Design and Development of a Mixed Reality Acupuncture Training System

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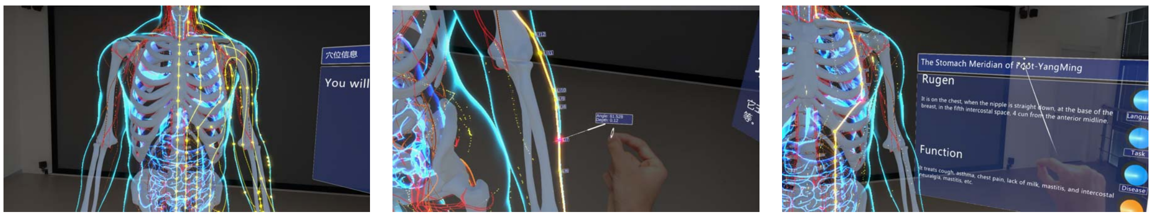

(a) (b) (c)

Figure 1: The interface interactions designed and developed for the acupuncture training prototype. **a)** The visualization of acu-points and channels distribution on modelled human body. **b)** Our hand tracking and pose estimation technique mimics the way the practitioners hold their acupunture needle in the real world. Small widgets are used to visualize the labelled points, selected meridian and the accuracy of a needle placement. **c)** the manipulation of the hologram window to navigate the acupuncture information.

Abstract

This paper looks at how mixed reality can be used for the improvement and enhancement of Chinese acupuncture practice through the introduction of an acupuncture training simulator. A prototype system developed for our study allows practitioners to insert virtual needles using their bare hands into a full-scale 3D representation of the human body with labelled acupuncture points. This provides them with a safe and natural environment to develop their acupuncture skills simulating the actual physical process of acupuncture. It also helps them to develop their muscle memory for acupuncture and better develops their memory of acupuncture points through a more immersive learning experience. We describe some of the design decisions and technical challenges overcome in the development of our system. We also present the results of a comparative user evaluation with potential users aimed at assessing the viability of such a mixed reality system being used as part of their training and development. The results of our evaluation reveal the training system outperformed in the enhancement of spatial understanding as well as improved learning and dexterity in acupuncture practice. These results go some way to demonstrating the potential of mixed reality for improving practice in therapeutic medicine.

Index Terms: Mixed reality—immersive technologies—virtual environments—; Chinese acupuncture—Medical education

1 Introduction

As technology advances, with affordable computational devices having ever faster processor speeds and improved graphical capabilities, various types of extended reality (XR) including virtual reality (VR), augmented reality (AR) and mixed reality (MR) are being increasingly applied in clinical medicine and medical training [34, 40, 50]. This paper looks at how mixed reality can be effectively applied in the Chinese traditional medicine practice of acupuncture.

Chinese traditional medicine is one of the world's oldest established systems of medicine based on a 2,000-year-old tradition and used by over two and a half billion people in one form or another. Acupuncture is considered to be one of the key components of Chinese traditional medicine. It involves the insertion of needles or pins onto the "acu-points" on the human body based on the postulation of Chinese ancient philosophy that the *qi* (or energy) flows between bones and muscles in pathways [3].

It can take a considerable number of years for a practitioner to be trained to become a clinical acupuncturist. This is due to the complexity and necessary expertise required of the discipline [65]. The traditional training system can also be expensive, requiring the use of a large number of needles that need to be replaced after each session. The training of acupuncture experts can be costly and time-consuming. This paper proposes a novel prototype which uses mixed-reality technology for acupuncture training and practice. Mixed-reality allows users to interact with virtual information with physical objects at same time, which is more suitable and intuitive for training acupuncture on treatment of various symptoms.

In this study, we aim to improve the effectiveness and efficiency of acupuncture training by providing a more natural way of interaction for needling practice. The paper is structured as follows. We begin by discussing the use of XR technologies used in the medical field, with a focus on state-of-art methods for acupuncture and needle insertion. We then outline the requirements for a simulation system and propose the design choices. We then introduce our mixed-reality acupuncture simulation system(Fig. 1) and present the results of a user study conducted to evaluate the usability of the training system in Chinese acupuncture training.

2 Related Work

XR simulations are considered as powerful and efficient tools used in education and training. They allow learners practice a task repeatedly in a safe and immersive virtual environment without the need for special equipment or a controlled environment [50]. Although there are a number of XR applications/simulators developed for medical training and clinic medicine, only few systems have been designed

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for the practice of Chinese acupuncture using augmented-reality technology. Jiang et al. [35] recently introduced a system to map the acupuncture points which uses an augmented-reality approach. These existing AR applications are different from our system in that they do not provide a direct interaction between the physical and computer-generated worlds, neither enhanced and visualized pathological manifestations. Our system implements the concept of a mixed-reality based training system using Microsoft Hololens2 offering a variety of direct interactions and functions in an immersive blended environment.

According to the statistics provided by Viglialoro et al. [60], only about 9% of research work has employed a mixed-reality approach in building simulators. The choice of a mixed reality implementation for our acupuncture training system can be regarded as the most appropriate technology for this application. It also helps inform future developments using this technology. None-the-less, as XR technologies have many similarities in how they are designed and implemented, it was necessary to look at a variety of XR technologies (including AR and VR) when preparing for this project.

2.1 VR/AR/MR in Medical Training

As the original type of XR technology, Virtual Reality (VR) technology offers completely artificial computer-generated 3D content for users to interact with [37]. For example, Falah et al. [9] designed a medical training system based on VR technology for anatomy education. Through the study, they found that the immersive 3D environment has a positive effect in the medical training. The role of VR in surgical simulation has increased in recent years due to inherent inefficiency, high cost and safety issues associated with surgery in the real world [67]. A classic example is the LapSim [2] simulation which utilizes a virtual environment and medical models with haptic feedback to allow for training in laparoscopy.

The majority of VR-based training systems offer rich visualization and different ways to interact utilizing a variety of functions and interface techniques. They are, however, less effective for simulation tasks that require strong perceptual skills. They can suffer due to low fidelity of the way of interactions with virtual objects and insufficient visual feedback.

