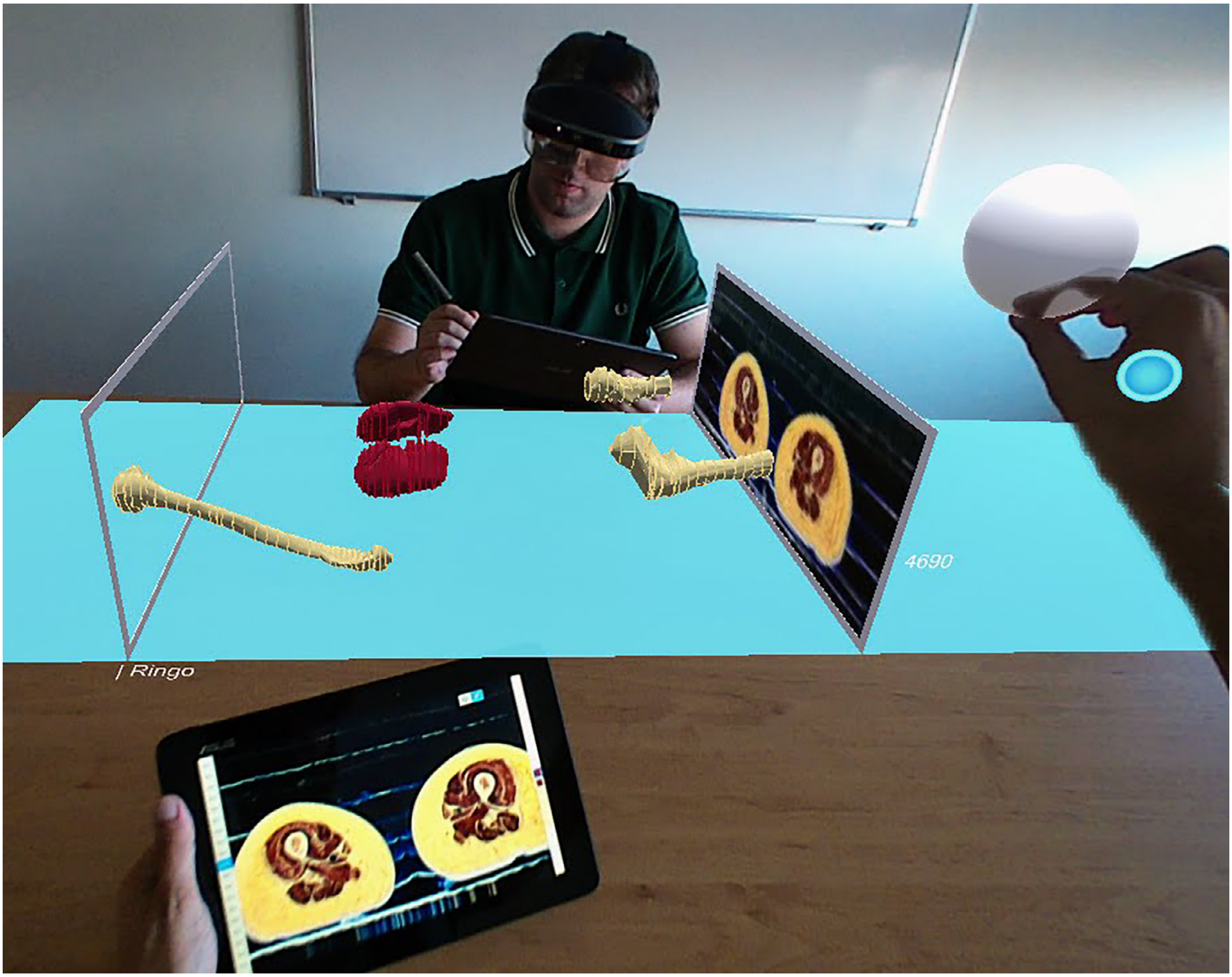

Fig. 1. Overview of Anatomy Studio, a collaborative MR dissection table approach where one or more anatomists can explore anatomical data sets and carry out manual 3D reconstructions using tablets and styli.

By default, 3DRAS tools are designed for laborious manually segmentation forcing an expert to trace contours around anatomical structures throughout many sections. Once a set of segmented curves is assembled, it is then possible to reconstruct a 3D organ. Again, we remark that current 3DRAS tools promote single-user slice navigation and manual segmentation. These tasks are often performed using single flat display and mouse-based systems, forcing multiple scrolling and pinpointing mouse clicks. Such limited deployment is the foundation for the work presented in this paper.

Clearly, this specific application domain presents a situation of limited deployment and underdeveloped usage of mature technologies, namely interactive surfaces and Mixed Reality (MR) that bring high potential benefits. Therefore, we hypothesize that group interaction conveyed through spatial input and interactive surfaces can boost 3DRAS related tasks and attenuate dissection workload. In this paper, we present Anatomy Studio, a collaborative MR dissection table approach where one or more anatomists can explore a whole anatomical data set and carry out manual 3D reconstructions. Although Anatomy Studio could easily be extended to teaching or educational purposes, this study did not address these scenarios. Fig. 1 illustrates Anatomy Studio by highlighting the spatial interaction to navigate throughout the data set, to visualize the reconstructed model, and select slices within medical imaging data, which are tasks required by anatomists.

Anatomy Studio mirrors a drafting table, where users are seated and equipped with head-mounted see-through displays, tablets and styli. Our approach adopts a familiar drawing board metaphor since tablets are used as sketch-based interfaces to trace anatomical structures, while simple hand gestures are employed for 3D navigation on top of a table, as shown in Fig. 1. By using hand gestures combined with mobile touchscreens, the anatomists can easily access any cryosection or 2D contour and follow each user's contribution towards the overall 3D reconstructed model.

