INFO90009 Project Visual Report

Exploring Mixed Reality for Enhanced Visual Feedback in Medical Simulators

Jiayi Wu 1067805, Qiting Ma 1174225

Supervisors: Dr Arzoo Atiq, Dr Antony Chacon

November, 2024

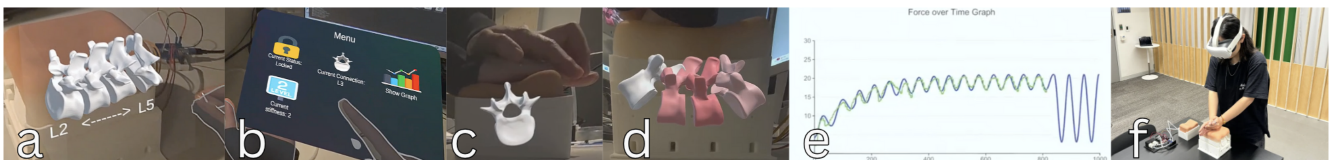

Figure 1: Mixed reality application for spinal mobilisation: a) object calibration, b) interactive interface, c) spinal mobilisation visualisation - transverse rotation, d) spinal mobilisation visualisation - sagittal rotation, e) force vs time graph, and f) student practising with the medical simulator

Abstract

Back pain is a widespread health issue, with chronic cases significantly impacting daily activities and affecting a substantial portion of the population. Physiotherapists play a crucial role to alleviate this ailment. However their education is not always optimal. Traditional physiotherapy education is constrained by inability to mimic the conditions of real patients and limited visual feedback for spinal mobilisation. To enhance training, we developed a mixed reality (MR) application intended to work with physical simulator devices, *SpinalLog* and *vARtebra*, using Unity engine and Meta Quest 3. This application offers real-time visual and haptic feedback of bone activities on applied force, enabling realistic spinal mobilisation for physiotherapy training. A user evaluation with physiotherapy experts and students provided positive and useful feedback, validating the effectiveness of this application and highlighting the potential to improve the functionality accuracy and user experience of the system. Future work will focus on streamlining calibration, enhancing sensory feedback, expanding functionality for more comprehensive and immersive training experience, and validate short and long term learning effects.

1 Introduction

Back pain was one of the most common health issues in the world, with approximately 80 percent of the population experiencing it at some point of their lives [7]. Chronic back pain, which affects approximately 4 million people in Australia [1], and has become a significant challenge preventing people from engaging in works as well as their everyday activities.

Due to the increasing number of people experiencing back pain, there is also a growing demand for physiotherapy who are able to treat and manage this condition. However, there are many challenges in current physiotherapist training. Most physiotherapy schools follow the traditional classroom settings to train physiotherapist where students practice techniques with each other under supervision. Nevertheless, this setting has various limitations.

For examples, inexperienced students practising with each other can lead to risk of injury, and feedback from the instructor is mostly verbal. It is hard for students to fully understand the correct techniques and recognise their mistakes. Since students practice with each other, they are not exposed to a variety of back conditions, which limit their ability to develop comprehensive mobilisation techniques in treating different cases. Additionally, the instructor can only teach one student at a time (as shown in Figure 1), making the overall learning process lengthy and less efficient [5].

Given these challenges, there is a need to develop an educational tool for physiotherapy students that provides safe, effective and realistic training experiences. Nowadays the extend reality (XR) technologies are increasingly used in various field of medical education and trainings. For instance, surgical simulations and procedure training, offering reusable, cost-effective solutions and showcase the ability to significantly enhance the learning outcomes. Therefore, we have proposed a novel medical simulator for spinal mobilisation training, along with a Unity built mixed reality (MR) application on Meta Quest 3 to visualise internal bone movements in response to different mobilisation techniques and provide feedback on the applied force which enhance the learning experience for physiotherapy students. Both of them were developed in collaboration with the Department of Physiotherapy.

This report primarily focus on the detailed development of the MR application, covering various aspects from related work to the design and implementation of the key features. This report also includes a comprehensive user study, explaining the methodology used for the usability testing, feedback and comments, as well as an analysis of the results. Finally, the report outlines future directions for further development and improvements.

This research is significant as it offers innovative solutions to the limitations of traditional physiotherapy training. The VR application we developed provides insights of how technologies can be effectively utilised to train physiotherapists. It contributes to the community of physiotherapy education, as well as provide directions on how to enhance the current application in the future.