Augmented and Mixed Reality technologies are making an increasing contribution to the development of technology-driven modern medicine. There are a number of existing applications that have been shown to significantly benefit medical training and practice [1, 14, 57, 66]. For example, PalpSim [14] allows practitioners to see their actual hands while palpating virtual patients with virtual needles in needle insertion practice, in contrast to full immersion in 3D environment of VR approach; Abhari et al. [1] proposes an augmented-reality system to optimize surgical planning of brain tumour resection interventions. The system provides intuitive visualization for practitioners to gain spatial understanding and cognitive ability, though it fails to offer adequate interactions and functions for users to practice. These applications demonstrate that the adoption of mixed-reality technology can be effective in improvement of precision and accessibility for training in medicine. However, lack of interaction and feedback in depth and the high cost of the hardware and equipment is identified as a limitation of these types of application.

2.2 VR/AR/MR in Acupuncture and Needling

Liao et.al. [41], Cao et al. [12] and Liu et al. [47] have developed PC-based virtual acupuncture training simulators that simulate primary acupuncture techniques through the use of a mouse and keyboard. However, a major drawback of these systems is the lack of immersion and user interactions. In an effort to improve the user experience, researchers [62] have proposed a VR-based acupuncture training system that incorporates the concept of ”know-how”. This system allows for visualization of acupuncture points, meridian distribution, and anatomical structures, and facilitates navigation in 3D volumes to enhance conceptual understanding through synchronous learning. It would be interesting to see how this system improves training for practical puncturing skills.

Many existing VR and AR simulators [27, 31, 52, 54] for needle insertion and syringe use pre-defined and pre-interpreted values instead of real-time data to display the correct insertion intensity, angle, and acupuncture methods for learning reference. However, these technologies have limitations as they fail to collect and visualize real-time insertion data (i.e. needle’s depth and angle) for analysis, which is an important element for training. Additionally, none of the simulators visualize internal anatomical layers such as blood vessels, nerves, and meridian distributions, making it impossible to determine if the layers are being penetrated during the operation. They also do not provide real-time visual effects of energy flow and organ feedback.

To enhance users’ haptic perception in acupuncture simulation, Heng et al. [29, 30] proposed a simulation system that integrates VR and haptic devices (such as touch and omega). Similarly, haptic gloves are used in other work [69] for haptic perception. However, the use of haptic devices is not always appropriate and is generally limited by cost, unnatural experience, and operating space. Other studies, such as [56], have overlaid virtual objects on physical mannequins for insertion practice, but the main issue with using passive materials for haptic feedback is that they can wear out over time [15, 18] after repetitive practice, which can impact the accuracy of haptic simulation.

These works have been evaluated through comparative user studies. Researchers [62] have evaluated the effectiveness of the simulator by comparing the learning outcome of the students who used it to a control group that learned using PPTs. The work presented initial findings that the application of VR acupuncture simulator can increase students’ motivation to learn, and improve their comprehensive understanding in acupuncture operation. Previous studies, such as [54] and [70], have employed hand-held controllers (e.g. HTC VIVE and Quest) for simulating needle insertion practice. A comparative study was conducted between a therapy simulation group and a non-VR group (i.e. those who learned from textbooks and in-class teaching). The conclusion was that the use of game controllers or devices may not always be effective in improving needling dexterity due to the lack of realistic interaction experience.

Although many simulators have been proposed in surgical and acupuncture training, most of them [14, 30, 35, 36, 43, 68] have employed tangible interaction techniques that are relying on some tangible objects, such as electromagnetic (EMC) sticks and hand-held controllers, to mimic the needle placement. These approaches may lead to an unnatural experience for learners, potentially impacting their understanding and retention of knowledge. Our project aims to improve this by proposing a more natural method of interaction, using AR technologies to visualize the position and orientation of the virtual needle, and using bare fingers for virtual needle insertion practice. Additionally, our simulation includes dynamic and realistic anatomical structures and layers to show energy flow in real-time, increasing the realism and immersion of the simulation. The ultimate goal is to enhance the effectiveness and efficiency of acupuncture training.

2.3 Pinch Interaction

One of the significant elements in 3D interface design among the Human-Computer Interaction (HCI) community is how to create a natural form of the interaction which effectively simulates corresponding real world actions and tasks [23]. Researchers who studied aspects of interface interaction such as naturalism and fidelity [6, 24, 39] suggested a high level of closeness that the virtual objects relate to the actions used in real world as this improves the users’ practical skills and overall experience and performance.

Task Domain	Task Details
Medical theory	Familiarization with anatomy and physiology;
Acupuncture theory	Understanding of the principles and concepts of traditional Chinese medicine (TCM) and channel theory
Needle insertion techniques	The use of acupuncture needles including insertion and removal
Indications	Familiarity with indications and treatment plans

Table 1: The fundamental tasks of Chinese acupuncture.

The authors [32] used finger interaction by tracking on the thumb and index finger to manipulate AR content on a board game. Similarly, recent research [5, 7, 25] demonstrated the effectiveness and realism of designing and implementing a natural hand or finger interaction with virtual objects in a simulated environment. McMahan et al. [10] also in their comparative study concluded that it is more natural to interact objects with direct hand manipulation than the controllers or data devices. Panzoli et al. [46] and Du et al. [20] argued that utilizing hand-held controllers or other abstract interactions leads to an unnatural experience of performing acupuncture, and they also stated the bare-hand interaction can be used to effectively deepen the naturalness and authenticity of handling a needle.

3 System Design

3.1 System Requirements

The report published by the World Health Organization at 1999 [44] states that proper needling techniques, including depth, duration, manipulation, withdrawal, and contraindications, requires significant practice. Acupuncture practice involves both explicit knowledge, such as understanding what acupuncture is, and implicit knowledge, which is gained through hands-on experience [19]. Currently, a common approach for acupuncture training is for students to practice needling techniques on themselves and their classmates, as a traditional method. This approach is often used due to limited teaching resources. However, it poses potential risks to the health and safety of both the students and their classmates.

