Working with Forensic Practitioners to Understand the Opportunities and Challenges for Mixed-Reality Digital Autopsy

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ABSTRACT

Forensic practitioners analyse intrinsic 3D data daily on 2D screens. We explore novel immersive visualisation techniques that enable digital autopsy through analysis of 3D imagery. We employ a user-centred design process involving four rounds of user feedback: (1) formative interviews eliciting opportunities and requirements for mixed-reality digital autopsies; (2) a larger workshop identifying our prototype's limitations and further use-cases and interaction ideas; (3+4) two rounds of qualitative user validation of successive prototypes of novel interaction techniques for pathologist sense-making. Overall, we find MR holds great potential to enable digital autopsy, initially to supplement physical autopsy, but ultimately to replace it. We found that experts were able to use our tool to perform basic virtual autopsy tasks, MR setup promotes exploration and sense making of cause of death, and subject to limitations of current MR technology, the proposed system is a valid option for digital autopsies, according to experts' feedback.

– **Warning:** This paper contains sensitive images which are 3D visualisation of deceased people.

CCS CONCEPTS

• **Human-centered computing → Interaction techniques**; **Empirical studies in HCI**; **Visualization application domains**.

KEYWORDS

mixed reality, forensics, pathology, autopsy, user-centred design

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1 INTRODUCTION

Forensic medicine institutions have traditionally relied on integration of information from a variety of sources, such as physical evidence from crime scenes and autopsy, as well as police reports, medical history and imagery. However, such information is increasingly digitised and 3D spatial data from CT and MRI imaging is becoming a centrepiece of investigation. Currently, examination of such imagery is done via 2D screens. However, this mode of interaction comes with limitations:

- Extensive training, experience and anatomical knowledge are required to mentally reconstruct 3D reality from such 2D medical desktop applications to determine cause of death.
- Further, not all forensic analysts are trained doctors (e.g., forensic anthropologists) and their knowledge of 3D anatomy and medical imaging software may be limited.
- It is difficult to use traditional computer interfaces (such as mouse and keyboard) while hands are gloved and contaminated with body fluids.
- The size of the screen limits the amount of information that can be presented to provide context for the imagery.

Emerging mixed-reality technologies offer the possibility to make this digital information available in a context that more closely resembles traditional physical autopsy, providing a natural spatial mapping to visualise and interact with the 3D data. In the longer term, technologies which can accurately replicate the fidelity of traditional autopsy techniques, or even supercede them in terms of information fused from different sources, may reduce the need for

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physical dissection. Such dissection is time-consuming and distressing for families. However, inspecting the body outside and inside with such technology is under-explored.

In this paper we investigate the possibilities and challenges of using mixed-reality for forensic autopsy, evaluating and iterating on the design of several prototype techniques. Feedback from expert users is enthusiastic about the mixed-reality paradigm and proposed techniques but cautious about the technological readiness of the underlying headset capabilities.

In particular we contribute:

- initial formative interviews with six domain experts (in pathology, anthropology and radiology) to elicit opportunities and requirements for mixed-reality technology in autopsy (see Section 4.2);
- a larger workshop with 15 pathologists which further elicited use cases and identified interaction ideas as well as limitations (see Section 5.2);
- the iterative design of new, embodied, gesture-based interaction and visualisation techniques for pathology related medical imaging data analysis in mixed-reality environments (see Figure 1, and Section 3, 5.1, 6.1, and 7.1);
- findings from two rounds of qualitative user testing as part of this user-centred design process, evaluating the proposed techniques with two real forensic use cases to show the capabilities of the techniques in real scenarios (see Section 6.2 and 7.2);
- a report on the limitations of the current state of the art (see Section 9).

2 BACKGROUND

The presented work pertains to immersive analytics with embodied interaction [26], virtual autopsies, and data deformation techniques for 3D datasets.

2.1 Immersive Analytics and Embodied Interaction

Immersive analytics [16, 48] aims to provide users with data analysis possibilities within an immersive context (e.g., AR, VR, MR). Research has demonstrated the role of immersion for data analysis and sensemaking, such as the possibility of unlimited screen space [4, 32, 46, 61], effects on spatial memory [58], 3D spatial interaction [10, 53, 62], collaboration [45, 65, 67], engagement [9, 19, 20, 49, 54], and entertainment [9, 78]. Immersive analytics scenarios can be implemented in a variety of contexts, ranging from handheld mobile devices providing e.g., see-through augmented reality, to head-worn devices or caves [7, 10].

Many research projects have sought to utilise and apply immersive analytics techniques in a variety of other research disciplines ranging from fluid dynamics and flows [8, 17, 40], surgery planning and medical data [13, 57], molecular and microscopic data visualisation [71], or astrophysics and particle physics [64, 74]. In our work, we propose to implement a prototype of immersive analytics for forensic autopsies which relies heavily on 3D data analysis and would therefore likely benefit from immersive environments.

Immersive environments offer the possibility for embodied interaction replacing traditional mouse and keyboard interactions. Such interaction is arguably more natural [26] but relies on technologies that are still under development (e.g., accurate hand tracking) and also requires redesign of interactions that have become standard on desktop and touch computing. For medical applications, touch-less gestures also eliminate concerns of contamination.

2.2 Immersive Autopsies

Immersive technologies have been used in fields closely related to forensic medicine such as radiology [23, 55, 68], surgery [22, 50], and anatomy training [2, 33]. More related to our investigation are the immersive renderings used in crime scene investigation [28, 56, 66, 73] or demonstration to the court [41, 58], yet only a handful of prototypes address the specific needs of forensic autopsy described in section Section 4.1. One early prototype [70] investigated the possibility of performing remote autopsy with surgical haptic robots in an immersive environment. Another study [42] developed a method to register 3D visualised medical data on the cadaver eliminating the need for tracking markers. This way, a user (pathologist or operator) can conveniently see 3D imaging data on the deceased person's body surface via a tablet with a mounted range camera. While hand-held immersive displays (e.g., [39]) and tangible interaction (e.g., [23]) can be used in a variety of the prototypes and application domains mentioned in Section 2.1, their use deprives experts of their freedom of actions and their possibility to use other diagnostic tools they require in their work. Consequently, Affolter *et al.* [1] developed a system relying on the Hololens' mid-air gesture detection and an additional face shield. This prototype was argued to reduce the risk of contamination on computer systems, decrease pathologists' movements and interruptions during the autopsy, thus enhancing their concentration and minimising their need for an assistant. Further evaluation of the prototype [15] highlighted that the headset is generally used in the first half-hour of the autopsy. Muscle fatigue due to mid-air gestures and technological limitations, including partially transparent images on bright surfaces, a low field of view, and low battery capacity, are some of the problems reported by pathologists in this study. Closely related to autopsies are forensic examination of injured people for which Koller *et al.* [43] developed a VR tool. The prototype creates a 3D model of a person that a forensic examiner can use to mark, measure, and document injuries. Measurement in the virtual environment appeared in their evaluation to be more accurate than approximations from forensic photo documentation, although not as accurate as photogrammetric measurement in dedicated software tools. Our work is inspired from these approaches which have, overall, demonstrated the potential benefits of augmenting autopsies and forensic sciences with immersive and embodied interaction. However, our investigation goes beyond the relatively simple possibilities given by previous systems in that we implement interaction techniques allowing domain experts to directly manipulate 3D data beyond what would be possible with classical systems or bodies.