2 Related Work

2.1 Physiotherapy Training for Lumbar Spine

The traditional method for training physiotherapists in lumbar spine mobilisation involves the instructor demonstrating the techniques and the force pattern on a volunteer or manikin. Afterwards, students are asked to practice on each other, attempting to replicate the same force pattern [5]. While the traditional approach has several limitations. One significant constraint is its inability to mimic the conditions of real patients. For example, individuals of different ages, genders, and health conditions have different degrees of spinal stiffness. Another challenge is that as the instructor demonstrating force patterns, the movement of bones is internal and subtle, making it difficult for students to visually observe and understand how much force is needed. At the same time, it is also challenging for the instructor to assess provide feedback to students based on the visual observation alone, which lead to inconsistent learning outcomes.

Figure 3: Typical spinal manual therapy demonstration during classes [16]

There are various tools and technologies that used for the current training of spinal mobilisation with different strengths and weaknesses. For examples, the manikin as shown in Figure 4-a serve as a physical model on which students can practice positioning and manual techniques [6]. The digital simulation platform in Figure 4-b help students understand the structure and motion of the spine. Additionally, Treatment tables equipped with force sensors in Figure 4-c and the skin-mounted sensors in Figure 4-d allow the use of manikins or human volunteers to provide real time force data.

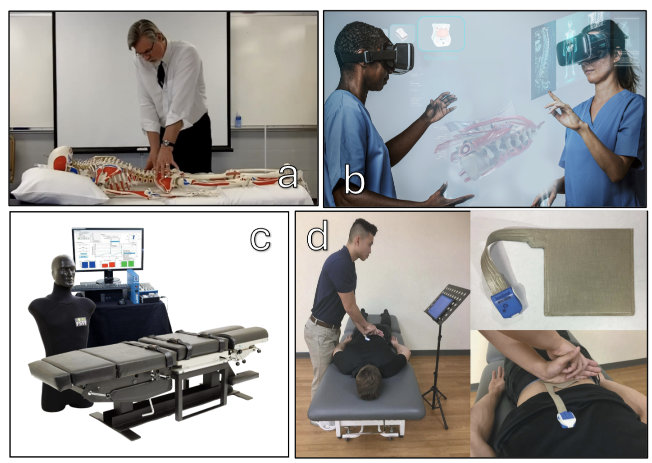

Figure 4: Common visual technologies employed for spinal manual therapy education: a) manikins or models of the spine [21], b) digital platforms employing extended reality applications to visualise the spine [23], c) treatment tables with embedded force sensors and screens intended to visualise forces applied to manikins or human volunteers [4], and d) skin-mounted force sensors [20].

However, these technologies have shortcoming in accurately simulating the real-world situations. They lack the diversity needed to simulate various spinal conditions, and failed to provide genuine and real time tactile feedback on the force applied [12]. Besides, they offer limited visual feedback, and there are potential risks associated with students practising on human volunteers. In this work we explore the use of extended reality technologies combined with a physical device that mimic the haptic feedback of a human back to address these issue.

2.2 Extended Reality in Medical Simulators

Recently, Extended reality (XR) technologies, containing virtual (VR), augmented (AR) and mixed (MR) reality have been gradually adapted to medical education and training. Using these devices would help trainees better understand the complex 3D structure and engage in the medical procedures. Mixed reality applications in medical training is crucial as it has great potential to improve learning experiences for medical professional training by blending digital elements with the real physical environments [2]. Research has shown that extended reality has several advantages compare to the traditional way of learning [19] and using extended reality as an educational tools is a trend for future. For instance, the extended reality application for gross anatomy education is reusable and more cost-effective compared to cadaver-based learning, which is expensive and requires ongoing maintenance [9]. Extended reality applications are also used for surgical simulations and procedure training. The motion tracking and haptic feedback technologies make the surgical simulation more realistic. XR can provide useful information directly within the headset without distracting users, compared to the traditional display of information on monitors [3]. Moreover, extended reality technologies offer opportunities for trainees to practice without risking patients' safety [9] and without the fear of making errors [11] as it provide a save environment.
To the best of our knowledge, there is no existing work focused on the visualisation of spinal mobilisation for the training and education of physiotherapists. However, one existing example of XR applied in medical simulators which closely relates to spinal mobilisation is the use of XR in CPR training.
In CPR training, manikin with integrated sensors and virtual reality applications have been involved. These applications create a virtual environment that immerses individuals in realistic scenarios, making the training process as genuine as possible, which enhance the effectiveness of training [22].
The application gathers real-time data from manikin's force sensors, which record the depth and rate of user's chest compressions. This data is then processed and displayed in VR headsets, offering users dynamic feedback on their CPR technique [8]. In addition, the visual instructions, such as 3D demonstrations of correct techniques provide enhanced guidance which helped users to refine their skills, thereby improving the overall effectiveness and precision of the training.