Our goal was to understand the potential of Anatomy Studio for collaborative 3DRAS sessions. We derived our requirements from two workshops with experts in digital anatomy. Experts clearly stated that image tracing should be performed only manually by users with knowledge domain in anatomical morphology. Workshop participants also mentioned that conventional mouse-based input interfaces are cumbersome, labor-intensive, and not very user-friendly. Moreover, experts strongly suggested that virtual dissection interfaces should promote collaborative segmentation as 3DRAS is conventionally performed individually. Feedback from experienced anatomists was gathered during real working sessions with the think-aloud method, by conducting post-hoc surveys and through semi-structured interviews. MR emerged as an adequate response to the needs of medical practitioners. Furthermore, by contacting experienced anatomists, we identified the central requirements for 3DRAS tools: (1) easy manual segmentation, (2) sharing slice and 3D content, (3) collaboration between users to alleviate dissection workload, and (4) a low threshold for usage learning.

The main contributions of this research include: (1) a new virtual dissection tool for interactive slicing and 3D reconstruction; (2) a description of the design of a set of interaction techniques that combine MR and tablets to addresses the challenges of virtual dissection; (3) a usability study to evaluate the potential of Anatomy Studio next to experienced anatomists and medical professionals; and (4) a discussion of usability issues, domain insights and current limitations. In what follows, we discuss the most relevant related work, describe our approach and its contributions to the state of the art. We also describe the user tests and evaluation, followed by a discussion of the main results and present avenues for future research.

2. Related work

Since the advent of the Visible Human Project [6], interactive solutions have been proposed for virtual dissection, yet still the Windows, Icons, Menus and Pointer (WIMP) paradigm prevails ecumenical for image segmentation within the 3DRAS community [10–13]. More effective approaches are sorely needed as conventional WIMP interfaces are known to hamper 3D reconstruction tasks because they rely on mouse-based input and 2D displays [14,15]. Besides lacking direct spatial input and affording limited navigation control, WIMP approaches for 3DRAS also promote single-user interaction, even though several studies refer to the importance of collaborative drawing [16,17] such has not been performed for a strictly 3D reconstruction purpose.

Another serious limitation of WIMP is that they prescribe timely slice-by-slice segmentation. For instance, the Korean Visible Human took 8 years to segment using mouse input [7,18]. Clearly, there is a need to speedup the segmentation process without discarding manual operability, as anatomists feel more in control to produce meticulous and informed contours manually [19,20]. Another restriction consists of the limited 3D perception offered by WIMP interfaces, as this induces a greater cognitive load by forcing anatomists to build a 3D mental image from a set of 2D cryosections.

Other interaction paradigms have been proposed for 3DRAS, namely, Augmented Reality (AR) and Virtual Reality (VR) have been explored for medical visualization [21], since immersion can improve the effectiveness when studying medical data [22]. For instance, Ni et al. [23] developed AnatOnMe, a prototype AR projection–based handheld system for enhancing information exchange in the current practice of physical therapy. AnatOnMe combines projection, photo and video capture along with a pointing device for input, while projection can be done directly on the patient's body. Another related study proposed the introduction of AR above the Tabletop for the analysis of multidimensional data sets, as their approach facilitated collaboration, immersion with the data, and promoted fluid analyses of the data [24].

Another advantage of AR and VR paradigms is that they promote expeditious navigation of volumetric data along complex medical data sets. To this regard, Hinckley et al. [25] adopted two-handed interactions on a tangible object to navigate multiple cutting planes on a volumetric medical data set. Coffey et al. [26] proposed a VR approach for volumetric medical data sets navigation using an interactive multitouch table and a large scale stereoscopic display. Sousa et al. [27] introduced a VR visualization tool for diagnostic radiology. The authors employed a touch-sensitive surface to allow radiologists to navigate through volumetric data sets. Lopes et al. [28] explored the potential of immersion and freedom of movement afforded by VR to perform CT Colonograpy reading, allowing users to freely walk within a work space to analyze 3D colon data.

Furthermore, the combination of immersive technologies and sketch-based interfaces [29] have been proposed for 3DRAS education and training, but not for accurate 3D reconstruction [30–32]. Immersive solutions usually place anatomical representations within a 3D virtual space [32–34], similarly to plaster models used in the anatomical theater, or consider virtual representations of the dissection table [30,31] but often require dedicated and expensive hardware. Only recently have VR approaches been considered to assist the medical segmentation process [35,36] but the resulting models continue to be rough representations of subject-specific anatomy. In turn, sketch-based interfaces have been reported to complement or even finish off automatic segmentation issues that rise during anatomical modeling [5,37]. Although tracing can be guided by simple edge-seeking algorithms or adjustable intensity thresholds, these often fail to produce sufficiently accurate results [4,38].

Given the size and complexity of the data set, coordinating 3D reconstruction with navigation can be difficult as such tasks demand users to maintain 3D context, by choosing different points of view towards the 3D content, while focusing on a subset of data materialized on a 2D medium. To assist the visualization task, head-tracked stereoscopic displays have proven to be useful due to the increased spatial understanding [26,28,39]. However, prior work has been primarily conducted within navigation scenarios and not for 3D reconstruction from medical images, thus, it is not clear if there are benefits of complementing 3D displays with 2D displays [40].

Despite the many advancements in medical image segmentation, most semi- and automatic algorithms fail to deliver infallible contour tracing. That is why clinical practice in medical departments is still manual slice-by-slice segmentation, as users feel more in control and produce a more informed, meticulous 3D reconstruction [19,20]. Note that, segmentation of cryosections is a labeling problem in which a unique label that represents a tissue or organ is assigned to each pixel in an input image.

Tailored solutions for 3D reconstruction that rely on easily accessible, interactive, and ubiquitous hardware, besides guaranteeing qualified peer-reviewing, are welcomed by the Anatomy community. While using HMDs or tablets to interact with 2D and 3D data is not new, combining them for 3DRAS has not been studied. Much research focuses on VR-based navigation for surgical planning and radiodiagnosis. However, our approach addresses 3D reconstruction. Moreover, we specifically worked with anatomists and our interaction was purposely designed to combine a 2D sketch-based interface for expedite segmentation with spatial gestures for augmented visualization.