2.3 Interacting with 3D Volumetric Data

Occlusion management in 3D volumetric data is a common issue [29], and many studies have sought to reduce this issue through interactive visualisation techniques for different applications [36,

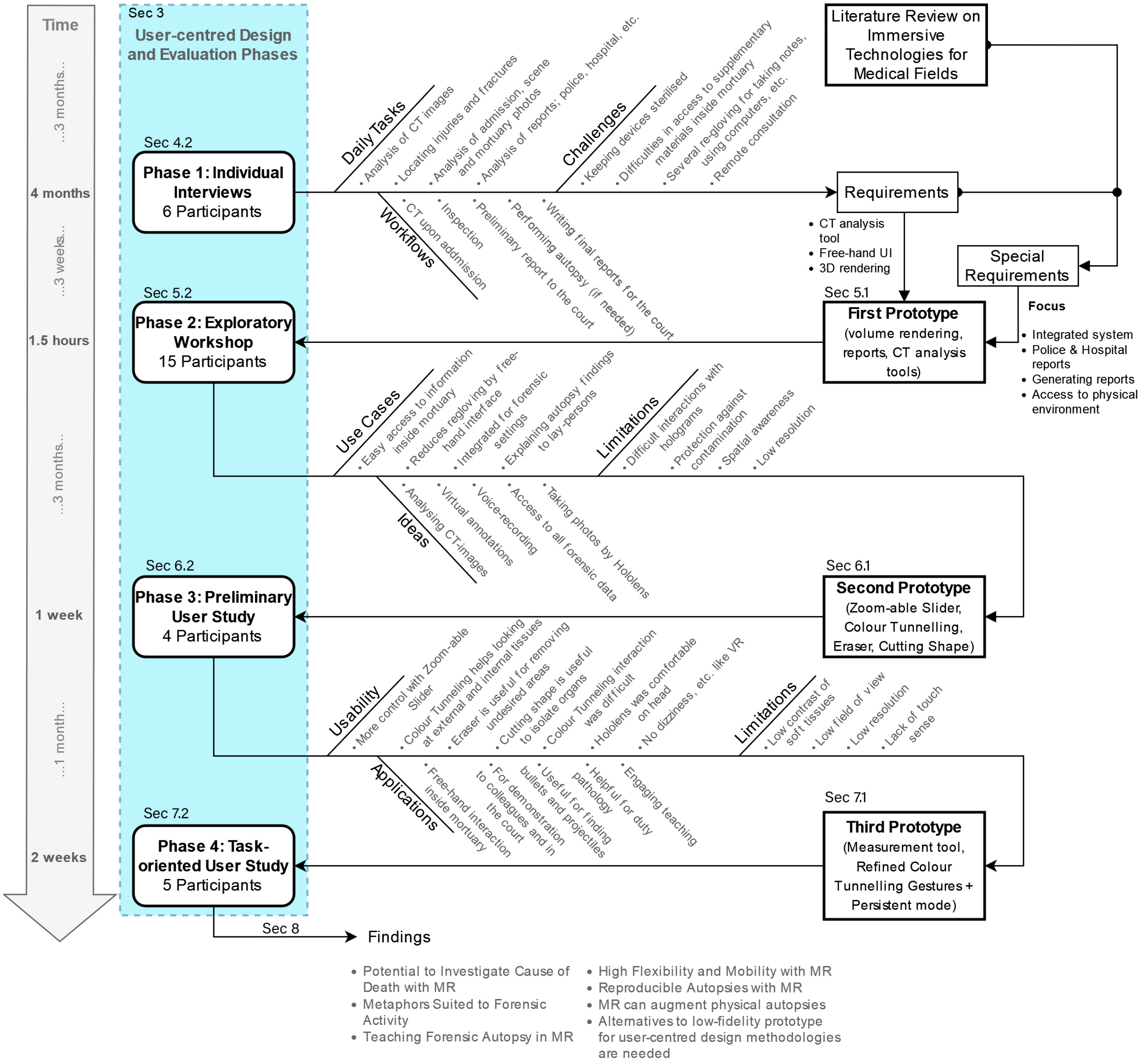

Figure 1: Overview of our user-centred design process.

37, 44, 76]. This issue is also one of the main challenges in visualising volumetric medical data. One of the approaches is using effects that temporarily modify the data through different methods such as specific transfer functions for illustrative visualisation [24], interactive lenses for data exploration [36] or volumetric pealing [52]. A recent survey has found that a large majority of 3D visualisation systems solely implement cutting plane manipulations and selection tools [10] despite the need for more specific and advanced interactive visualisation techniques. In contrast, our system implements a variety of tools to support the forensic workflow such as an eraser (to erase artefacts or undesired data), a new zoom-able slider (to browse CT slices precisely and quickly), an interactive colour tunnelling technique (to have more control over the visualised and hidden data), and a cutting shape (to select a region of the body with complex shapes).

Some of our MR techniques can be traced back to previous research for 2D displays and other application domains, however, completely new interactions and visualisations are needed in mixed-reality environment. We took inspiration from past techniques such as colour tunnelling [36, 72], cutting shape [34], and eraser [35], which we modified for MR environments and the specific needs of forensics science, as well as developing new techniques. To the best of our knowledge, there is, for instance, no interactive lens deformation in mixed-reality environment for medical volumetric data. Our work explores such possibilities with embodied interactions and fills this gap.

3 METHOD

We aim to use mixed reality to support the workflow of forensic medicine. Our first step, then, is to understand this workflow, as well as the unique requirements of forensic autopsy settings in comparison with other medical fields. We followed a user-centred approach to design, implement, and evaluate prototypes directly with forensics experts from the Victorian Institute of Forensic Medicine (VIFM), across four iterative evaluations and prototyping phases. Figure 1 details all the steps in our approach. Throughout, we worked with a variety of forensic experts from VIFM, with one involved through all four stages of our user-centred design (see Table 1 for their level and field of expertise).

We started with a literature review, followed by individual interviews (Phase 1) to understand the basic and unique requirements of forensic medicine and autopsy from the practitioners. We conducted one-hour interviews with six experts within different fields of forensic medicine (forensic pathology, forensic radiology, and forensic anthropology). We developed a prototype pathology system which demonstrated features elicited from these interviews. We then (Phase 2) conducted a 1.5-hour workshop with 15 forensic pathologists with a presentation of mixed-reality technologies, previous works, and a live demo of our first prototype. The workshop identified limitations of our system as well as additional use-cases inspiring our second prototype. We then (Phase 3) conducted a more formal qualitative user study of prototype 2 with four forensic practitioners for one hour each, walking through the tasks identified in Phase 2. Feedback from this phase led to prototype 3. The final study (phase 4) was conducted with five forensic experts who used our prototype 3 for about one hour each performing specific forensics tasks.

For all phases involving demonstrations or evaluations, we used the latest version of Microsoft Hololens (Hololens 2) as the mixed-reality device. We used a recent gaming laptop (11th Gen Intel i7-11850H, 32 GB RAM, NVIDIA T1200 Laptop GPU) that runs the mixed-reality application on the Unity game engine and streams the rendered scene to the Hololens and receives positioning data from the Hololens through a wireless network via holographic remoting provided by the Microsoft Mixed Reality Toolkit[1]. The source code and supplemental materials are publicly available on OSF at https://osf.io/f83v2.

4 INITIAL SYSTEM REQUIREMENTS

Our initial study of literature and interviews with forensics experts elicited important context which formed the basis for development of the first prototype, as follows.

4.1 The Forensic Activity

Forensic medicine institutes conduct a multiplicity of procedures in their activities. There are, however, a number of common processes: They receive incident scene of death and medical reports prepared by police and hospitals, examine the deceased person, and prepare reports for judicial authorities.