3 MR Application

Overall, our application is designed to let users participate in immersive, tactile physiotherapy training experiences by enabling hands-on interaction with both virtual objects and physical devices. This mixed reality app integrates various functionalities to interact with both SpinalLog and vARtebra. While both devices share core functionalities, each offers unique features that enhance user experience.
SpinalLog: (1)interactive interface (2)calibration (3)colour change (4)bone activity visualisation (5)instruction UI.
vARtebra: (1)interactive interface (2)calibration (3)colour change (4)bone activity visualisation (5)graph (6)stiffness.

3.1 Instruction UI

When users first access our application, the instruction UI (see Figure 5) provides an overview of the product along with step-by-step guidelines to help them get started smoothly. These instructions, including videos and text descriptions, ensure that users quickly understand the features and familiar with the process.

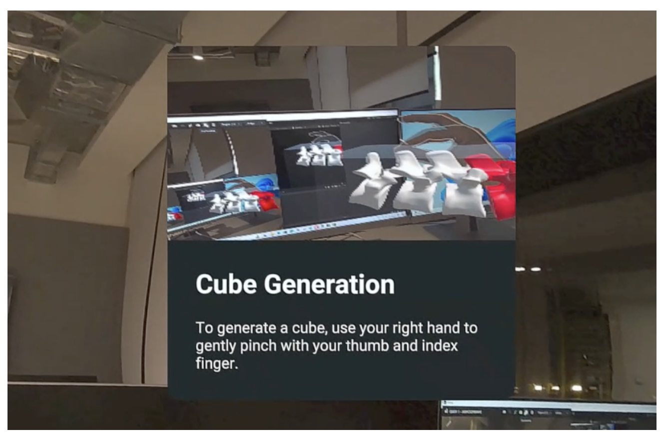

Figure 5: instruction UI to guide user through our application

3.2 Cube Generation and Calibration

Following the instructions, users can generate a virtual cube by performing a pinch gesture with their right thumb and index finger. Then, a virtual cube should appear at the pinch position as expectation. This virtual cube, containing bone models inside, represents the virtual model for the physical devices. To calibrate the virtual cube with its real-life counterpart, users need to grab and manually align it with the physical device (see Figure 6). This calibration process ensures accurate synchronisation between virtual and physical models.

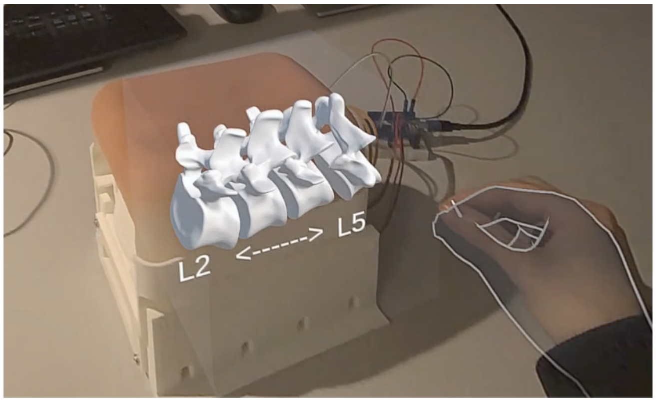

Figure 6: process to calibrate the virtual device with physical Spinal-Log device

3.3 Visual Feedback

After calibration, users can start pressing the devices. Our application provides realistic visual feedback on the applied force and responding bone activities.

3.3.1 Bone Activity Visualisation

While applying force to the device, users should be able to see how the virtual spine moves downward (displacement), as well as the transverse (Figure 7) and sagittal rotations (Figure 8) through the headset in real time.