3. Anatomy Studio

Our approach, Anatomy Studio, combines sketching on a tablet with MR based visualization to perform 3D reconstruction of anatomic structures through contour drawing on 2D images of real cross-sections (i.e., cryosections). While the tablet's interactive surface offers a natural sketching experience, the 3D visualization provides an improved perception of the resulting reconstructed content over traditional desktop approaches. It is also possible to interact with Anatomy Studio using mid-air gestures in the MR visualization to browse throughout the slices. The combination of mid-air input with interactive surfaces allows us

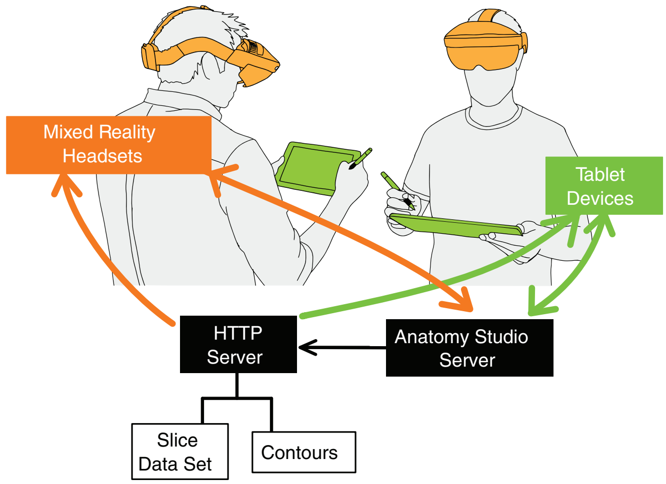

Fig. 2. Anatomy Studio's distributed architecture.

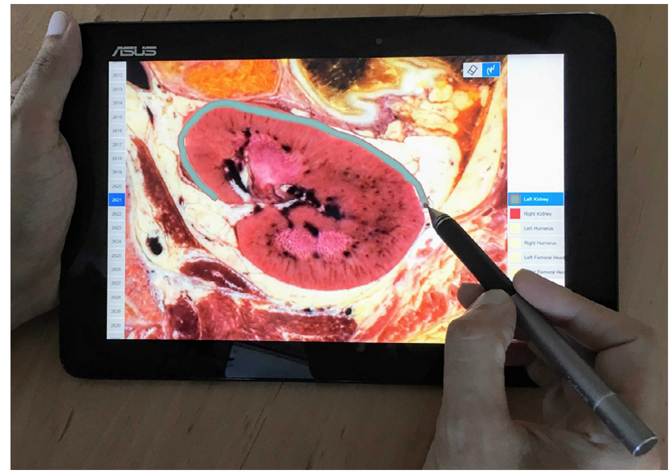

Fig. 3. Tracing the contour of a kidney with the stylus on the tablet. On the left pane there is a scrollable list of slices, and the right pane shows the available structures.

to exploit the advantages of each interaction paradigm, as most likely their synergistic combination should overcome the limitations of either modality in isolation, a result well known from multi-modal interface research. Additionally, Anatomy Studio enables two or more experts to collaborate, showing in real-time the modifications made to the contours by each other, and easing communication.

The main metaphor used in Anatomy Studio is the dissection table. Using MR, collaborators can visualize 3D reconstructed structures in real size above the table, as depicted in Fig. 1. The content becomes visible to all people around the virtual dissection table who are wearing MR glasses. Also, users can select slices from the common MR visualization to be displayed on their tablet device in order to perform tracing tasks.

Note that, according to [41], mobile devices such as tablets bring the potential of MR into every learning and collaborative environment. The self-directed approach allowed by MR can enhance experiential learning, engagement, whilst tackling challenging content in both medical practice and health sciences. In addition, previous research [42] reported that MR allows for better visualization of 3D volumes regarding the perception of depth, distances, and relations between different structures. Accordingly, we chose to follow these approaches, because when comparing MR through an HMD with a virtual window through a tablet, the first is more practical and natural, provides stereoscopic visualization, and can be easily combined with a tablet for 2D tasks, where these devices excel.

3.1. Distributed architecture

In order to support tablet and MR glasses for each user and the collaboration between all participants, Anatomy Studio uses the distributed architecture illustrated in Fig. 2. Anatomy Studio was developed using Unity 3D (version 2018.3.8f1), C# programming language for scripting and Meta SDK 2.8. Two applications were developed to run on both device types: Windows-based ASUS T100HA tablets and Meta 2 headsets. The whole data set, comprised of 12.2 gigabytes in high-resolution images, as well existing contours already traced, are stored in an Web Server, accessible by all devices in the session. However, to show immediate previews during slice navigation, each device displays thumbnails as slice previews, which consist in low-resolution images. All together, these thumbnails require only 36 megabytes.

Located on the same machine as the Web Server, is the Anatomy Studio server to which all devices connect. While only this server can make changes to the files in the Web Server, such as storing contours, all clients can read from it. The clients, both MR glasses and tablet devices, have an associated user ID so that they can be properly paired between each other. Every time a user changes his active slice or modifies a contour, the client device immediately notifies the server and all other clients through UDP messages.

3.2. Slice browsing

Existing digitizations of sectioned bodies consist of thousands of slices, each of which with a thickness that can be less than 1mm. As such, Anatomy Studio offers two possible ways to browse the collection of slices: one fast and coarse, useful for going swiftly to a region of the body, and another that allows specific slice selection.