Forensic institutes may be equipped with medical imaging technologies such as Post-Mortem Computed Tomography (PMCT) and (more rarely) Magnetic Resonance Imaging (MRI), which allow forensic pathologists and other forensic experts to locate internal pathology related to the cause of death. Imaging can assist autopsy planning, and can be used to determine cause of death alone in some cases, thus avoiding the need for invasive autopsy [77]. However, forensic experts do not often have formal training or expertise in reading volumetric radiology images, and thus require the consultation of a radiologist and auxiliary tools such as volumetric visualisation and segmentation software applications.

Forensic pathologists read police and medical reports, and examine photos, CT and MRI data prior to performing the autopsy. They look for injuries, fractures, evidence of both unnatural and natural death, and other pathology of interest to the case. They take notes, tissue samples, blood samples for toxicology, measure injuries, record their voice, and take photos of the findings. This process requires many 'hands-on', touch-based interactions with documents and devices during autopsy that can be difficult and time-consuming tasks, which impacts the practitioners' performance and accuracy. These data are archived in permanent storage and are also summarised in several formatted documents for use of the Courts, and for families.

This workflow and summary of the procedures provides a view of the complex nature of death investigation and how it involves different medical and scientific specialities working in concert to generate the final outcome. As newer technologies become available in death investigation, processes can be streamlined, and higher quality and accuracy may be achieved. Furthermore, since physical autopsy is an invasive procedure, digital alternatives may be more acceptable to families with different cultural and religious backgrounds [77].

4.2 System Requirements based on Individual Interviews

We conducted individual interviews to understand current procedures and challenges of a forensic medicine institute. We further divide the procedure into high-level *workflow* tasks and lower-level *daily tasks* and summarise the challenges they face which we aim to address with our prototype development.[2]

4.2.1 Workflow. Each day, there are many *reportable deaths*[3] that instigate forensic investigation. Many types of data are collected: photographs upon admission and inside the mortuary, police and medical reports, and CT images. Forensic practitioners write reports and sometimes present them in court.

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[1] https://docs.microsoft.com/en-us/windows/mixed-reality/mrtk-unity

[2] More details can be found in our supplementary materials.

[3] Definition of reportable death: deceased person from a car accident, suicide, homicide, any other accidents (e.g. fall from height), deaths where the person does not have a medical record in the 12 months prior.

Table 1: Participants information.

Participant	Phase 1	Phase 2	Phase 3	Phase 4	Expertise	Years of experience	VR/AR experience
P1			X		Pathology	30	Never used
P2	X		X	X	Anthropology	5	Once or Twice
P3	X	X	X	X	Pathology	20	Never used
P4*		X	X	X	Odontology	22	A few times
P5				X	Pathology	17	Never used
P6				X	Pathology	5	Never used

*This participant is a co-author of the paper.

4.2.2 Daily Tasks. Prior to autopsy, pathologists and radiologists meet to analyse CT images and police and medical reports to find potential fractures and injuries. During an autopsy, pathologists take samples for DNA and toxicology tests which they record on the computer, take notes of their findings and measurements on a whiteboard, and take photos. After the autopsy, they write reports based on the collected information.

4.2.3 Challenges. Forensic practitioners face many challenges with the current autopsy process. They need to reglove many times to take notes, record voice or use their computer. Access to supplementary materials (i.e., references) inside the mortuary is also cumbersome and remote discussions or consultations are not currently supported.

5 PROTOTYPE I AND WORKSHOP

Our first prototype was informed by the challenges identified in the previous section. The prototype was then introduced to participants in our first workshop, as follows.

5.1 System Concept (Prototype I)

Prototype I is depicted in Figure 2 and had the following key features: a 3D volumetric visualisation of medical imaging data,[4] three axial sliders and CT image viewer, a cutting plane that slices the visualised body, zoom in/out on CT images, visibility window (or windowing level to control visible voxels), floating police and medical reports, and a few other basic features that are common in any CT image analysis tools.

5.2 System Requirements based on Exploratory Workshop

Because MR technology is novel to forensic practitioners, we began our workshop with a live demo of Prototype I to familiarise them with the technology and establish a reference artefact to stimulate ideation. We discussed benefits and limitations of mixed-reality in general, and then with respect to the prototype. They provided a list of possible use cases, limitations, features and improvements, as follows.[5]

5.2.1 Use Cases. Almost all participants appreciated the benefits of free-hand gestures and the possibilities that this system could bring to their workflow, such as easy access to data inside the mortuary or demonstration of pathology outside the mortuary, as well as for teaching purposes.

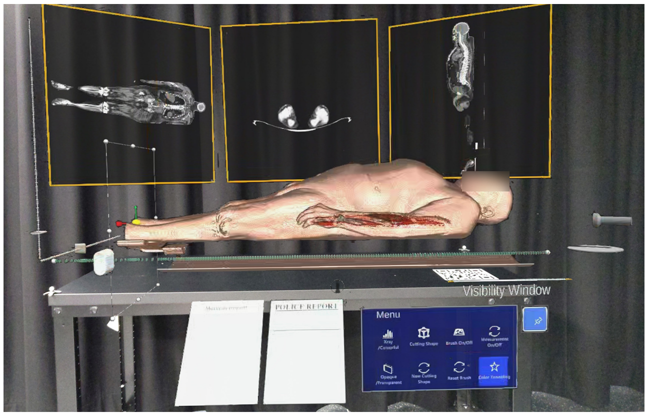

Figure 2: Prototype I: mixed-reality system concept with whole-body volume visualisation, CT images analytical tools and police and medical reports through Microsoft Hololens 2.

5.2.2 Ideas. Participants were keen to have more analytical tools. They proposed features that would enable them to draw and annotate on the body model for analysis and documentation purposes. They further suggested to implement voice recording, virtual snapshots, and virtual note-taking. They added that it would be valuable to be able to access all forensic-related data within the system.

5.2.3 Limitations. Participants were able to try our mixed-reality system and provided insightful feedback and comments. The majority of comments were focused on the Hololens: its low resolution and bulkiness, and the difficulties to interact without some visual feedback. Therefore, our revised implementation was aimed at providing more intuitive and direct dissection methods, as detailed below.

6 PROTOTYPE II AND EVALUATION

In this stage, we propose four techniques to support analysis of medical imaging data through 3D visualisation in MR, and evaluate them in a round of user studies.

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[4] Large imaging data from CT scanners takes a huge amount GPU memory which challenges current hardware. We therefore implemented a downscaling function for these large datasets, thus slightly reducing the rendering quality of the actual data.

[5] More detailed information can be found in our supplementary materials.

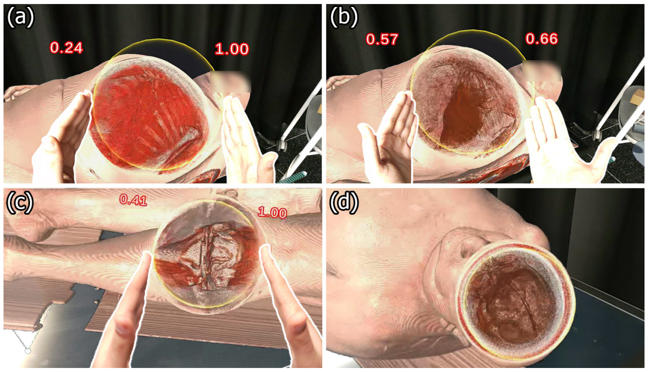

Figure 3: Prototype II: Using colour tunnelling to push away voxels and look inside the body. (a) Looking at the chest. (b) Changing the visibility range with hands rotation to hide ribs. (c) Looking at the knee. (d) Looking at the brain.

6.1 Image-based Autopsy Techniques (Prototype II)

In Prototype I, participants found the cutting plane method for sectioning the body problematic, requiring 'fiddly' interaction with virtual controls and a less direct mode of interaction than surgical dissection. It was difficult for them to isolate a particular area of the body while retaining the surrounding context. We therefore decided to focus Prototype II on novel ways for pathologists to perform direct manipulation with their hands, adapting filtering ("cutting shape" and "zoom-able slider" techniques) and Focus+Context [47] techniques ("colour tunnelling" and "eraser" techniques).