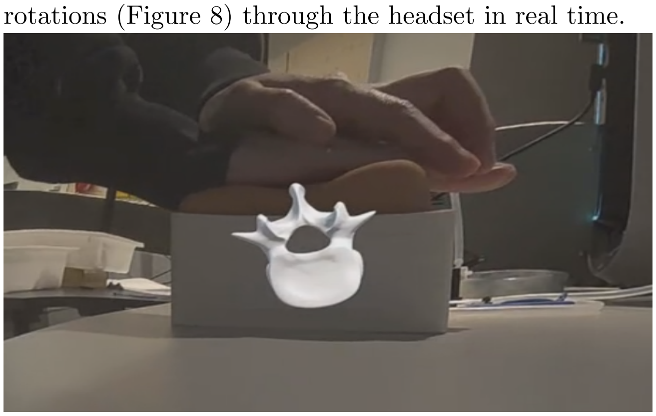

Figure 7: transverse rotation

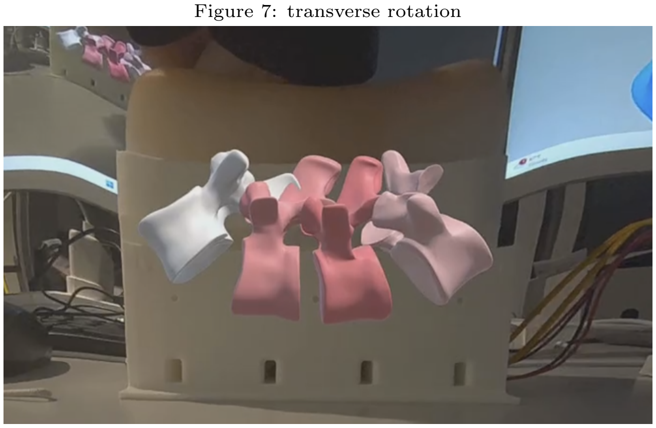

Figure 8: sagittal rotation

3.3.2 Colour Change

If users apply too much force, the bone will turn red (Figure 8), indicating that the force is too much. The colour-change feature in the application is designed to help users gain a better understanding of the correct amount of force they need to apply, enabling users to adjust their technique in real time.

3.3.3 Pressure Visualisation

Our application also have a graph that displays force over time (Figure 9). This graph allows users to load various patterns or techniques, enabling users to refine and practise their skills by comparing their applied force against ideal benchmarks. At the current stage, this feature is unique to the vARtebra device.

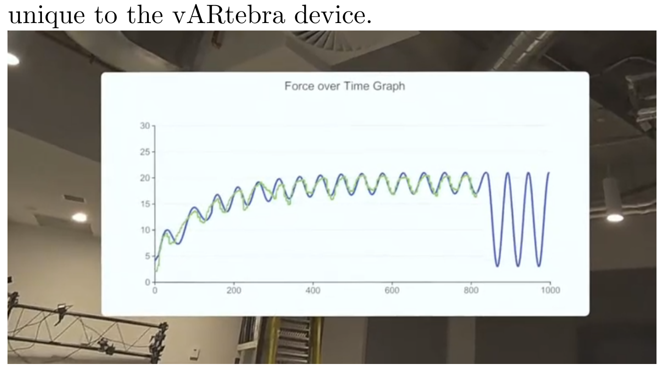

Figure 9: real time force vs time graph

3.4 Haptic Feedback

By clicking the 'Change Stiffness' buttons in our application, users can experience different levels of haptic feedback through vARtebra, simulating various muscle tightness conditions in patients.

3.5 Interactive Interface

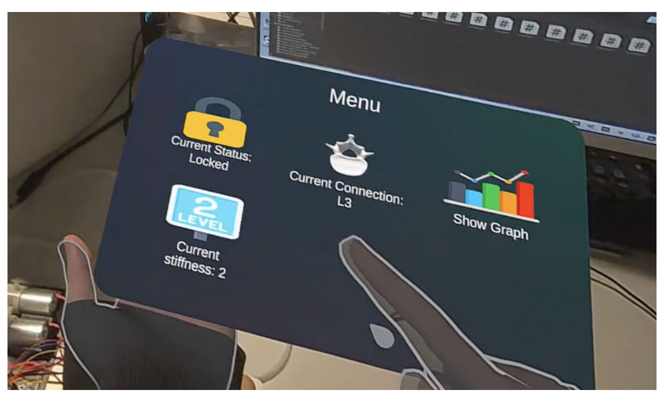

Figure 10: interactive interface in the MR application

The hand menu in the application provides an intuitive interface overlay that users can interact within the mixed reality environment. Most features are accessed through the hand menu (see Figure 10). The menu is designed to attach directly to the hand, making it easy to access. And the buttons on the menu were designed with images to reflect the current status.

4 Implementation

In this section, we will explain in detail how we implemented the various features of the application. Please visit our Git repository at: `https://github.com/qiting2270/SpinalLog_Quest3` for further reference

4.1 User Centred Design

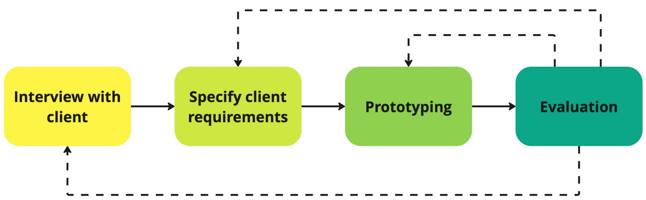

Figure 11: user centred design [10]

Before the development, we conducted a semi-structured interview with our client, Dr David Kelly (lecturer from the department of physiotherapy) to gather some fundamental requirements and desired features for the application. Throughout the development, we regularly presented the progress with our client to collect further feedback, and implement his feedback to refine the application iteratively. This ongoing collaboration helped us align and finalise the application's functionality to suits client's requirements, ensuring that the final product would be effective and intuitive for students undergoing physiotherapy training.