We list the most fundamental tasks which are required in the acupuncture learning and training in Table 1. We now explain some of these tasks in more details. Acupuncture training requires practitioners to have a good mastery of the theory of traditional Chinese Medicine (TCM) including the concepts of qi (energy) and meridians/channels (pathways through which qi flows in the body). The memorization of acu-points location, names and their indications plays a crucial role in acupuncture learning. Another significant part in training is the proficiency in the use of needling techniques such as insertion and removal. Mastering the correct depth and angle of insertion in acupuncture requires extensive practice. To aid in this training, our system should support learners in remembering acupuncture point locations and practicing needling techniques.

3.2 Design Choices

In the design of our system, we aim to achieve a balance of several complementary objectives through the use of appropriate visualization and interaction techniques. Our objectives include:

O1: visualizing anatomical representations
O2: manipulating the needles in an intuitive and natural way
O3: visualizing sensational manifestation

The first objective (O1) is to customize the virtual human assets to suit the needs of acupuncture training specifically. We aim to create realistic 3D models of anatomical layers (i.e. skin, blood vessels, nerves), acupuncture points and pathways using 3D modelling software such as Blender [8] and Zbrush [48]. Additionally, we plan to provide optimized virtual models in the simulator by employing the retopology technique of modelling, which reduces computational cost without compromising rendering quality.

Our second objective (O2) is to enable learners to manipulate the needles in an intuitive and natural way. We believe that finger/pinch interaction is the most suitable technique for this purpose, as it closely mimics the way acupuncturists manipulate needles in a clinical setting. This approach is supported by research on the use of finger gestures in mixed reality headsets such as Microsoft Hololens2, and by the observation that acupuncturists use their thumb, index and middle fingers to hold and move needles during treatment. By providing a safe and controlled environment for acupuncture training, our prototype aims to enhance interactions and visualizations, merge simulated and physical environments, and improve object tracking and spatial understanding.

Our third objective (O3) is to provide a dynamic and effective visualization of the sensation and energy flow in pathways in real-time. We plan to use code-controlled methods such as Shaders and animations in a game engine (like Unity) to create customized visual effects that simulate immediate feedback. This approach can effectively enhance practitioners' conceptual understanding of the physiological and energetic effects of acupuncture needling.

4 Mixed Reality Acupuncture Training System

The design of the training system is inspired by previous research work presented in [14, 55, 66]. This section describes three types of functions in our design (a) modelling and visualization, (b) virtual needling and interactions, and (c) visualization widgets and visual feedback.

4.1 Modelling and Visualization

4.1.1 Anatomy Model

Although there are a number of out-of-the-box virtual human assets we could use, we chose to build our own models for implementation to make customized representations for acupuncture practice. The anatomy model (Fig. 3) was developed and optimized by Blender [8], DAZ studio [16] and Zbrush [48] which includes a real size human body, bones, skin, zang-fu (visceral organs), and cardiovascular and nerve systems in a 3D context. The multi-layer structure(Fig. 3(a)) was built to enhance the visualization of simulated physiological sensation caused by needle placement.

The virtual bones and visceral organs were sculpted in Zbrush and then exported to Blender for geometry remeshing and topology to obtain more reliable performance of collision for later use. We also fine-tuned the shaders(a series of codes executed on GPU for rendering) designed for the models to achieve the best rendering performance in Microsoft Hololens2. The modelling of outer skin was constructed by DAZ Studio and Blender to become aesthetically pleasing and anatomically accurate at the same time.

In contrast to the above structure modelling work, we used spline tool offered in Blender alone to create the cardiovascular and nerve systems. We then optimized the models with the use of one of the remeshing techniques that is *even-numbered de-subdivisions* to make them usable in the game engine.

4.1.2 Acupuncture Needle, Points and Channel Distribution

The system aims to make a high fidelity of simulation for acupuncturing, therefore the locations of computer-generated acu-points and channels/pathways distribution have to be consistent with the ones on physical body. The design of the entire pathways and points was strictly referred to a physical acupuncture model (Fig. 2) and authorized materials [55] used by the medical practitioners to ensure the accuracy and consistency. 14 channels and 361 points (symmetrical

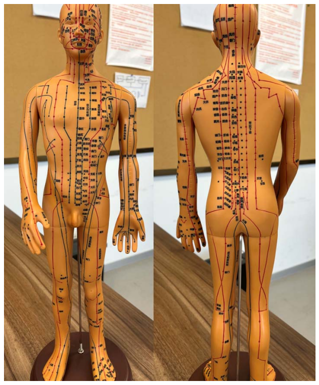


Figure 2: Physical model reflected on acupuncture points used by acupuncturists and practitioners.

distribution) were constructed on a full-scale human body (Fig. 3(b)) model in a clear and intuitive way, which were optimized to 63,060 meshes using retopology. The 3D virtual needle for acupuncture was constructed to 110mm as same length as a standard one in the real world, which consists of three segments: needle tip, needle body and needle shaft/handle (Fig. 3(c)).

All of meshes of the models we built in the working scene have been retopologized from triangles to quads for a more flexible geometry refinement [9] and better rendering performance. We used three classical retopology methods (RM) for model optimization: *manual*, *un-subdivide for even number of times* and *merge vertices by minimum distance*. This design contributes significantly to later interactions and functions development. The total number of meshes (faces) is reduced to 1 million in contrast to 6 million before the optimization. A comparative study has been conducted between our modelling work and a world leading commercial VR anatomy product called 3D Organon VR Anatomy [42] regarding the meshing. The results can be found in the Appendix.

4.2 Virtual Needling and Interactions

4.2.1 Game Engine and Device Setup

Unity3D [61, 64], as a cross-platform game engine was used for prototyping and further implementation in this project. The models described in Section 3.1, were imported to Unity3D where the virtual environment and programming interfaces and visual elements were created. C# has been utilized for programming, under Unity3D environment, to build necessary real-time functions and behaviours for our prototype. Microsoft HoloLens2 was used as the MR display facility for the system implementation. Microsoft's Mixed Reality Toolkit (MRTK) provides seamless integration between HoloLens and Unity3D. It brings with a number of useful components and features to work on for the design of interactions. The headset runs the Holographic Processing Unit (HPU 2.0) to process all the computer vision algorithms [38], and the device is equipped with several sensor units such as RGBD, IMU and gray-scale cameras.