6.1.1 Colour Tunnelling. In physical autopsy the pathologist routinely removes soft tissue to examine deeper structures. Colour tunnelling replicates this ability, by allowing the pathologist to delve into the body at a particular point by virtually removing soft tissue within a specified density range and radius around that point. As mentioned in Section 2.3, this technique is based on a screen-based technique introduced by Hurter *et al.* [36], but required adaptation for MR. In Hurter's approach, they use a cylindrical tunnel which eliminates all voxels within a radius of the ray cast into the view below the mouse cursor. For interactive MR users may freely move their point of view out of alignment with a cylindrical tunnel and furthermore we want a more limited scope of effect than a tunnel cutting through the entire volume. We therefore use a spherical cursor, whose diameter and position is adjusted continuously to fit between the user's hands. The user can also simultaneously adjust the density range of interest by rotating their hands around the palm's roll axis (see Figure 3). Furthermore, we introduce a performance optimization involving a simpler but more efficient voxel displacement animation than that proposed by Hurter *et al.* , to make it practical for use with large, whole body datasets.[6]

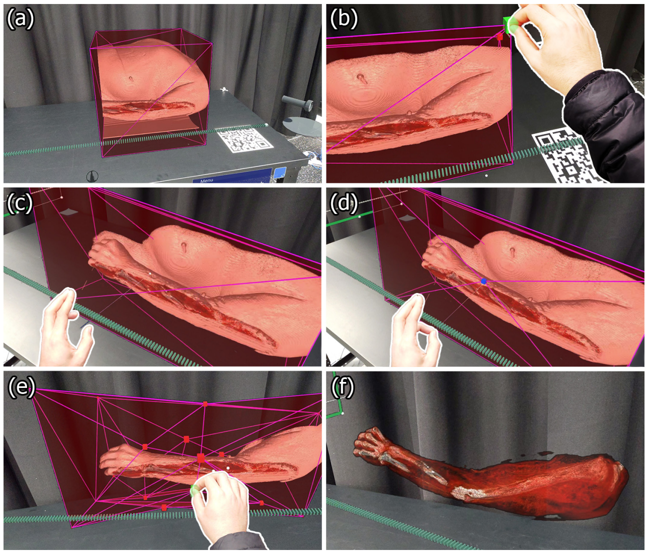

Figure 4: Prototype II: Steps of using the cutting shape to select a volume. (a) A cutting box isolates the visualised data. (b) User moves control points to manipulate the cutting box. (c) When the thumb's tip and ring finger's tip are close to each other, the user can see the location of the new control point (small white dot) that will be added. (d) When the user is satisfied with the location of new control point, taps thumb and ring finger to add a new control point. (e) The user manipulates the shape with many new control points added. (f) Final selected shape with different visibility ranges.

6.1.2 Cutting Shape. A box mesh that can be manipulated to form a flexible 3D shape to isolate a volume of interest, see Figure 4. Beginning with a cutting box, the user can move the box's control points (vertices) with a pinch gesture, and add new control points to shape the mesh (both convex and non-convex shapes are supported). A new control point merges two triangles as shown in Figure 4 (c and d), where the common edge of those triangles is nearest to the position of the control point (the closest point on the surface to the hand indicated by the white dot in 4.c). We chose the combination of thumb and ring finger for adding a new control point, because it is an uncommon gesture and unlikely to be done inadvertently or interfere with other hand gestures.

6.1.3 Eraser. This tool complements the cutting shape and colour tunnelling tools to precisely remove voxels. A pinch gesture with thumb and index finger erases voxels, and a pinch with thumb and middle finger restores erased voxels.

We have developed three types of eraser: hard, windowed and growing.

- The hard eraser simply removes any voxels inside a sphere with a specified radius.
- The windowed eraser only removes voxels that are inside the sphere but only if the value of that voxel is inside the visible range adjusted by the visibility window.
- The growing eraser is somewhat aware of tissue connectivity. It has hard and soft radii (hard radius < soft radius). The voxels within the hard radius are removed and an average of the values of those removed voxels is computed as the *average value* for growing phase. In the growing phase, other

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[6] More detailed information can be found in our supplementary materials.

> voxels within the soft radius join the removed voxels if there is a connected path from those voxels to the hard radius, and all of this path is inside the range of a *pre-defined threshold* around the *average value*.

Since there is no haptic feedback, we added a negative colour to assist the user to recognise which voxels will be removed or restored before the real action. Figure 5 demonstrates this tool in MR.

6.1.4 Zoom-able Slider. Correct positioning of a slicing tool can be challenging with the variable accuracy of mid-air gestures. To solve this issue, we offer a new technique called the "zoom-able slider" that has two states, normal and focused which effectively allow experts to manipulate slices with different control-display gains [12, 63], see Figure 6. In the normal state (6.a), the slider controls the cutting plane directly with a pinch gesture. However, pulling the slider perpendicular to its axis beyond a threshold accesses the focused state (6.b), after which, further perpendicular movement adjusts the gain of the slider. That is, the further the slider control is dragged from its axis, the higher the accuracy (6.c-d).[7] This technique thus proposes an embodied way to adjust the control-display gain (to navigate between 2D slices) which, to the best of our knowledge, has not been investigated in the literature before, although some tangible variations exist (e.g., [6]).

6.2 Preliminary User Study

The aim of this initial study is to obtain feedback on the techniques developed in Prototype 2. Our ultimate goal was to obtain preliminary feedback on the usability of the techniques, as they introduced novel, embodied controls for visual exploration of cause of death. Furthermore, we wanted to gain insights on the actual use of the immersive space and understand the limitation of our initial design. We collected feedback with structured questionnaires and open-ended discussion.[8] Four participants (P1, P2, P3 and P4) were involved in this phase.

6.2.1 Usability. Participants were asked to compare the immersive prototypes with the current 2D CT imaging analysis applications. Regarding the *Learnability*, *Ease of Use*, and how *Fast and Accurate* they can perform their tasks with each technique in comparison to their usual procedure. Participants were asked to provide their feedback verbally and with a score on a 5-point Likert's scale. The results are reported in Table 2.

For the zoom-able slider, all participants except P3 found the control over the speed of movement with the focused mode useful. P3 reported no preference for this. P2 and P3 still found it difficult to use the zoom-able slider while looking at the CT slices. Yet, we speculate that a wider field of view or a better windows arrangement could resolve this problem. P3 commented that it "*could be more responsive, I feel I'm a bit ahead of it sometimes*" but also mentioned that "*It's just a course of practice*".

The colour tunnelling technique was interesting for the participants. P1, P2 and P4 generally liked it. P4 found it to be a "*more sophisticated 3D visualisation*" than conventional 2D software applications offer. However, P3 found it "*confusing*". We asked whether it is helpful to see inner organs inside the tunnel while the rest of the body is in a different windowing level, to which they responded: (P1) "*It's like digital dissection*", (P2) "*It's nice that you can see both mediums. Sometimes you're interested in something external, and sometimes you're interested in something internal at the same time*", (P3) "*For teaching, yes. But not in everyday practice*", and (P4) "*Particularly useful for injuries, tracks of stab wounds, and types of injuries*". Users found it easy and intuitive to change the tunnel radius with their hands. However, most of them found it difficult to remember and to control the range of visibility window in their first practice. However, they considered it fast and accessible eventually.

Table 2: Participants' feedback on different measures for each technique (5-point Likert's scale).