4.2 Meta Quest 3 Setup

The first step is to set up the development environment, this include register a meta developer account, connect the quest 3 to pc, enable pass through mode, enable developer mode and other initial configuration. One essential package that needs to be imported into unity is the 'Meta XR all-in-one SDK' [14] in order to achieve the multiple interaction features like hand grab, poke interaction, etc.

4.3 Bluetooth Connection

To ensure the application runs smoothly, one key prerequisite is the successful connection of the Bluetooth. Since the application require real time communication with the physical device, without a stable connection, almost all features of the application will be unavailable. We utilised Arduino Bluetooth plugin from Unity Asset store [24] to establish the Bluetooth connection, as well as read and send data between devices.

4.3.1 ESP32 and Unity

To receive data from the esp32 and process it in Unity, the first step is to import the ArduinoBluetoothAPI, Once imported, we can scan the nearby devices by name using *BluetoothHelper.GetInstance("Device Name")*, after identifying the correct device, we use *BTHelper.Connect()* to establish a connection with the esp32. Once the device is connected, we start continuously read data from the esp32 to achieve real time data processing.

4.3.2 SpinalLog and vARtebra

To switch between devices, the method *BTHelper.Disconnect()* is used to disconnect the current device first, then repeat the same approach as before, find the device by its name, and establish connection with the new device.

4.4 User Interaction

4.4.1 Device Calibration

Unity's *Building Blocks* extension was integrated to facilitate hand interactions within the application. The HandGrabAPI [15] was used to enable natural hand movements, allowing users to grab the virtual objects. Through the API, the user's hand movements and gestures are accurately mapped to a virtual hand model, ensuring that all actions are replicated and synchronised in real time.
To spawn the virtual bone, user are required to perform a pinch gesture using their right thumb and index finger. this is implemented using the method *OVRInput.GetDown(OVRInput.Button.One)*, where the pinch gesture is equivalent to pressing Button one on the controller [13]. The local position of the virtual hand is then captured and recorded using *OVRInput.GetLocalControllerPosition (OVRInput.Controller.RTouch)*. Subsequently, the position of the virtual bone is set to align with the virtual hand, thus achieving the virtual bone spawns at the position of the right hand when a pinch is made. Since the hand grab building block is added to the virtual bone component, users can grab the cube with thumb and index finger just like the way they generate it. release the finger will end the grab. To improve the accuracy of the calibration, it is crucial to ensure that the virtual bone remains parallel to the horizontal plane at all times. this was achieved using *forward.y = 0* so that y axis will not change.
when the virtual bone has been moved and placed in the desired location, user can lock the position of the bone in the menu to fix its position.

This is achieved by finding the hand grab component with *cube.transform.Find("[BuildingBlock] HandGrab")* and then disabling it using *cube.GetComponent¡Renderer¿().enabled = false.*

4.4.2 Menu

A canvas is attached under the left OVR hand model game object, ensuring that the canvas's position will change along with the left hand. Additionally, the flip detection and a menu button is added to control the visibility of the menu, allow users to show or hide the menu as needed.

Flip detection for hand has been implemented by automatically monitoring the hand's rotation angle through the *handEulerAngle* property in the *OVRHand* component. The hand map will only be shown when the palm is facing up which means the handEulerAngles is between 180 and 360 degree.

A menu button employs a similar approach by attach the button to the left wrist. An OnClick listener is added on the button, and pressing it will make the menu visible with the command *menu.SetActive(true)*.

4.5 Displacement and Rotation

a. SpinalLog

The ESP32 micro-controller on the SpinalLog device transmits a string containing eight data points, representing depth measurements from L2 left sensor to L5 right sensor. Each string is received by Unity and converted into float values using the *ToFloatArray(String message)* function.

Each bone in the system is managed by a dedicated *BoneController* class, which processes both the left (D_{left}) and right (D_{left}) distance data. These distances represent the measured gap between the top magnet and the corresponding magnetic sensor. The *BoneController* class then uses this data to update the position and rotation of the bone.

b. vARtebra

The ESP32 micro-controller on the vARtebra device sends out a string message in the format of "distance, transverse rotation, sagittal rotation" each time. Unity does not have to do further analysis and calculation on the received data.

4.5.1 Up-Down Movement

a. SpinalLog

The *UpDownMove()* function firstly calculates the average depth between the D_{left} and D_{right} of each bone. Then, it will compare the current average depth with the initial depth, and update the local position of each bone in the bone group set.

b. vARtebra

Since the distance data sent from vARtebra measures the displacement from the initial position, Unity can directly use the received data and update the local position of the L3 bone.