Fast Region Navigation: To perform a quick selection of a slice in a region of the body, Anatomy Studio resorts to mid-air gestures. Attached to the frame representing the current slice in the MR visualization, there is a sphere-shaped handle, as depicted in Fig. 1, that can be grabbed and dragged to access the desired slice. This allows to switch the current slice for a distant one efficiently. Slices selected by other collaborators are also represented by a similar frame, without the handle, with the corresponding name displayed next to it. To ease collaboration, when dragging the handle and approaching a collaborator's slice, it snaps to the same slice.

Precise Slice Selection: The very small thickness of each slice ($\leq$ 1 mm) together with inherent precision challenges of mid-air object manipulation [43], makes it difficult to place the MR handle in a specific position to exactly select a desired slice. Thus, Anatomy Studio also provides a scrollable list of slices in the tablet device (Fig. 3) that only shows a very small subset of 20 slices around the currently selected one. This list is constantly synced with the MR handle and, after defining a region, users are able to unequivocally select a specific slice. Of course, due to the high number of slices, this scroll alone was not feasible to browse the whole data set, and needs to be used in conjunction with our Fast Region Navigation approach. In addition, slices' numbers are accompanied with the name of the collaborators that have them currently selected, which makes them reachable by a single tap. In Anatomy Studio only coarse slice selection is done in mid-air, as more precise slice selection is performed through the tablet device.

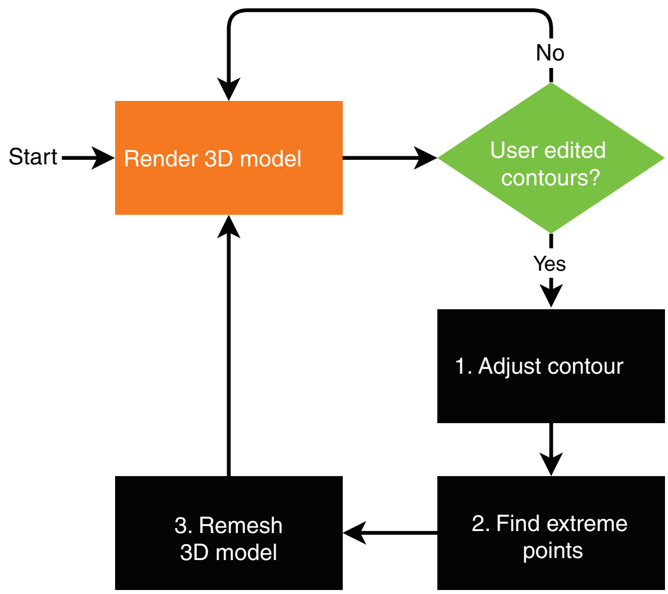

Fig. 4. Interactive 3D reconstruction flowchart.

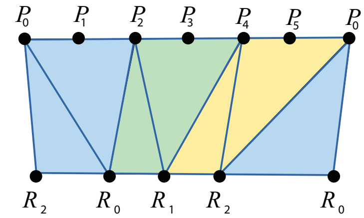

Fig. 5. Simple example of triangle strip remeshing. For each point in the line *R*, we create two triangles using one point out of every two in line *P*, given the ratio between both lines.

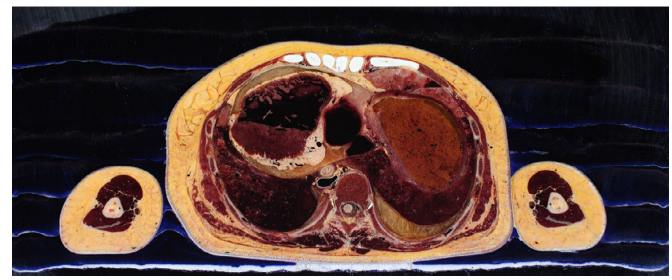

Fig. 6. Sample slice from the data set used in the user evaluation.

3.3. Contour tracing

To provide a natural experience that fashions sketching on paper with a pen, Anatomy Studio offers anatomists a tablet device and a stylus. The overall process uses an interactive sketch-reconstruct and re-display technique depicted in Fig. 4. After selecting the intended structure from a pre-defined set, as shown in Fig. 3, users can rely on a stylus to trace new contours on the currently shown slice, or erase existing contours.

To ease the tracing process, the image can be zoomed in and out, to provide both overall and detailed views, as well as translated and rotated, using the now commonplace Two-Point Rotation and Translation with scale approach [44]. After each stroke is performed, either to create or erase contours, Anatomy Studio promptly propagates the changes to the MR visualization making them available to all collaborators. It also re-computes the structure's corresponding 3D structure according to the new information, offering a real-time 3D visualization of the structure being reconstructed. Further details on the procedure are contained in Section 3.4.

3.4. Structure reconstruction

We implemented a custom 3D reconstruction algorithm that uses the strokes created by the users to recreate an estimated three-dimensional mesh of a closed 3D model. Each time a user changes the drawing made on a certain slice, a localized reconstruction process is initiated that comprises 3 steps:

1. Contouring can be performed by inputting smaller strokes. The algorithm goes through each stroke and estimate a single closed line. This is done by going through the first and last points of each stroke, connecting the closest ones with a line segment. This stops when a point is connected to a stroke already part of the line, thus, creating a closed line.
2. The algorithm then iterates through the line to find the extreme points, which will help iterate through the line during reconstruction. The starting point is set as the top-right corner, and the direction clockwise.
3. A mesh is finally created by connecting two closed lines from neighboring slices. Slices are distributed along the Z axis, so each point in the estimated line has a coherent 3D coordinate. Then, for each pair of neighboring lines, we create a triangle strip connecting them both, creating two triangles per point in the shortest line. The most populated line is sampled down using the ratio of points between the two lines. Fig. 5 shows a sample of the process. In this case, the top line P has 6 points, and the bottom line R has 3 points, giving us a ratio of 2:1, meaning we take 1 point out of each 2 of the most populated line. If the result is non-integer, we use the remainder of the division as set number of extra points we have to use in the top line, and add them incrementally in order to keep the sampling uniform.