Technique	Measure	P1	P2	P3	P4
Zoom-able Slider	Learnability	3	3	4	4
	Easy to Use	3	4	4	4
	Fast and Accurate	4	4	-	5
Colour Tunnelling	Learnability	2	5	1	3
	Easy to Use	2	5	2	3
	Fast and Accurate	3	4	3	4
Eraser	Learnability	5	5	4	5
	Easy to Use	4	5	3	5
	Fast and Accurate	4	4	3	5
Cutting Shape	Learnability	2	5	5	3
	Easy to Use	2	5	5	5
	Fast and Accurate	4	5	5	4

The eraser technique was most favoured in terms of usability and learnability (Table 2 shows a similar result). Even though P3 found the eraser easy to learn and easy to use, tracking issues occurred a few times and resulted in a lower score from them. They did not report similar issues with our other techniques. All found the technique useful in selecting a region or removing distracting parts, however, P3 asked for more control over the layers that are removed. P2 and P4 found the negative colour preview a useful visual cue to see where the erasing or adding starts, the others did not mention it.

The cutting shape technique was also of interest to many participants, especially for P3 that was not very satisfied with other techniques as visible in Table 2. All participants found it helpful to focus and isolate a specific part of the body to examine more closely. The capability to delete extra points, having curved shape instead of edged shape, and drawing instead of moving control points were the missed features suggested from the participants.

All participants mentioned that remembering the hand gestures especially for colour tunnelling was a bit difficult, and more visual guidance may help.

We also asked participants if they considered the virtual tools as real objects. Only P4 found the intuitiveness of interaction with objects conveys the feeling of interacting with a real object. Other participants did not have the same feeling mainly due to the lack of haptic feedback.

The techniques together were comparable to current systems for P1, P2, and P4, yet they believe training is required to use them effectively. P3 believes current 2D software applications are convenient

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[7] More detailed information can be found in our supplementary materials.

[8] Further results can be found in our supplementary materials.

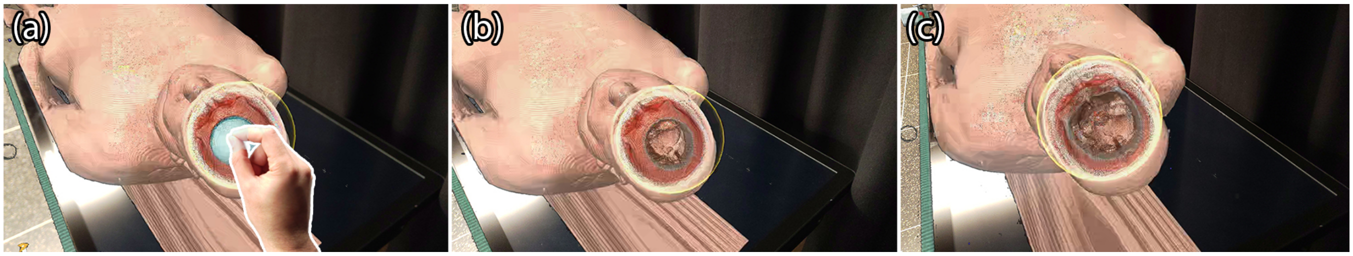

Figure 5: Prototype II: The eraser technique while using colour tunnelling gives different layers of visualisation. (a) Negative colour shows the region that will be removed if users pinch. (b) The erased part of the skull helps users view the inside of the skull. (c) More voxels are erased and the inner side of the eyes is visible.

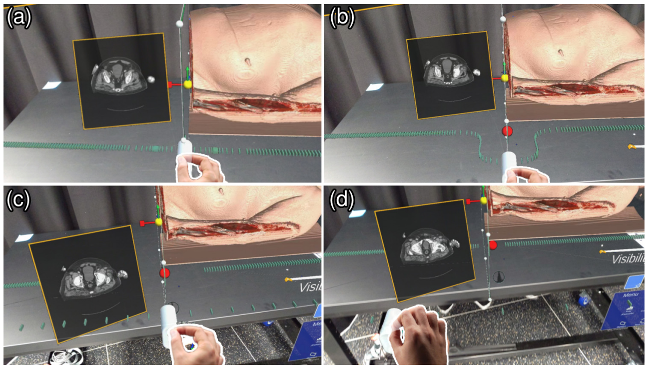

Figure 6: Prototype II: Zoom-able slider. (a) normal state: hand movements are mapped 1:1 to presented slices. (b) pulling the slider past a threshold changes to focused state. (c) focused state: the zoomed tick marks indicate the slider gain. (d) at high gain the red sphere shows the centre of the zoomed range on the original slider axis.

enough, however P3 does not use 3D visualisation which is the base for many of the proposed techniques. Still, most participants said the free-hand gestures and immersive nature of interactions are big advantages. P2, P3, and P4 found it helpful in accessing the required information, however, P3 commented the system is still not very good for soft tissues. P1 believes the system could be helpful in the future with more features available.

All participants found the system a bit distracting because it was new to them. P4 asked for some parts of the virtual environment to be less complex and invisible when features are not required for that task.

Real-size 3D visualisation of the whole body in MR was also appreciated by all participants, except P3 who does not use 3D visualisation. Others reported that it "*makes it more like dissection*", and is "*better than looking at 2D screen*".

6.2.2 Applications. All participants believe this system can be an effective way of teaching and creates new opportunities for students. In addition, P1 found it useful for autopsy planning outside the mortuary, while P2 preferred to use it inside the mortuary. P2 believes using this technology at the office would seem a little awkward. P1 and P4 both believe there are potential applications of using this system for demonstration to colleagues and in the court. P3 think it can be useful for finding bullets and projectiles. P4 also mentioned that it is definitely helpful for duty pathology which is regular inspection for all cases they first come in.

Regardless of this system, we asked participants to brainstorm ideas for using immersive technologies to facilitate their daily work. P1 and P3 believe it can be helpful mainly for teaching purposes, but P2 and P4 see more potential for immersive technologies. P4 addressed other issues regarding voice recording, accessing information and generating reports via an integrated immersive environment. P2 thinks this technology "*makes life easier. You don't have to keep taking off gloves, putting gloves on constantly.*" and further:

> *sometimes you're interested in taking certain measurements of bones and things like that as well. So normally, we would have to use that CT [imagery] on the desktop [software] to take those measurements, which we'd have to do back at our desk. If we were in the mortuary and we could do those measurements digitally, that would be even better. It just means we could get it done more timely.*

6.2.3 Limitations. We also received feedback on difficulties when working with these techniques. All participants mentioned that learning the interactions was slightly difficult. P3 commented "*matter of remembering which different hand signals for which different action*". P4 mentioned that pinching and grabbing occasionally fail to work properly.

The interesting feedback was that all participants except P3 found the Hololens comfortable, however, P3 said "*it's fine, but I couldn't wear it for a long time*". Noteworthy, the fact that they could access the physical environment was a real advantage of mixed-reality over fully immersive virtual reality. P1 was not very satisfied with the image quality but deemed it still acceptable. All participants recognised the narrow field of view of the Hololens as a disappointing limitation.

7 PROTOTYPE III AND EVALUATION

Informed by previous feedback, we aimed to refine interactions for colour tunnelling, and to add a new persistent mode and a measurement tool to the system. These were evaluated with a task-oriented user study.

7.1 Refined Image-based Autopsy Techniques (Prototype III)

The third prototype addresses the most critical issues we found in the first user study (see Section 6.2), and prepares the system for a real forensic task in the second user study (see Section 7.2). Based on the participants' feedback, we identified that the colour tunnelling interactions caused the most usability issues. Additionally, the participants had limited control over the layers removed by the eraser in a few situations. We therefore modified the colour tunnelling technique with new gestures and a persistent mode to improve these issues. We have also added a feature to perform the measurement tasks which was asked by the participant as a useful tool for their tasks in the mortuary.