4.5.2 Transverse Rotation

a. SpinalLog

The *TransverseRotationDegree()* function computes the transverse rotation of a single bone based on the difference in depth between the left and right side of the bone (see Figure 12). The function uses the bone's length L_{bone} as a scaling factor:

- If only one side is pressed down (i.e. $D_{\text{left}} = 0$ or $D_{\text{right}} = 0$), the rotation is based on the available depth:

$$\theta = \sin\left(\frac{D_{\text{left}}}{L_{\text{bone}}}\right) \quad \text{or} \quad \theta = \sin\left(\frac{D_{\text{right}}}{L_{\text{bone}}}\right)$$

- Otherwise, the rotation is computed based on the half distance:

$$D_{\text{half}} = \frac{D_{\text{left}} + D_{\text{right}}}{2}$$

$$\theta = \sin\left(\frac{D_{\text{half}}}{L_{\text{bone}}}\right)$$

Once the rotation angle is calculated, the function determines the direction of rotation based on the relative value of D_{left} and D_{right}:

- if $D_{\text{left}} > D_{\text{right}}$, the bone will rotate in the positive direction: θ,
- if $D_{\text{right}} > D_{\text{left}}$, the bone will rotate in the opposite direction: $-\theta$.

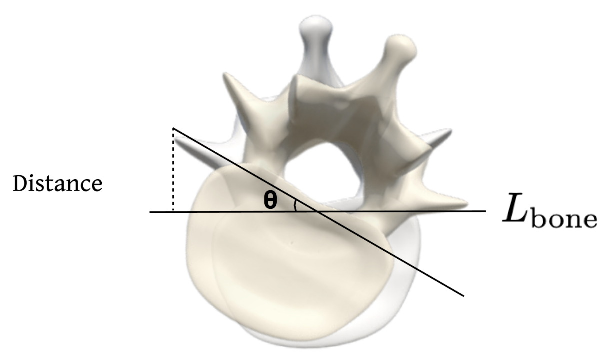

Figure 12: transverse rotation angle

b. vARtebra

The gyroscope sensor on the vARtebra device continuously sends out transverse rotation angles. The sensor output the data with positive and negative values, indicating the direction of the rotation.

Since the gyroscope sensor has provides the rotation angle and rotation direction, Unity can directly use the received data and update the game object's transverse rotation using the *Quaternion.Euler()* method.

4.5.3 Sagittal Rotation

a. SpinalLog

The process of calculating sagittal rotation begins with identifying the focus bone in each Unity frame, and the focus bone does not have sagittal rotation. *FindFocusBoneDepth()* function is used to identify the bone with deepest distance by comparing the depths of all bones in the bone group.

The next step is to calculate the rotation angle based on the relative position of the target bone to the focus bone:

$$\theta = \tan\left(\frac{D_{\text{diff}}}{D_{\text{gap}}}\right)$$

Here, D_{diff} represents the depth difference between the target bone and the focus bone, while D_{gap} is a constant used to scale the distance between the target bone and the focus bone (see Figure 13).

The rotation direction is then determined by the position of the target bone relative to the focus bone. By comparing their IDs:

- if thisBoneID < focusBoneID, the bone will rotate in the negative direction: $-\theta$,
- if thisBoneID > focusBoneID, the bone will rotate in the positive direction: $-\theta$.

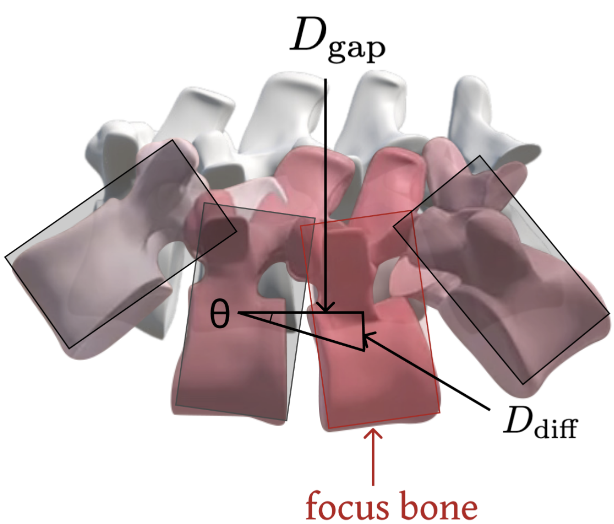

Figure 13: sagittal rotation angle

b. vARtebra

Similar to the transverse rotation, the gyroscope sensor on the vARtebra device can measures real-time sagittal rotation angles and their corresponding directions. Unity can use the received angles to automatically update the game object's sagittal rotation with the *Quaternion.Euler()* method.