Therefore, each individual triangle is created so the normal vectors are coherently oriented to the outside of the final 3D model. By applying this simple process to each pair of neighboring lines, we can create a complete closed 3D model in real time, so alterations can be immediately reflected on the 3D augmented space.

4. Evaluation

To assess whether Anatomy Studio can be used as a mean to enable collaboration and aid in the process of anatomical 3D reconstruction, we conducted a user study with experienced anatomists and medical professionals. To this end, we resorted to a data set that consists of serial cryosection images of the whole female body from the Visible Korean Project [45]. This data set included 4116 slices (thickness 0.2 mm) of the upper body (from the vertex of the head to the peritoneum) and 819 slices (thickness 1.0 mm) of the lower body (from under the peritoneum to the toes), resulting in a total of 4935 images (JPEG format, pixel size 0.1 mm, 48 bit color). Fig. 6 shows one of these images.

4.1. Setup and apparatus

For testing our prototype we used two Meta2 optical see-through head-mounted displays to view the augmented content above the table. This device provides an augmented 90° field of view, which facilitates the visualization and interaction with the augmented body being reconstructed. The Meta2 headsets were also used to perform the interaction in the environment, as they possess an embedded depth camera similar to the Microsoft Kinect or the Leap Motion that, besides tracking the headset position and orientation, also track users' hands and fingers, detecting their position, orientation and pose. Each of the MR glasses was linked to

Fig. 7. A pair of participants during a user evaluation session.

a PC with dedicated graphics card. Each participant was equipped with a Windows-based ASUS T100HA tablet with a 10 inch touchscreen and an Adonit Jot Pro-stylus. An additional Microsoft Kinect DK2 was used recording video and audio of the test session for further evaluation.

4.2. Procedure

Participants were grouped in pairs, seating at a table, facing each other as shown in Fig. 7. Each was equipped with an optical see-through head-mounted display, a tablet and a stylus. Firstly, researchers outlined the goals of the session and provided an introduction to the prototype. Prior to start, participants were asked to fill a demographic questionnaire, regarding their profile information and previous experience with the tested technologies (MR glasses, virtual dissection applications and multitouch devices), as well as an informed consent. A calibration process was performed to enable each headset to locate the virtual objects in real space. Then, both participants were instructed to perform a training task, individually, where they were free to interrupt and ask questions whenever they deemed necessary. This was followed by the test task, in which participants where asked to collaborate to achieve the final result. To prevent excessively long sessions, both the solo training task and the collaborative test task were limited to 15 minutes. Participants were then asked to fulfill a questionnaire about their user experience. Finally, we conducted a semi-structured interview in order to gather participants opinions, suggestions and to clarify the answers obtained from the questionnaires.

4.3. Tasks

Participants were asked to perform a training and a test task, based on reconstructing different anatomical structures using sketches. In the solo training task, each user had to reconstruct the left or the right femoral head, respectively. Next, in order to use a similar structure to the one selected for the training task, the test task consisted in the 3D reconstruction of the humerus (Fig. 8), a long bone in the arm or forelimb that runs from the shoulder to the elbow. To aid the reconstruction process users were able to freely collaborate using verbal communication and MR visual cues to locate on which part the other is working on the tablet.

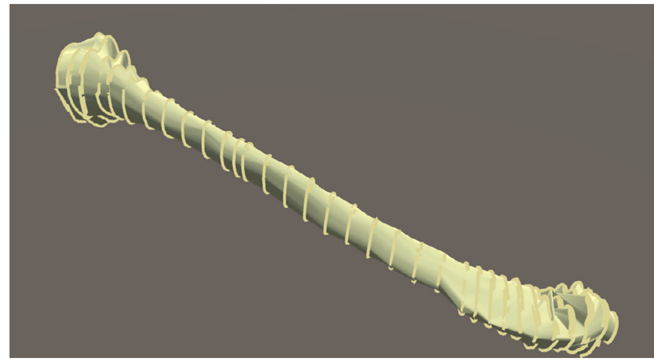

Fig. 8. Example of a reconstructed humerus made by participants using Anatomy Studio.

4.4. Participants

We conducted usability testing and evaluated our prototype with ten participants (one female), eight of which were medical professionals and two were medical students, recruited during an international congress on Digital Anatomy using a convenience sampling strategy. Participants' ages varied between 23 and 69 years old ($\bar{x} = 43.6$, $s = 19.5$). Having this particular sample size also ensured that we met recommended minimum criteria for usability evaluation of the intervention. According to [46], in a group of ten people, 82 - 94,6% of usability problems will be found. Participants who have evaluated our prototype are domain experts, have worked for a long time and have many years of experience. Because of this expertise, the expert is a trusted source of valuable information about the topic and the domain [27,47–49].

Among the professionals, four were radiologists (with an average of five years of experience), one neurologist, one surgeon, one dental surgeon and one internist with 27 years of experience. The majority (80%) were familiarized with touchscreen devices, but 70% reported having no prior experience with optical see-through MR technology. Five participants stated to perform virtual dissections, four of them on a daily basis. Fig. 9 shows the alluvial diagram that highlights important user characteristics emphasized by color and node clustering.

5. Results and discussion

We reviewed the usability testing videos and identified five interaction modes that users adopted using Anatomy Studio. Fig. 10

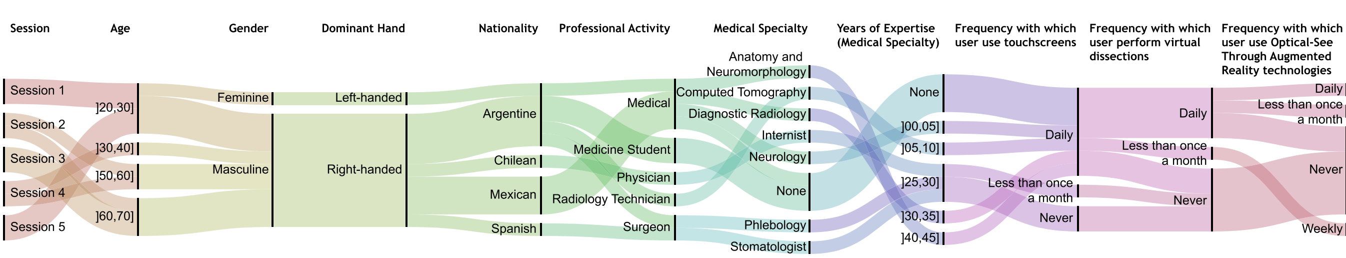

Fig. 9. Alluvial diagram of general participants' profiles of the usability testing.