7.1.1 Persistent Colour Tunnelling. We added a persistent mode to the colour tunnelling, which means that the tunnel remains but the minimum and maximum values are adjustable for the whole persistent tunnel later. It is conceptually like having two visibility window levels, one for the whole body and one for the persistent tunnel, both being adjustable. This cannot be done with the eraser since the layers are permanently removed and user has less control over it. To switch between the regular and persistent mode of colour tunnelling, user can perform a simultaneous pinch gesture with both hands. Figure 7 demonstrates this feature in MR.

7.1.2 Gesture-related Design Choices for Colour Tunnelling. As described in Section 6.1.1, our first implementation involved a combined gesture to adjust the density range and to position and resize the cursor. In the refined technique, we decoupled density range selection from the cursor control gesture. Density range selection is now invoked by directly tapping on either the lower or upper threshold numbers, followed by hand rotation to change the value. To fix the range at the desired value, the user can tap the same number with the other hand or tap the middle of the index finger with one of their hands. Thus, less actions occur simultaneously and the operations can be carried out by either hand. Figure 7.b and Figure 7.c show this new interaction.

7.1.3 Measurement Tool. This allows the user to measure (potentially non-linear) length across a sequence of control points. A basic measurement tool is proposed by Koller *et al.* [43] for injury examination in VR with controllers. We propose a similar but more sophisticated tool here with different hand gestures. With our tool, a user can add as many control points as they want to create a segmented path through three gestures:

- Index finger+thumb pinch to move control points freely.
- Middle finger+thumb pinch to start a line from the current point or add a new control point to the current line. Additionally, if this gesture is performed on an existing control point, it is less likely that the addition of a new control point was the intended action. Therefore, a dialogue box containing options to *add*, *delete*, *select line* and *cancel* will be shown instead (see Figure 8.b). By default, new control points are added to the most recent segmented path. However, if the *select line* option is chosen, new control points will be added to the selected segmented path.
- Ring finger+thumb pinch to delete a control point.

Figure 8 shows measuring several organs in MR.

7.2 Task-oriented User Study Results

After refining the techniques in the third prototype based on the feedback from the preliminary user study, we conducted another study. P2, P3, P4, P5, and P6 participated in this study. This time, we aimed to examine the use of the measurement tool and our new interactions for the colour tunnelling. In this user study, we selected a real case from VIFM, and asked the participants to measure several body organs and external objects. Therefore, we have obtained two categories of data: qualitative results from the participants' answers to the questions, and the quantitative results from the measurements.[9] Figure 9 shows a preview of the task on the 3D visualised body of a deceased person.

7.2.1 Qualitative Results.

Interaction Techniques. We asked the participants who participated in the previous user study to compare the new interactions for colour tunnelling with the previous one. P2, P3, and P4 found the new set of interactions and gestures more memorable and easier to use at the cost of performance to some extent. P6 found the hand rotation to adjust minimum and maximum values of colour tunnelling very easy and intuitive, while others did not find it intuitive but improved their performances with it. P3 had issues with high physical demanding and embodied interactions. P2 also believes the sequential gestures and previously-known interfaces are more convenient in comparison with simultaneous gestures in the previous version of colour tunnelling. They also found that the transition between temporary and persistent modes of colour tunnelling by pinching with two hands is very intuitive and easy. This participant added that doing a similar segmentation for a specific part of body is possible on computer, however, this mixed-reality system is "*it's one step, and a little bit more streamlined*".

Regarding the measurement tool, all except P6 found it very easy to learn and use, and interactions were intuitive. P6 had some issues in creating control points due to issues in hand tracking, as well as undetected and wrong gestures. P6 and P4 also found the positioning is not always accurate and P6 said

> *When you move the line there's a little bit of delay so when you let go, it's never at exactly the point you want it.*

This is due to thresholds set for each hand gesture to trigger a function. P4 also found usability should be the prime focus of future improvements.

Visualisation. We asked the participants if they can visualise and find the organs injured by the external object (knife). P3, and P5 could not do this task properly. P3 found the contrast for soft tissues or the resolution too low. Only P6 and P4 could do it. P6 found "*The cartilage of the fourth and fifth rib is through the sternum, and it was through the heart*". P4 found "*sternum, ribs and liver*", and P2 found "*sternum and ribs*" but was unsure about the other organs.

In this user study, our focus was on the colour tunnelling as the visualisation technique. Almost all participants appreciated the opportunity to view internal organs while the rest of the body remained intact.

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[9] Further results can be found in our supplementary materials.

Figure 7: Prototype III: Refined colour tunnelling. (a) Persistent mode of colour tunnelling. (b) Tapping on the maximum value with one hand to enable adjustment and rotating the other hand to change the value. (c) Rotating the hand changes the entire tunnel's visibility range (compare the bone in b and c).

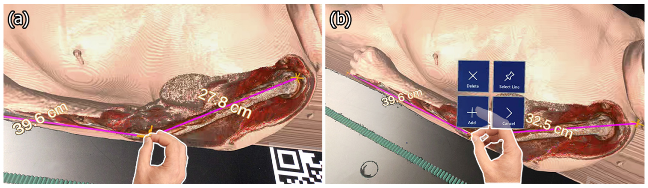

Figure 8: Prototype III: Measurement tool with three control points measures the arm and forearm+hand. (a) Moving control points by grabbing with a pinch gesture. (b) Pinching with the middle finger and thumb on existing control point shows a dialogue box with different available options.

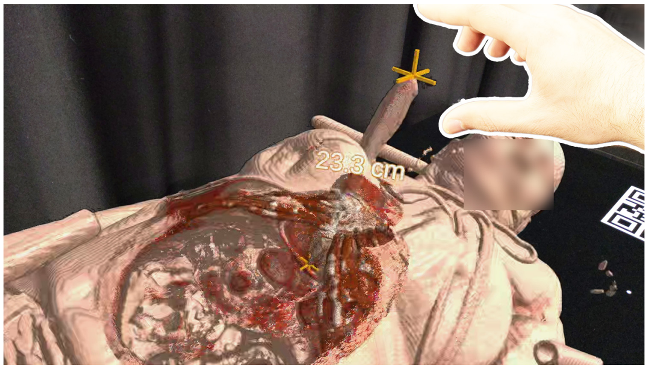

Figure 9: Prototype III, Study 2 task: Measuring the knife's length in MR using persistent colour tunnelling and the measurement tool. Two control points (yellow cross objects) show the two sides of the knife. The number in the middle shows the length in centimetres.

Despite the similarities of eraser and persistent mode of colour tunnelling, P2 found it more useful as they said "*like just permanently removing those layers, and then you can adjust the layers*". Noteworthy, P6 used windowing level to see internal organs but changed the windowing level back to see the whole body and used colour tunnelling instead to look at the injured organs with the knife. P6 reasoned

> *I've felt that if I do this [changing windowing level] then I'm going to lose a lot of structures … so now I know all the soft tissues are there because they're all visible and then with the colour tunnelling I can look more specifically.*

We can mention "*better perception of the 3D organs with real dimensions*", "*depth perception with stereoscopic view*", and "*ability to walk around the 3D visualised body*", as the most appreciated benefits of 3D immersive visualisation of medical data for forensic practitioners. There are downsides to this visualisation as well, specifically addressed by P6; "*Smoothing filter on the data and the removal of details*", "*the translucent organs*", and "*lack of proper separation between the heart, lungs, and liver, which have relatively the same radiodensity*". These, however, pertain to volume rendering itself and not mixed-reality.