In this project, we've used hand tracking technique to estimate the hand pose and update camera's current position in order to capture the motion of moving objects in real-time. This technique allows compelling interactions and is able to enhance the spatial relations between the holograms and real environment in contrast to traditional modality of projection of 3D models and navigation.

4.2.2 Needling Interaction

We use direct pinch needle manipulation (Fig. 4) to mimic the way of performing a needle insertion in real world. This technique allows users being able to see through their bare hands manipulating directly with virtual content with no need to familiarize themselves with the hardware beforehand. The modelled needles spawn on the top of virtual workbench for use when the application is launched.

To apply a needle placement, users hold the virtual needle using pinch interaction and insert it into a labelled point located on its meridian. The direction, angle and the depth of the insertion can be refined and adjusted as many times as they want during the process to keep away from nerves, blood vessels and bones. The system provides a visual indication when the needle has made successful contact, and the effect disappears when the needle is removed. Additionally, we have fine-tuned the refreshing rate of rendered graphics in HoloLens through parameter optimization to maximally reduce the system lag caused by hand tracking.

Selecting meridians/channels is done through touch/button interaction on the targeted area. Pressing with one finger on the 3D visualization of the human body will display the selected channel, as visual effects transition from off to on (Fig. 1(a)).

4.2.3 Insertion Accuracy

In this section, we discuss a collision method that was used to determine the angle and depth effectiveness of virtual needle insertion on a specific acu-point as shown in the Table 2. Colliders [28] were utilized for simulating the collision units associated with the Rigibody component in Unity3D, which can provide constraints on models and triggers mechanism.

The Algorithm was developed based on the crosscutting interface model of the insert point and skin (see Fig. 5) to gauge the depth and angle of a needle insertion. C_N denotes the input collider applied to the front red part of the needle; Area O refers to the outside layer of the acu-point and Area T, Area I, Area D refer to the inside layers. The algorithm first calculates if the virtual needle has collided with Area O properly - the insertion is considered as effective practice only if the collisions with the Area O and one of the other areas are detected. The three areas indicate three levels of depth resulted from needling, where Area T denotes as *shallow*, Area I the *middle*, and Area D represents *deep*. Volume of the three areas varies on different acu-points. In addition, we calculated the angle (AN_N) from tangent at a point to the needle collider and recorded the data for later analysis.

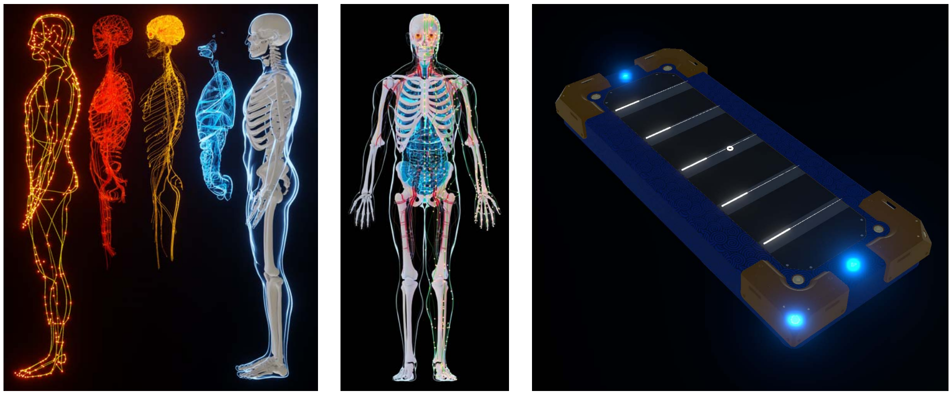
4.3 Visualization Widgets and Visual Feedback

The system is expected to be effective and accessible as a technology aid for learners to acquire skills and knowledge for Chinese acupuncture. To better deliver user experience interacting with our system, we aim to design the system that provides necessary tools and user interfaces to make the simulation as intuitive and instructive as possible. In the following, we address a number of functions and features regarding control interfaces and post-processing effects.

4.3.1 UI Elements

A rich user interface has been exploited that provided 3D visual aids including images, buttons, text and tracked 3D objects to visualize the knowledge of functions of each point and channel on human body. Since UI for holographic is illustrated in 3D, the design has to be different from tradition applications in 2D, where more dynamic elements and information can be demonstrated in small space areas. Those visual elements can be categorized based on their properties, and on their display space (display-anchored, feature-anchored). The location of a display anchored object is defined with respect to 2D screen coordinates.

We create a hand menu and a control panel for users to *1)* reposition the human model and needle workbench; *2)* navigate the settings and tools during interaction. The control panel (Fig. 6) includes a language setting, a panel for simulated tasks, knowledge base and needle reset. Our system provides bilingual service to enable switching between Chinese and English. We build the window-style



(a) (b) (c)

Figure 3: The structure of multi-layers built for the model: (a) the modelling of the blood vessels, nerves, bones and meridians etc., (b) the visualization of the anatomy model with distributed meridians, and (c) the virtual needles constructed for performing the acupuncture tasks.

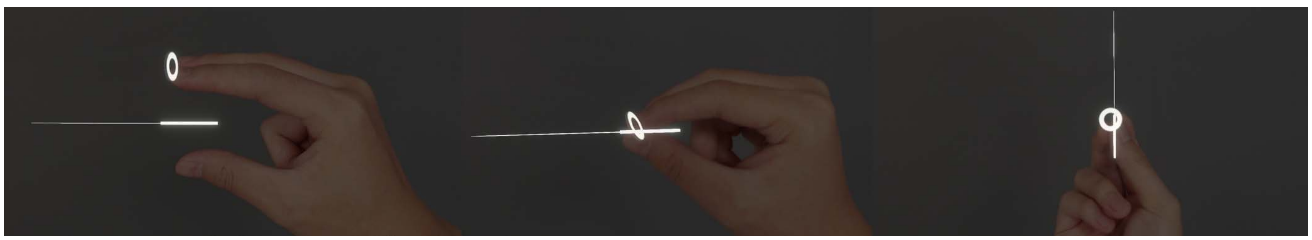


Figure 4: Direct finger interaction with a virtual acupuncture needle. The first left and the middle images describe a natural way to interact with the needle as similar as it would be hold in the real world. The first right image shows the motion tracking and hand pose estimation.