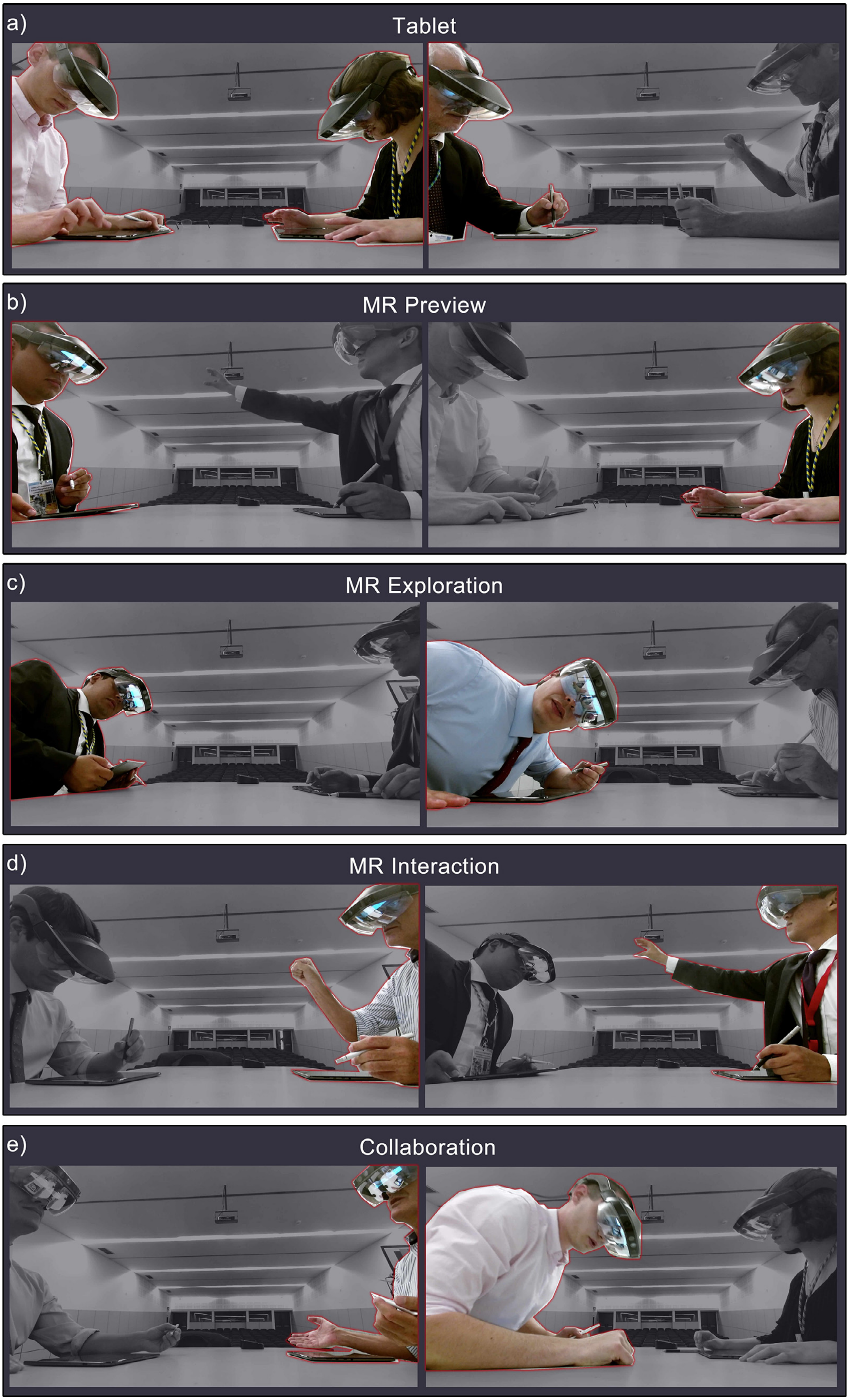

Fig. 10. Instantiations of different interaction modes identified during usability testing: a) Tablet: user focuses on tablet usage. b) MR Preview: user focuses in the MR environment. c) MR Exploration: user explores the MR environment. d) MR Interaction: user interacts with the NR environment using his/hers hands. e) Collaboration: user interacts with other participants through conversation. (Participants adopting an interaction mode are highlighted with a red line and vivid colors)