Interpretability in Measures. Participants had different interpretations on how to measure organs or the location of the injury. For example, to measure the size of the whole person, some of the participants measured from the top of the head to toes, and some to the left heel. For the location of the injury, we asked them to measure the length to the anatomical landmarks, some considered the shoulder, some above the head, some left or right heel as the anatomical landmarks. This resulted in different numbers we discuss in the quantitative result (Section 7.2.2).

User Interface. Although the majority of the participants had no previous experience with immersive technologies, interaction with the user interface appeared intuitive to them without training. Yet, they reported having some issues. The biggest one was the amount of pressing a virtual button to trigger an action. The other issue with the user interface was that they wanted to press the buttons from a distance that was not reachable, which is due to several reasons including the difficulty in estimating the distance, preference to move less, as well as some of them expected to be able to click from a distance. The other issue was that they sometimes forgot where they placed the menu or where a certain tool was located in the immersive environment. The narrow field of view of the Hololens plays a significant role in losing track of position of objects in MR. A participant mentioned it may be easier to select tools with voice commands.

VR/MR Comparison. The participants had more positive thoughts about using mixed-reality than with virtual reality; "*Interacting with the surrounding environment and not encountering obstacles*", " *being practical in the workplace*", "*talking and interacting with other people in collaborative activities*", "*3D visualisation of CT data next to the real body*", and "*preventing VR sickness and dizziness*" are among the advantages of mixed-reality compared to virtual reality. However, the "*narrow field of view*" from P2, and the need to be "*in a quiet room otherwise it will be very distracting*" from P6's point of view were the disadvantages of MR compared to VR.

Use Cases. In terms of performing autopsies digitally or physically in the mortuary, forensic practitioners appreciated and prefer to examine cases without performing real autopsies as much as possible. There is a high benefit in terms of performance as well as reducing ethical and cultural considerations of autopsies. They also found our immersive prototype very useful for measurement, accessing analysis tools in the mortuary, recording and accessing documentations. Our prototype was thus more flexible: "*It's got a lot of flexibility on where you do your analysis*", "*You can do it anywhere, and you can talk about it with anyone*" (P2).

In comparison with their traditional tools on desktop computers, there seems to be benefits and drawbacks. On the one hand, having mobility and flexibility of accessing data anywhere, walking around the 3D data, and using free-hand gesture interfaces instead a 2D mouse and keyboard to interact with the system while gloved, are some clear advantages. On the other hand, mixed-reality requires more physical movements, needs more space for visualising data in the environment, and the low resolution offered by current hardware are clear limitations.

Now that the forensic practitioners have been able to see and interact in mixed-reality, we were curious to see if they thought that digital autopsy could completely replace conventional autopsy in the future. There were different opinions in this regard. They see the potential of being used more in their daily task to some degree including to "*walk the jury through a 3d and show them*" which is currently impossible. Nevertheless, they expressed on the possibilities that imaging technologies could provide them a complete picture on all cases. Indeed, P6 specifically mentioned "*Fluids, types of fluids, you can't do histology, you can't really dissect from an anatomical perspective, so you can't take muscles apart from each other or look between the layers of the skin*". Yet P6 believe digital autopsy can be really useful for remote autopsy and in biohazardous situations even at this stage.

Ideas from Experts. One asked the possibility of more precise measurements on CT instead of a 3D object in the mixed-reality environment, or a combination of these 2D and 3D would be beneficial. Another idea was the recording and reporting on cases in real time, and being able to capture images and text together in a file. The idea of developing a digital twin of deceased person that its organ and tissues react realistically to their touch/interaction was also suggested.

7.2.2 Quantitative Results. Although each person's interpretation of the boundary of some organs is different and the accuracy of using these tools cannot be obtained based on the measured numbers, we still wanted to see if these tools can be used for measurement and whether the results are close to each other. In Figure 10, the base-line is the average of length from all participants. P3 could not measure the injury location to the left heel and the right of midline due to their limited time. P6 reported 13.4 to 14.2 cm for the length of knife penetration, because the injury is big and depends on where one considers the entry of the knife. We used the average (13.8 cm) in this chart.

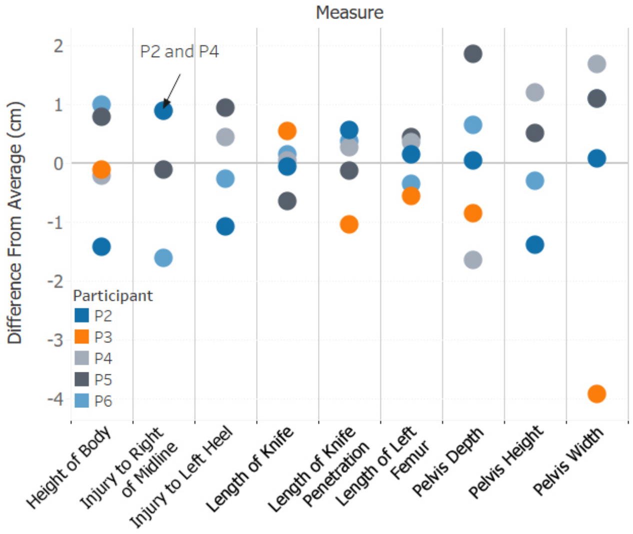

Figure 10: Measurement comparison between all participants. The base-line is the average of each measure. The average length for each measure (in centimetre) from left to right is 171.2, 3.1, 124.0, 23.6, 13.4, 44.5, 18.8, 14.6, 25.9 respectively.

8 DISCUSSION

Throughout the four phases of our user-centred design, we have collected feedback, results and observations on how users of forensic imaging data could use a 3D immersive platform to investigate the cause of death. In the following we discuss the findings we made after analysing this set of complex results, usability issues, and some lessons we learned on our methodology.

8.1 Findings

The results of our studies indicate both opportunities and challenges of MR for digital autopsy, as follows:

3D immersive visualisation in mixed-reality has potential to investigate cause of death. MR technology provides a large 3D space for visualisation, stereoscopic view and motion parallax, and intuitive navigation by body and head movement. In this space, forensic users are able to visualise the whole body in real dimensions, walk around the body, and analyse the 3D data which provides more realistic environment for forensic analysis and educational purposes in comparison to 2D software applications. Moreover, the spatial awareness provided by the Hololens enhances navigation as the physical world serves as visual landmarks, making it easier to locate virtual objects in 3D space. There is also a distinct advantage of immersive visualisation in comparison to 2D applications: there is no gap between input and output system since both hand movements and data visualisation occurs in a physical-virtual environment. Immersive visualisation and hand gestures provide an opportunity to resemble similar physical processes with the digital data. As a result, it is easy to use and intuitive, promoting engagement with the data and using complementary analytical tools. In the second user study, while forensic practitioners had basic training in a limited time, and little to no experience with immersive technologies, they were able to accomplish their assigned tasks satisfactorily within a reasonable amount of time. Although we did not ask the participants to perform the tasks as fast as possible, therefore a valid quantitative comparison is not possible, they did most of the length measurements in less than 30 seconds each.

The embodied interaction metaphors are well suited to the forensic activity and understandable by the experts. As mentioned in Section 2.1, embodied interaction is essential in mixed-reality applications to increase performance and intuitiveness. Our prototypes were designed with embodied interaction in mind; we leveraged interaction metaphors for 3D exploration of medical images (e.g., digging tunnels or boring transient holes with the users' hands, rotating hands to adjust the visibility windows, rubbing with an eraser to remove 3D visualised data). According to our results and observations, we conclude that those interactions are easily recognised by the users and do not require a too steep learning curve. According to participants' feedback, the techniques well matched with the forensic autopsy settings and was considered a "*digital dissection*" most probably because of embodied interaction. In addition, embodied interactions reduce the number of virtual menus and buttons in a mixed-reality environment, which makes the virtual environment less distracting. This finding echoes past research on the benefit of embodied interaction to investigate spatial data [10, 25, 26]

However, as we stated in the design of the third prototype based on the feedback from the first user study, a balance should be established in the use of embodied interactions, otherwise it will increase the complexity of the system, user confusion, and likely reduce the chances of the system to be adopted, thus confirming past research results on the potential of virtual environment to integrate in experts' workflows [31, 74, 75].