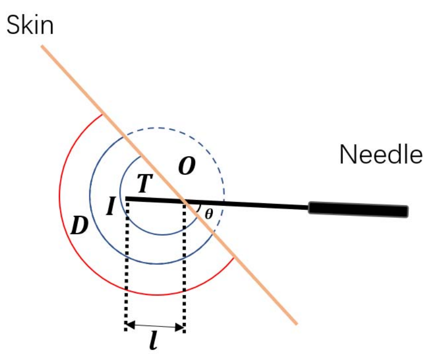


Figure 5: The crosscutting interface model of the effectiveness detection mechanism.

Algorithm of Needling Effectiveness Evaluation	
Input:	Needle Collider C_N
Output:	Needle Angle AN_N, Needle Effectiveness EF_N, Needle Depth DP_N
1:	b_1 = CollideAreaO(C_N);
2:	if not b_1, end; else, to 3.;
3:	b_2 = CollideAreaT(C_N);
4:	b_3 = CollideAreaI(C_N);
5:	b_4 = CollideAreaD(C_N);
6:	if not b_2, end; else, to 7.;
7:	$AN_N = \theta$;
8:	$DP_N = l$;
9:	if not b_3, EF_N = Weak, EF_N = Weak,end; else, to 9.;
10:	if not b_4, EF_N = Middle, end; else, EF_N = Strong, end;

Table 2: The Algorithm used for measuring the insertion accuracy in depth and angle factors.

controls for displaying text and images from knowledge base to allow users navigate acupuncture-related information.

User interface for indicating the current angle and depth of insertion applied is also developed for users to monitor their status. It is positioned right next to the targeted point during needling. The window to be hovering in front of the users is possible despite the needled orientation.

4.3.2 Visual Effects

The "sensational" manifestations on visceral organs resulting from a needle application are visualized by adding programmed shaders under universal render pipeline to change the colors and materials of the models (Fig. 7). The skin of the whole body is rendered in the mode of transparency so as to reveal the energy flow in the underlying pathways and nerve system. Additionally, we create animations with code-controlling displacement for the dynamic display of interfaces to visualize the results of acupuncturing operation. Another benefit of using polygon modelling technique is that it makes the shader easier to apply to the meshes.

4.3.3 XML Datasets

We manually create our own datasets using XML (Extensible Markup Language) as the data source files to store all the entries including acu-points names, labelled codes, indications and locations. Collision dataset also records the collision data and task completion time. Being able to integrate the data into XML files, allows the data to be edited offline easily and loaded to a new project [22] and makes communication between different programming language and independent data structure with high scalability [9, 58] possible.

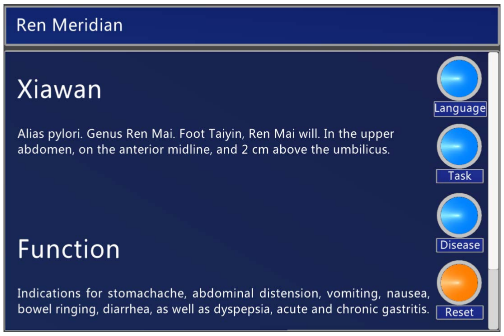


Figure 6: The panel with control functions and interfaces.

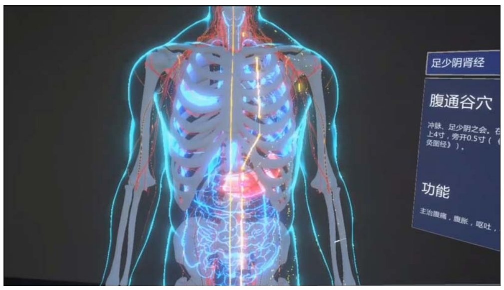


Figure 7: The stomach region flashes in red colour when insertions on a group of acu-points are applied.

5 User Study

5.1 Study Design and Tasks

The aim of the user study is to learn the usability of our training prototype in the Chinese acupuncture practice. Thus, we conducted a comparison study to compare the new prototype (the Simulation Group: SG) with the traditional textbook (the Control Group: CG) in two learning and training aspects, explicit knowledge (e.g. spatial positions and point indications) and implicit knowledge (e.g. needling) in acupuncture practice. We also seek to investigate whether the understanding of spatial relations for the users was enhanced, and to what extent. In addition, we are eager to collect subjective feedback from the users regarding the usability and rendering graphics of the tool. Therefore, we have the following hypotheses:

H1: SG participants will have a more comprehensive understanding of the spatial distribution of channels on the human body.

H2: The memory on acupuncture knowledge will last longer for the SG participants.

H3: SG from second trial will be faster than the same group from first trial in terms of task completion time.

H4: SG from second trial will perform more accurate needle practice than the first trial in terms of accuracy of insertion.

	Indication	Stimulation(ground truth)
Task1	Cough	Perform oblique insertion to BL13 and LU7 with 0.18 and 0.15” depth accordingly; then apply 0.2”perpendicular placement on LI4.
Task2	Diarrhea	Apply perpendicular insertion to ST25, ST37, LI4, SP6 respectively with depths of 0.35”, 0.4”, 0.2” and 0.35”.
Task3	Vomit	Perform 0.35” and 0.4” perpendicular needling to RN12 and ST36; then apply 0.25” oblique insertions to PC6 and BL21.

Table 3: The details of the tasks simulated for acupuncture practice.

Figure 8: The task panel displayed for instruction and information.

The same experiment was performed twice by SG within a one-week interval – the first and second trials. In the first and second parts of the study, we conducted complex comparisons on 1) SG V.S. CG; 2) SG from the first trial (T1) V.S. SG from the second trial (T2). The former aimed to compare the learning performance qualitatively of the two groups; the latter was used to gauge the effectiveness and accuracy of needling practice from two trials to determine improved dexterity and skills in acupuncture practice. In addition, we collected qualitative data from surveys regarding the overall functionalities and usability of the system in the third part of our study. The data can be utilized to guide our future improvement and optimization of our prototype.