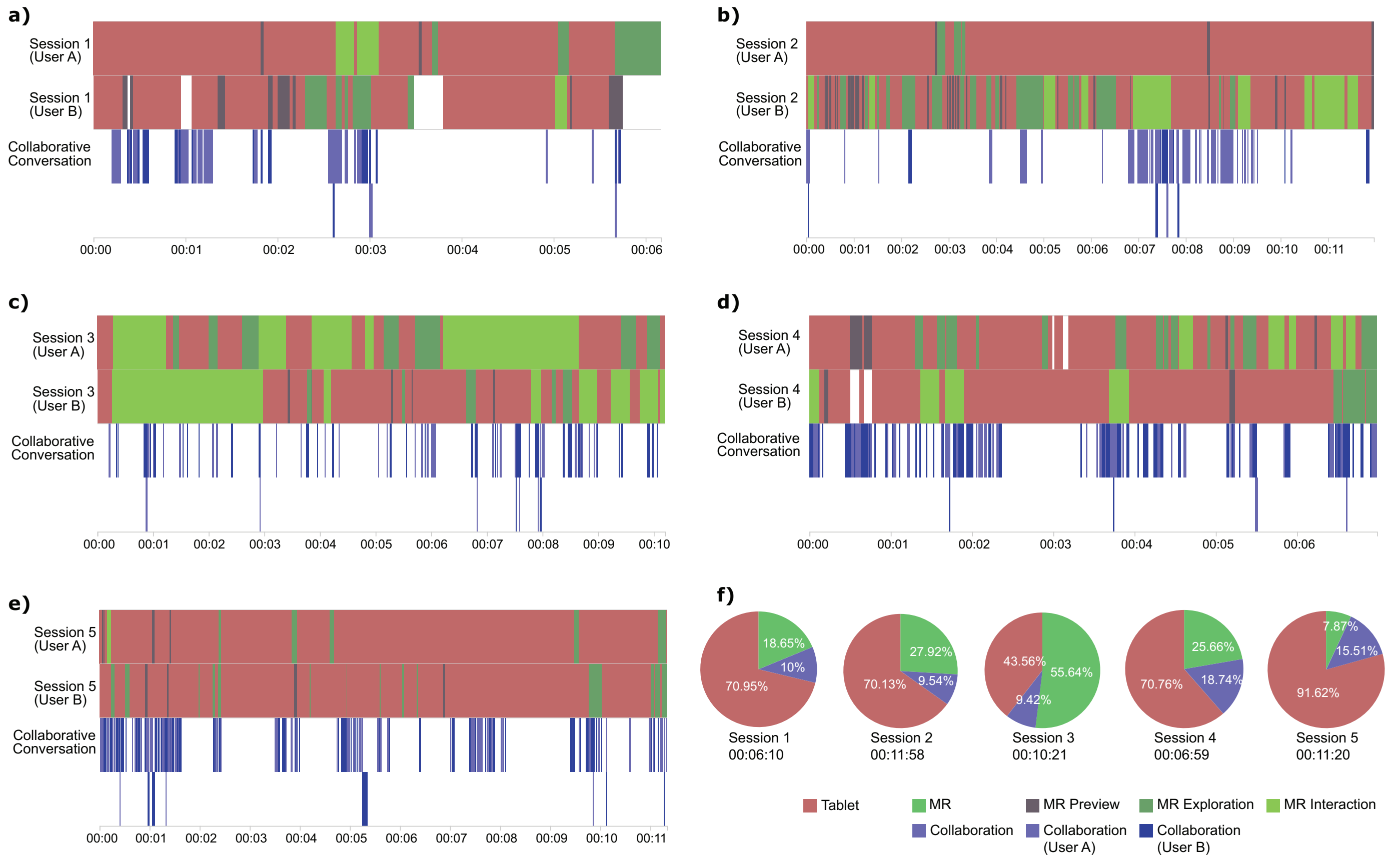

Fig. 11. Intervals of user interactions and collaborations in the usability testing. a–e) Identification of the interaction and collaboration times of each user in the session. f) total time used in each session and the general percentage of interaction modes.

shows some instances of the identified interaction modes. We observed that users behaved in three ways when they were focusing on the MR environment. We identified (i) MR preview when the user raised his head and looked at the environment, (ii) MR exploration when the user analyzed the environment moving the head or body to different directions and kept a fixed eye on the environment of MR content, and (iii) MR interaction when the user interacted with the environment using his hands. We also noticed that participants did use collaborative conversation to complete the task. This ability is an outcome-driven conversation aimed at building on each other's ideas and a solution to a shared problem.

Fig. 11 shows the interval of user interactions for each session according to the interaction modes shown in Fig. 10. Blank gaps represent discomfort or loss of user focus. Two participants (Session 1 and Session 4) experienced discomfort when using Meta2. Two pairs of participants, who had no AR/MR experience and little experience using touchscreen devices, asked for assistance during the usability test. However, we noted that participants over 50 years old, with little or no experience in AR/MR, were the ones who used most this sort of technology during the usability test. For instance, during Session 3, both participants (62 and 63 years of age) spent 55.64% of the total time of the experiment interacting in the RA environment, on the other hand, users (23 years of age each) of Session 5 focused on the tablet (91.62%).

We assessed user preferences and experience through a questionnaire with a list of statements for participants to score on a 6-point Likert Scale (6 indicates full agreement). Table 1 shows the participants' reception to the proposed features of Anatomy Studio, showing that all were well received.

Furthermore, and regarding the overall prototype, the participants found it easy to use ($\tilde{x}$=5, Inter-Quartile Range (IQR) =2) and, in particular, considered the combination of MR and tablet sliders to function well together ($\tilde{x}$=5, IQR=0.75). They also considered that the tablet's dimensions were appropriate for the tasks performed ($\tilde{x}$=5.5, IQR=1), and that contouring using a stylus was an expedite operation ($\tilde{x}$=5.5, IQR=1.75). Participants that perform virtual dissections professionally found it easier to segment slices using Anatomy Studio when compared to the mouse-based interface they are acquainted to ($\tilde{x}$=6, IQR=1). All participants remarked that Anatomy Studio is a viable alternative to conventional virtual dissection tools ($\tilde{x}$=5.5, IQR=2). They also noted that the visual representations of the 3D model and the slices above the virtual table are appropriate for anatomical study ($\tilde{x}$=4.5, IQR=1.75). The participants agreed that the 3D model overview allowed them to rapidly identify and reach anatomical locations ($\tilde{x}$=6, IQR=1). Furthermore, the augmented 3D space created a shared understanding of the dissection tasks and promoted closely-coupled collaboration and face-to-face interactions ($\tilde{x}$=5, IQR=2).