4.6 Colour Change

If the bone reaches MIN_DEPTH, indicating that the force applied to the device is too much, the bone starts turning into red. To achieve the functionality of colour transition, the factor t is calculated using *Mathf.InverseLerp* method, which map the *currentDepth* to a normalized range between MIN_DEPTH, the depth at which colour change begins and MAX_DEPTH, where the bone completely transition to red. Then, the colour of bone can be calculated and smoothly changed from white at MIN_DEPTH to MAX_DEPTH by using *Color.Lerp* method.

4.7 Graph

The graph in the application displays two lines with different colours. The blue line is static which serve as a baseline reference for students or users to follow, the green line is designed to be responsive and can demonstrate the change of force in real time. To implement the graph, it is required to import XCharts API which is a data visualisation and chart making tools [26]. and setup the chart. for example, using *lineChart.EnsureChartComponent¡Title¿().text = ”Force over Time Graph”* to set the title of the graph, and other features like tool tip, legend, x and y axis name, type, etc. After setting up the general chart information, lines can now be added to the chart. A total of 1500 force data points are stored in a csv file, which the system is designed to process and display 2 data per second to make the baseline look smooth, giving the total duration of 30 seconds.

To display the baseline data into the chart, the method *LoadDataFromCSV(string path)* is used to read and add data. this method skip the csv file's title, read the data line by line, and add the data from each line to the chart with the command expertTrial.AddData(i-1, y), where i is the index representing x axis and y is the force data corresponding to y axis.

To display the real time force data, the real time force data from the esp32 is continuously recorded through Bluetooth, when the force user applied is greater than 1, it triggers a session and a timer *timer += Time.deltaTime* and the timer is limited to 30 seconds, after 30 seconds, the graph will be reset. during the session, the force that user applied will be added to the chart using *studentTrial.AddData(timer++, yaxis force)*.

4.8 Change of Stiffness

The application also supports adjusting the stiffness level of the physical device. *BTHelper.SendData(”1”)* method is used to send a message to the device, where the 1 represents the desired stiffness level. Three levels of stiffness are available in the system, with level 3 being the most rigid.

5 Evaluation

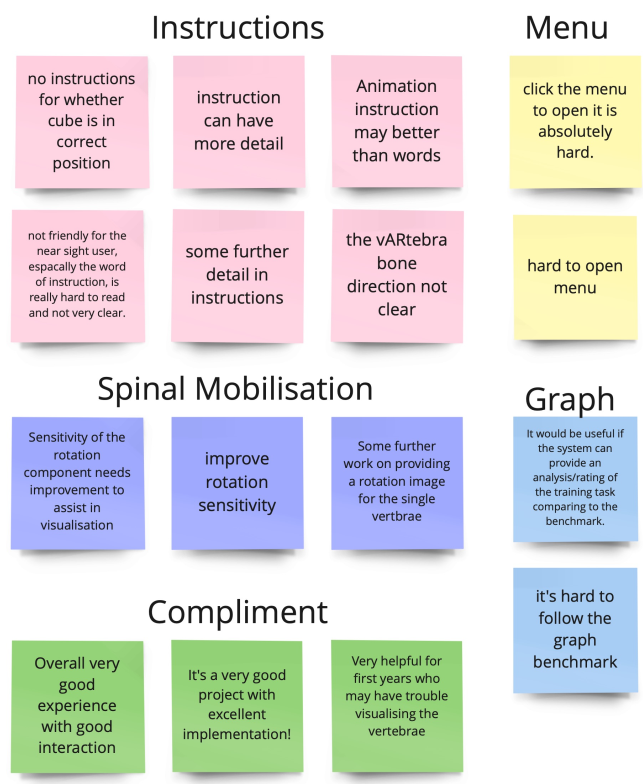

Figure 14: Affinity Diagram

The purpose of this evaluation was to validate usability, accuracy, and effectiveness of our application for physiotherapy training. We conducted user evaluation including usability testing, interviews and surveys to capture qualitative data on participants' experiences and views about the application, we generated interview and survey question forms based on the NASA Task Load Index [17]. Through usability test, we can capture plenty of extra information about participants such as tone of voice, body language, facial expression, etc. These social cues would help us understand more about participants' opinion and attitudes [18].
A group of 10 participants, including physiotherapy experts, students and the general public participated in the user evaluation, and they were were asked to complete tasks which cover all application functionality. Afterwards, these participants were required to fill out a structured questionnaire covering aspects of usability, user experiences and improvements (see Appendix B). This questionnaire focused on several key aspects of the application:

- **Instruction Clarity**: address how clear and useful is the provided instructions for guiding the participants' interaction with our application.
- **Calibration**: validate the efficiency of calibrating the virtual device with the physical one.
- **Device Transition**: assess the ease of switching between SpinalLog and vARtebra.
- **Spinal Mobilisation Accuracy**: examined how our application accurately tracks spinal mobilisation activities, including up-and-down movement and rotation.
- **Sensory Feedback**: evaluate the effectiveness of colour change and data visualisation (graph).