H1 and **H2** were measured through the Knowledge Test performance which provided us with tangible evidence of the learning outcomes. The test questions were skillfully and carefully planned to make the results comparable. 2 out of 7 questions in the test were designed regarding the point's functions and indications; 3 about the location of the labelled points on human body and the rest of two asked about the procedure of the stimulation. To test **H3**, we built a timer system to record the completion time that the users spent on individual tasks (denoted as AT) and single movement/insertion (ST) from the first and second trials. Further, we introduced three factors to gauge the accuracy of needling [21]: depth factor (DF), angle factor (AF) and number of mistakes (MT) made in each movement to verify **H4**. As mentioned in Section 3.2, we created a sophisticated detection mechanism to accurately record the data of needling angle and depth and stored them to XML files.

Simulated tasks: we designed three tasks for the SG participants to conduct in our MR system. Each task was designed to perform an acupuncture treatment to relieve given symptoms (Table 3,Fig. 8), which required three or four movements (insertions) minimum. The labelled acupuncture points can be referred to the guideline [44]. The benchmark of angle and depth is made upon the nature of the physiology of the area and intended effect on zang-fu (visceral organs). There are three types of angles of insertion [21] commonly used in clinical practice: perpendicular (90°), oblique (45°) and transverse (10° to 20°) insertion.

Questionnaire: a questionnaire was implemented with 14 questions using 7-point Likert scale and a few open-end questions as a complement to study the user performance and preference regarding the application. We designed and grouped the questions based on six dimensions: usability factor (UF) [11], motivation factor (MF) [51], engagement factor (EF) [45], naturalism (NF) [53], sensory factor(SF)and other factor(OF) [63]. We selected a subset of questions from existing standardized questionnaires in order to construct our own survey for the purpose of evaluating usability, user satisfaction, motivation, and ease of learning.

5.2 Participants

20 students from local medical school (2 females and 18 males, mean age=20.23 years old, SD=2.12) were recruited to the study.

Two-way ANOVA for PL scores					
Source	Type III Sum of Squares	*df*	Mean Square	*F*	*p*
Intercept	6.553	1	6.553	101.624	0.000**
Trial	0.025	1	0.025	0.38	0.541
MR	0.333	1	0.333	5.165	0.029*
Error	2.386	37	0.064		

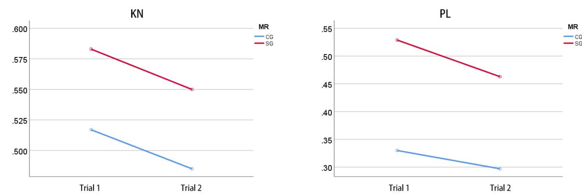
* p<0.05 ** p<0.01

Table 4: The result of Two-way ANOVA of KN scores.

Two-way ANOVA for KN scores					
Source	Type III Sum of Squares	*df*	Mean Square	*F*	*p*
Intercept	11.396	1	11.396	717.956	0.000**
Trial	0.011	1	0.011	0.665	0.42
MR	0.043	1	0.043	2.703	0.109
Error	0.587	37	0.016		

* p<0.05 ** p<0.01

Table 5: The result of Two-way ANOVA of PL scores.



(a) (b)

Figure 9: The estimated marginal means of (a) KN and (b) PL scores.

All participants had fundamental understanding of anatomy and physiology. The majority of the participants had a prior experience in accessing virtual and augmented-reality content. The participants were evenly divided into two groups (10x10), as inspired by the similar studies [4, 49] – one group of students were trained by our system (Simulation Group: SG) while the other group learnt the knowledge from textbook and written materials (Control Group: CG). The participants were randomly assigned to the groups.

5.3 Procedure

The ethics for the study was approved by the authors' institutional Ethical Review Panel (No.: ER-SAT-0788065720220408210614). Before proceeding with the experiment, participants from both SG and CG were given a description of the tasks that they would need to accomplish accordingly. Further, a short briefing on how to use the Hololens headset was provided to SG users. We ensured the interaction with the system would be taken place in a safe environment by the users and supervised by teachers and research students.

At the first trial, the SG subjects were instructed to familiarize themselves with the interaction and manipulation techniques offered by the system. CG participants were asked to acquire the knowledge directly from written learning materials (which had tailored content relating to final Knowledge Test) in meantime. Afterwards, the SG users started to perform the three tasks with the completion of time and needled accuracy recorded. Users from the two groups were required to provide the answers to the knowledge test when they finished the tasks. The first trial study took 40˜50 min to complete.

The second trial was carried on in a week later and all the subjects were required to answer one more time of the knowledge test to make a record of their performance. Afterwards SG users proceeded performing the same tasks with data gathered while CG users ceased to. The second trial study took 20˜25 min to finish. A 10-minute online survey was taken after the completion of the experiment using 7-point Likert Scale questionnaire to evaluate the usability and functions of the overall system.

6 Results

The section presents a detailed analysis of data gathered from the user study. The data was initially obtained from the designed knowledge test, questionnaires, and the output file of Application on HoloLens. IBM SPSS 26 and an online platform SPSSAU were used to perform the statistical analysis [33, 59]. Since the sample size was less than 50, to ensure the effectiveness of the presented results, we analyzed the data using the Shapiro–Wilk test to verify if they were consistent with a normal distribution. The results (p>0.05) were confirmed that all data follows the normal distribution.

6.1 Knowledge Test Performance

A two-way mixed design ANOVA was conducted to assess the effect of using our simulator on the assimilation of acupuncture knowledge. The results, presented in tables 4 and 5, indicated that there was a significant difference in point location task performance between the simulator and textbook groups (F(1, 37) = 5.165, p = 0.029). However, no significant difference was found in acupuncture knowledge between the simulator and textbook groups (p=0.42). Additionally, no significant difference was found in the tasks of point location (p=0.541) and acupuncture knowledge (p=0.109) when comparing results from two separate tests .

Details of differences in participants' knowledge test performance are further illustrated in the figures of estimated marginal means (EMMs) of acupuncture knowledge (fig. 9(a)) and point location (fig. 9(b)). The results indicate that simulator received notably higher EMMs scores than textbook on point location (PL) of the knowledge test in T1 and T2. Also, both two groups performed worse on KN and PL in the second trial than in the first trial.