Mixed-reality can further be used as a teaching tool. The participants widely recognised the application of MR for teaching purposes. This technology is capable of delivering a more realistic simulation of an autopsy operation than the tools they currently use. Interacting with the 3D representation of medical imaging data also enhances the anatomical and procedural perception and understanding for forensic students. This highlight further the already postulated potential of (embodied) interactive systems as education tools [38, 69, 79, 80].

Mixed-reality brings flexibility and mobility to the forensic autopsy workflow. A major benefit of MR in the forensic autopsy workflow is the mobility and flexibility of where the data is accessed and analysed. MR headsets are gradually becoming lighter, making them more like eyeglasses that can be carried everywhere. Free-hand gesture interfaces in MR also provide more flexibility to workplaces such as a mortuary. Because of these factors, it is compatible with a variety of situations without the need to switch between devices and can augment the current workspace of experts, mimicking past findings from different domains [74]. P2 emphasised that mixed-reality has "*got a lot of flexibility on where you do your analysis*". However, there were contrasting opinions about where the mixed-reality platform can be most effective. P2, P4 said "*mortuary*" for its free-hand gesture interface which is consistent with other studies' findings as well[1, 15], P1 said it is more useful in "*office*" for pre-planning purposes, however, P1 and P4 found its application for "*demonstration to colleagues and in court*", and P3 found it "*more useful for teaching*". All these comments highlight the flexibility of using this technology in different settings. We can postulate that a clearer workflow integration should emerge with more practice or wider adoption.

Mixed-reality tools can foster more reproducible autopsies/analyses. Our observations and results from the task-oriented user study indicate that the anatomical measurements can be interpreted to some extent and are ultimately reported as only words and numbers. Technology can improve this procedure even though it is presently an accepted procedure in forensic medicine. Through mixed-reality technology, forensic practitioners are able to visualise measurements on a 3D model in mixed-reality while taking measurements on a real person's body or the CT data, thus eliminating or minimising interpretability issues and fostering greater reproducibility of results. While we have not used a real body for the measurement task in this experiment, it is not difficult to conclude that mixed-reality technology could easily be used to accomplish the same operation on the real body. In the era of reproducibility as major concern for many scientific fields [3, 21], this property of immersive autopsies is certainly a major advantage.

Real Autopsy vs. MR Digital Autopsy. Currently, mixed-reality technology cannot replace a real autopsy. In a real autopsy, forensic practitioners are able to see tissues' colour and material, feel tissues' texture, smell them, cut them to see through different layers, and even take samples for more examination in specialised laboratories. This is currently not possible with mixed-reality technology while some attempts show promising opportunities [5]. However, this technology offers several advantages that are impossible or very difficult in a real autopsy. Among these benefits are the following: quick examination of deep parts of a body, using different transfer functions (colour mapping) to hide or to highlight some parts of the body, digital autopsy can be done remotely, unlimited examinations without damaging the data or the body, no risk of contamination or exposure for the practitioner, more accessible and cost-effective way of teaching, and less ethical and cultural issues.

8.2 Usability Issues

We used the Microsoft Hololens 2, which is the best device we have so far to implement prototypes for mixed-reality digital autopsy. However the technology is not perfect, and some of our results might indicate challenges in usability. Most criticism can be traced back to the Hololens 2 itself; narrow field of view, hand-tracking issues, display resolution, etc. Some of these technological limitations of the device led to more usability problems. For instance, the inaccurate hand-tracking of the Hololens caused hand-tracking errors and frustration. However our study shows that applying embodied interactions and their designs are valid for forensic practitioners, as they were able to achieve tasks representatives of their work.

In terms of the quality of 3D visualised images, P6 said "*lack of proper separation between the heart, lungs, and liver*", and other participants addressed this issue as "*low contrast*". The problem of perception of translucent images exists in all volume rendering applications despite many efforts to resolve this issue with complementary techniques [14, 30, 57]. Volume rendering displays all of the volumetric data, but generates translucent images [27].The alternative technique, surface rendering, is not suitable for medical images, due to removing many parts of data and needs sophisticated, intelligent segmentation algorithms. It can be worse in forensic cases whereas the body is intensively deformed. On the other hand, CT imaging does not distinguish soft tissues well, which causes lack of contrast between different organs in visualised images. Therefore, although volume rendering helps locating the organs of interest and accelerates analysis, we still suffer from lack of contrast. When MRI imaging is introduced to the system, with its far better differentiation of soft tissues, we expect to resolve this issue.

8.3 Lessons Learned on the Methodology

Designing novel immersive interfaces for 3D imaging data visualisation and analysis is not yet well understood and documented. At multiple points in our user-centred design process, we expanded our knowledge of domain expert user requirements (Phase 1 and 2), but in the second and third prototype we built an interactive solution based on state-of-the-art techniques not known to users. This highlights the problem of co-designing mixed-reality applications at this point in time; participants with no knowledge and expertise in extended reality (XR, i.e., MR, AR, VR) will not necessarily contribute in effective ways to solve their problems. This is a problem encountered in other XR design fields, though efforts exist to normalize the design process of immersive applications [60].

Our methodology aimed to reduce the technological gap between users and the capabilities of immersive environments. While validating that our design process is more efficient than other user-centred approaches is out of the scope of this paper, we feel we have had success developing a functional immersive prototype with our method.[10]

9 LIMITATIONS

We acknowledge that various limitations have influenced our results. In terms of hardware, we have developed the system for the Microsoft Hololens 2. Other MR devices such as video pass-through AR headsets with wider field-of-view or light-weight optical see-through glasses could have been considered. However, the Hololens 2 is currently the best trade-off in terms of computing power, freedom of movement and bulkiness.

We also worked with a limited number of participants, which is due to the highly specific nature of forensic medicine practice. However, the participants involved in this research belonged to the same institute and represented a significant portion of the forensic workforce within the institute and the country (more than 10 percent of the forensic specialist workforce in Australia). Furthermore, it is conventional for HCI studies focusing on domain experts to present with a sample size similar to ours (see e.g., [8, 11, 51, 59, 74]), as shown in analysis of past CHI research [18]. Hence we believe our results, while limited by the number of participants, still contribute new insight for this activity. Due to the participants' limited time, we were not able to explore many aspects of our prototypes in depth. Furthermore, training time was limited, which possibly affected the practitioners' experience. However, we ran a follow up study with three participants from the previous round (five in total) which mitigated limited learning, and allowed us to gain deeper information about embodied interaction to explore cause of death.

10 CONCLUSION

In this research, we explored how forensic practitioners could benefit from an immersive, embodied visualisation of CT images to practise digital autopsies and help forensic experts find causes of death. This area, to the best of our knowledge, has been the focus of only a marginal amount of research work. We developed a mixed-reality system informed by a series of interviews, a workshop and iterative prototype evaluations. Our design exploration resulted in prototypes that were validated by forensic practitioners for medical imaging analysis tasks. Our prototypes were implemented on the Hololens 2, which is subject to the limitations of current display and tracking technology. We believe this research contributes to the early exploration of the design of advanced embodied, mixed-reality visualisation systems for practical applications, and provides useful insights on the user-centred design approach used to elicit the design of such systems.

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