We also gathered observational notes taken during evaluation sessions and transcripts of recorded semi-structured interviews, in order to obtain participants' opinions, suggestions and to clarify the answers from the questionnaires. Participants stated that Anatomy Studio is adequate to "distinguish the several structures" and "understand the spatial relation between [them]". Therefore, "[with tools like Anatomy Studio] we do not need a corpse to learn anatomy". Notwithstanding, "virtual is different from cadaveric material, because we do not have the feeling of cutting tissue". Lastly, the collaborative capabilities of Anatomy Studio were praised, since "working in groups is more effective because, as medics, the

Table 1
Results for the user preferences questionnaires: Median (Inter-Quartile Range).

	Contouring	Scale	Rotation	Pan	Slide MR	Slide Tablet
1. The feature is useful.	5 (2)	5 (1)	5 (2)	5 (1.75)	5 (1.75)	5 (1.75)
2. The operation is adequate.	5 (1.5)	5 (0.75)	5.5 (1)	5.5 (1)	5 (1)	5 (1.75)
3. It was easy to use.	5 (1)	5 (1)	5.5 (1)	6 (1)	5 (2)	5 (1)
4. It was easy to remember.	5.5 (1)	5.5 (1)	5.5 (1)	6 (0)	6 (1)	5.5 (1)
5. It was easy to understand.	5.5 (1.75)	5 (0.75)	6 (1)	6 (1)	6 (0.75)	5 (0.75)

experience counts a lot to do a better job, and there should be a mixture of experiences during these sections”.

Overall participants daily work alone and rarely collaborations. Participants said that collaboration offered an equal opportunity to share ideas. Assisted in understanding and respecting diversity better, make team-focused decisions leading the team to a swift achievement of a common goal. The most observed benefit of collaboration was of the less time spent to complete a task.

Also, the participants mentioned some challenges. Two participants said that the stylus contour was very thick and made it difficult for the task. Another mentioned that they had to adapt to the orientation of the drawing presented on the tablet, because the orientation in the computed tomography image is so that the anterior is on top, posterior is bottom, left of the patient is on the right side of the image and the right is on the left side of the image. One participant reported that initially, Anatomy Studio seemed complex because it has many gadgets. Another suggestion mentioned by two participants is the need for prior training to get accustomed to the environment of MR. Another participant mentioned with although the virtual does provide a good interaction, the experience is not identical to that of the real body. In a real body can feel the difference through touch and cutting the tissues.

The advantage of using technological tools for teaching anatomy is that, in addition to the static figure, one can also understand and demonstrate the dynamics of movement. However, there are challenges to be explored. These challenges limit the actual use of these applications in the routine of health professionals and the transfer of this technology to the productive sector, on the other hand, these challenges create opportunities for research and development.

A significant challenge in the area is to make applications that offer realistic simulations of anatomical features. It is interesting to develop techniques that improve user perception, tactile sensitivity and spatial correlation between physical and virtual objects. Furthermore, [50] expressive finger-gestures may assist in identifying comparisons between scans, or unique anatomical variations and features when compared to using a mouse-and-keyboard approach. Also, introducing new teaching approaches in traditional culture is a current challenge for the applications that work in the area of health education.

6. Conclusions and future work

In this paper, we presented and evaluated a collaborative MR dissection table where one or more anatomists can explore large data sets and perform expedite manual segmentation. Our evaluation with medical experts suggests that MR combined with tablets can be a viable approach to overcome existing 3DRAS issues.

Our results show that collaborative virtual dissection is feasible supporting two tablets, and has the potential to scale to more simultaneous collaborators, whereby users that can choose the slice to trace on simultaneously, thus contributing to mitigating the reconstruction workload. Moreover, our approach provides for a portable and cost-effective 3DRAS tool to build anatomically accurate 3D reconstructions even for institutions that do not have the possibility to perform actual dissections on real cadavers.

Our main goal was to assess whether collaborative tools such as Anatomy Studio can provide viable alternatives to current methods, and whether these would be well received by the medical community, focusing on qualitative valuations rather than basic performance metrics. To this end, we gathered expert medical practitioners conversant with existing virtual dissection and 3DRAS tools. Our results illustrate the perceived potential of the approach, and its potential to motivate novel developments. Furthermore, all test sessions involved real drawing tasks, in a realistic setting, where participants were asked to build a 3D reconstruction of an anatomical structure as best as they (anatomists) could. While the work presented in this paper represents a first step towards MR for virtual dissection, as future work, we intend to conduct a comprehensive user evaluation with non-experienced students, to compare the learning curve and the ease of use of an iterated version of Anatomy Studio against the most common approaches to 3DRAS. Furthermore, we will look into Design Based Research approaches towards improving collaborative scenarios and perform extensive user centered design to improve the efficiency of collaborative content creation. On a related topic, previous studies found that high interruption rates could have a negative impact on task performance [51]. This could be an interesting direction for future research.

It has been suggested that Anatomy Studio could benefit from voice streaming and outside participant rendering for remote collaboration. However, it would be necessary to include a Natural Language Interface for command activation and to synchronize tasks. We consider this as very interesting future work.

Wearing an HMD can force the wearers to modify their posture and potentially affect their performance [52,53]. Although fatigue, stress tests and cognitive load are important variables to understand the limitations of the proposed tool, they were not considered in this paper, as the focus of our work was to explore the potential of Anatomy Studio as an MR tool to perform virtual dissection through sketches by enabling collaboration between multiple users. We intend to study such variables in the near future. While the work presented is exploratory, we see it as the precursor to a new generation of collaborative tools for anatomical applications.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The first author would like to thank the São Paulo Research Foundation (FAPESP) for support of this research: grant#2018/20358-0, FAPESP. This work was also partially supported by national funds through FCT with reference UID/CEC/50021/2019, IT-MEDEX PTDC/EEI-SII/6038/2014, and SFRH/BD/136212/2018.

Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.cag.2019.09.006.

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