6.2 Needling Accuracy and Time

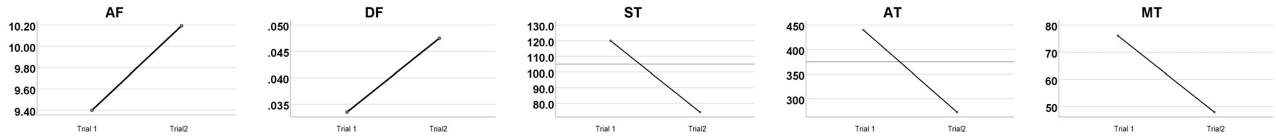
We used the Repeated Measures ANOVA method to analyze needling accuracy and completion time based on AF (Angle Factor), DF (Depth Factor), ST (Single Insertion Time), AT(Individual Task Time) and MT(Number of Mistakes) factors. As indicated in tables 6 to 10, there was no significant difference between trials on AF (p = 0.405) and DF (0.062). Meanwhile, the test determined that the results of ST ($F(1,9) = 625.511, p = 0.405$), AT ($F(1,9) = 19.740, p = 0.002$) and MT ($F(1,9) = 13.615, p = 0.005$) varied statistically significant over time. The EMMs data shown in Fig. 10 revealed that there was a slight increase in angle (AF) and depth (DF) factors between trials whereas ST, AT and MT dropped significantly.

6.3 Qualitative Results

The qualitative feedback gathered from the questionnaire was measured to reveal the correlations among UF, MF, EF, NF, SF and OF. We used Spearman's rank correlation coefficient to calculate the data, and the result can be seen in Fig. 11. EF shows a close correlation with NF ($\rho = 0.693, p < 0.05$) and SF ($\rho = 0.761, p <= 0.01$), OF reveals a significant correlation with UF ($\rho = 0.770, p < 0.01$) as same as NF to SF ($\rho = 0.920, p < 0.01$).

Six out of ten (60%) participants stated that, "the models and the visual effects are so impressive", and "the needling interaction is very interesting and I like the modelling of the channel distribution which is very clear and illustrative". One participant specifically appreciated the skin of the human body is rendered as transparent so she could observe the pathways and nerve system easily.

Regarding the naturalism of the technique, 40% subjects agreed our interaction with the virtual needle is very similar (scale 6) to the way of holding a one in real world, whereas one participant



(a) (b) (c) (d) (e)

Figure 10: The performance comparisons in needle insertion between the two trials. DF, AF show smaller error value with smaller S.D. whereas ST, AT and MT show significant decreases in the second trial.

Repeated Measures ANOVA of AF					
Source	Type III Sum of Squares	*df*	Mean Square	*F*	*p*
Trial	3.147	1	3.147	0.762	0.405
Error	37.169	9	4.139		

* *p*<0.05 ** *p*<0.01

Table 6: The result of Repeated Measures ANOVA of AF.

Repeated Measures ANOVA of DF					
Source	Type III Sum of Squares	*df*	Mean Square	*F*	*p*
Trial	0.001	1	0.001	4.534	0.062
Error	0.001	9	0.000		

* *p*<0.05 ** *p*<0.01

Table 7: The result of Repeated Measures ANOVA of DF.

Repeated Measures ANOVA of ST					
Source	Type III Sum of Squares	*df*	Mean Square	*F*	*p*
Trial	188853.391	1	188853.391	652.511	0.000**
Error	2604.832	9	289.426		

* *p*<0.05 ** *p*<0.01

Table 8: The result of Repeated Measures ANOVA of ST.

Repeated Measures ANOVA of AT					
Source	Type III Sum of Squares	*df*	Mean Square	*F*	*p*
Trial	140134.558	1	140134.558	19.740	0.002**
Error	63889.569	9	7098.841		

* *p*<0.05 ** *p*<0.01

Table 9: The result of Repeated Measures ANOVA of AT.

(10%) and two (20%) stated they are extremely (scale 7) and slightly similar (scale 5). Meantime, 60% (scale 6) mostly agreed that direct object interaction with bare hands is more natural than hand-held controllers. Half of the users appreciated the user interfaces and control panel to be clear and instructive (scale 6) and helped them accomplish the tasks, where two found extremely helpful (scale 7).

Eight (80%) subjects stated that they were concentrating more using the MR application to learn the acupuncture from as opposed to the written textbooks. We received positive feedbacks from all of the participants (100%) on improved sense of engagement: 20%, 60% and 20% for scale 5 to 7.

Regarding the comments on needling interaction, three participants discovered it was harder to perform needle insertion on points near legs and foots areas where a clear pose and estimation of the insertion was not able to obtain. One participant reported that the human model was expected to allow rotate, pan and zoom for a closer inspection during training.

Besides the above feedback given regarding some features, users also suggested a multiple degrees of freedom can be added to the needling angles to improve the realism of needling interaction. It was expected that a tracked report of ratings and evaluations can be automatically generated by the end of training to improve the learning efficiency of learners on acupuncture. They also recommended the system may record the learner's acupuncture operation on labelled points for a later playback, which is important for the learner's reflection and skills improvement.

7 Discussion

We expected that the subjects would outperform the spatial awareness in the location of the points and channel distribution by employing the MR application in contrast to the control group, as stated in **H1**. The participants from both groups completed the Knowledge Test questions at the end of T1 and the beginning of T2 respectively. Although we did not find a significantly enhanced assimilation of acupuncture knowledge and points location within the simulation group over time, the simulation group tended to gain remarkably higher Knowledge Test scores overall and outperformed the control group in marking the correct location of given points due to a boosted awareness of space in a blended environment. Thus, **H1** is supported based on the findings. We were able to support this based on the score of Q13 from the questionnaire which was ranked distinctly high among users, suggesting they could easily recall the location of one given distribution. The result indicates that the overall MR experience leads to an enhanced memory of meridians distribution with the help of improved spatial understanding. In addition, no significant difference in performance was found between MR users in T1 and T2 when compared to the non-simulation group, which means **H2** cannot be supported.

However, there were no distinct differences found in performance relating to memorizing text information (such as the point names and indications) between SG and CG. The possible reason is that it may be difficult at the first place for human to perceive a large amount of 2D content despite the display transformation. This could be possibly improved by adding more learning activities in the system and practices.

Regarding the efficiency of performing the tasks, we expected the participants from second trial would complete the tasks faster than they did in the first trial, as stated in our third hypothesis **H3**. We recorded the completion of time for each task and movement from both trials to measure the difference. According to the results, the participants on T2 used much less time to complete the three tasks, and they became more efficient and confident in each insertion. Therefore, **H3** is supported. The hypothesis **H4** states that T2 would outperform needling accuracy than T1, we recorded the data of

Repeated Measures ANOVA of MT					
Source	Type III Sum of Squares	*df*	Mean Square	*F*	*p*
Trial	3957.422	1	3957.422	13.615	0.005**
Error	2615.911	9	290.657		

* *p*<0.05 ** *p*<0.01

Table 10: The result of Repeated Measures ANOVA of MT.

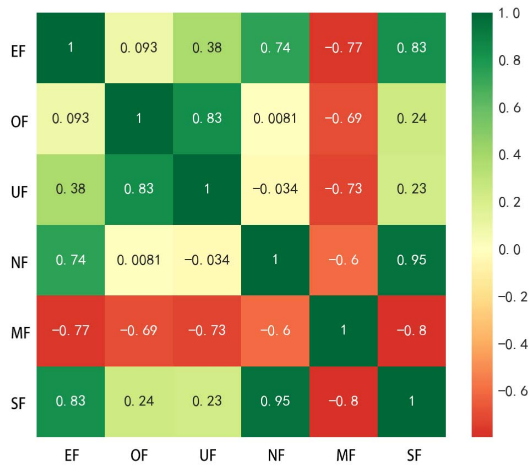


Figure 11: Correlogram among factors analyzed from the qualitative results.

needled angle and depth in each movement meantime to gauge the accuracy and compare them with the benchmark. Though we did not find a notable statistical difference between T1 and T2, a slight decline in the mean and SD values of angle factor (AF) and depth factor (DF) in T2 can be spotted. Thus, it can be said that the subjects gained certain degree of ease performing needling tasks in the system. The hypothesis was also supported by Q1 and Q2 results from the survey regarding the naturalism of our interaction, the participants appreciated our virtual needling interaction that is able to share a great similarity and closeness to the real insertion on human body. Thus, **H4** is supported. The results above indicate our application helps to build implicit knowledge and develop skills and dexterity needed in acupuncture practice through a more immersive and intuitive learning experience.

We looked further into why the results of the needle accuracy comparison were not statistically significant. Some users reported difficulty in following the clear position and posture of the needle. The narrow field of view (FOV) display of the HoloLens may be a contributing factor to the lack of improvement in accuracy.

According to traditional Chinese medicine (TCM), the locations and distributions of acupuncture points and meridian can vary across individuals due to differences in anatomical features such as height, weight, and gender [13, 17, 26]. In practice, the insertion force and penetration velocity of the needle are crucial factors for acupuncture training, as they vary depending on patient characteristics and tissue inhomogeneity (i.e. the proportion of fat and muscle) [18]. However, currently, the simulator does not take into account these variations and tissue layers, due to limitations in the project's timeline and budget. To address this limitation, we plan to integrate machine learning to map corresponding points and channels on various human bodies, and to develop a pseudo-haptic approach to visualize the scales of needling resistance for future improvements.

Previous work similar to ours was proposed by [27, 54]. However, we did not directly compare our work to theirs as our project has different objectives. In contrast to the purposes of their works that mainly focused on content visualization and insertion points localization, our project aims to provide a novel design of interaction for acupuncturing. Additionally, textbooks and PPTs are still considered the most traditional and effective means for learning knowledge related to acupuncture points. Therefore, prior research has primarily focused on comparing new approaches with textbook-based education. However, our goal is not to replace textbook education, but rather to design and develop an immersive MR-based approach as a supplement to traditional textbook teaching.

8 Future Work

The conducted user evaluation will guide the improvement on our interface and interaction design and assess the overall potential for software like this to affect an impact on the industry. We shall ease the needling interaction by enabling multi-degrees of freedom for the angle of needle during insertion, based on the qualitative findings. One limitation is due to one of the defects of using HoloLens which performs poorly handling 3D perspective relations particularly in the lower part of the space. We will test different AR/MR headsets in future to make a comparative study regarding the perspective performance. Another limitation is possibly the lack of force feedback for needling – we've already built a dynamic visualization to indicate a successful collision between the needle and point and will design a pseudo-haptic approach to convey the spectrum of needle penetration force in future work. Overall, a number of valuable comments and data we gathered from this user study will be addressed on our future improvement.

In order to take the human variations into consideration and create a lower barrier for access, we will use a data-driven approach to adjust points and meridians for different individuals using AR/MR technology. This will be a key focus of our future development.

9 Conclusion

The work in this paper proposes a novel design and development for acupuncture where the user interacts directly with the virtual needles using their hands in a mixed reality environment. Our evaluation demonstrates the potential of this type of application to improve the process of training practitioners in the field of acupuncture. The prototype uses mixed-reality technology which is evidenced to be effective in teaching and learning enhancement. It is concluded that the system has potential to provide the users with a safe and natural environment to develop their acupuncture skills simulating the actual physical process of acupuncture. The study revealed improvements in both the acquisition of acupuncture knowledge and manual dexterity. Although the statistical results did not provide enough evidence to validate the transfer of practical skills, the use of the system proved to be beneficial for the learning process. Having a robust understanding of explicit knowledge is vital for mastering implicit knowledge, such as needling skills. We are interested in exploring the potential improvement of needling skills if users were to undergo extended training with the proposed simulator. In order to achieve acceptable levels of responsiveness for affordable mid-range computing hardware, the computational cost of rendering in the MR display is a major design consideration. This contrasts with the majority of AR/MR systems which are designed to run on high-spec machines where computational cost is less of a consideration. It is also worth mentioning that our system is designed to act as a supplementary mean together along with traditional classroom learning to achieve the best outcomes of acupuncture training.

This paper discusses the methods and functions that the system has realized so as to provide a cost-effective, accessible and time-saving simulation. In summary, the prototype exploits blended immersive technology and provides valuable insights into the potential of mixed-reality technology for teachers and practitioners in Chinese medicine education.

Acknowledgments

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