To prevent potential ethical issues, participants will be required to read and sign the consent forms, to ensure that they fully understand the procedure and agree to participate in the interview. Participants will also be informed that any data collected during the interview session will be securely stored.
We employed affinity diagramming (Figure 14) to organise qualitative data we received from the interviews and survey (Appendix C). This method helped to identify common patterns and themes, making the data more structured and easier to analyse.

6 Discussion

6.1 Findings

The interview session with our client conducted before the development phase identified various needs and challenges within the field of physiotherapy training. One of the challenges in physiotherapy training is the need of participants, it could be time consuming and costly to find available participants for students to practice the mobilisation techniques. Our client mentioned that there are currently limitations in translating demonstrations effectively to allow students better understand key concepts. Therefore, he hopes for a method that allows for accurate visualisation to enhance students' learning experience of spinal mobilisation. Our clients prefer using their hands to interact within the application. He mentioned that hand interaction feels easier and more intuitive, it simulate the experience of interacting with objects in real life.
The user study conducted after the development provide insights about the accessibility and the usability of the application. The feedback of the application is somewhat polarised as some participants find it extremely easy to use while others experience some difficulty. This is probably due to differing levels of familiarity with the extended reality technologies. Particularly, younger participants who have previous experience with VR tend to be more comfortable with the interactions within the app.

6.1.1 Calibration Process

Nearly half of the participants found the calibration process challenging. specifically about 40 percent of participants reported that grabbing and moving the virtual cube was somewhat difficult, and 30 percent found it somewhat difficult to align the virtual cube with the physical device. Since the full process of calibration requires generating a cube, and then grabbing and aligning it with a physical device, the complexity might overwhelm first time users. Additionally, one participant mentioned that it would be useful to have some hints or tips that indicate whether the cube is in the correct position.

6.1.2 Interaction with Menu

Thought observations, there were noticeable issues with hand interactions. For examples, many participants struggled with pressing down the menu button located on their wrists and the buttons within the menu. They often thought they had pressed it but in reality they were just hovering over it. The result of survey also reflect that with generally 80 percent of participants have positive attitudes toward the interaction with menu, around 30 percent found it neither easy nor difficult to open and press the button within the menu.

6.1.3 Instruction UI

Feedback on the instructional interface was generally positive, with most finding the instructions very useful. While through observations, a few participants did not follow the instructions despite that instructional texts and videos were provided at the beginning. Therefore, they lacked the understanding of how to use hand gestures effectively. Participants tend to prefer video demonstrations over text descriptions for instructions. One participant with nearsightedness pointed out that text descriptions are not friendly to people like him.

6.1.4 Visual Feedback

The majority of participants affirm that the displacement and rotation of the virtual bone felt genuine and responsive. However, one participant mentioned that the sensitivity of the rotation components could be improved for better visualisation. This was because we deliberately exaggerated the amount of rotation for demonstration purposes, as otherwise the rotation would be too subtle and hard to see.

6.1.5 Graph

All participants agree that the graph is useful and could help students learning and they believe that this application is extremely useful for the learning of spinal mobilisation. However, one participant state that it would be useful if the system can provide an analysis or rating of the training task comparing to the benchmark. This feature would be quite useful for the self learning of students and could be included in the future.

6.2 Limitations

Lack of camera access for calibration: Since meta quest does not provide access to its front camera, we were unable to use the QR Code-based Calibration method [25] which is using QR codes as reference markers, allowing virtual object to load at a precise position when QR code was scanned. Users have to manually calibrate the virtual object with the physical devices and it is difficult to accurately map them together.
Limited precision and haptic feedback: current MR devices lack the precision needed for complex tasks like medical simulations and realistic haptic feedback is challenging to achieve. Although our application provides multiple sensory feedback, haptic feedback only works on stiffness functionality, impacting the realism for user experience.
Lack of real data: threshold for colour changes and pressure force displayed on the graph are not calibrated to the real data, limiting accuracy and realistic.

6.3 Future Work

Streamlining calibration: Since the current calibration process lacks accuracy in aligning with the physical devices (SpinalLog and vARtebra), we should develop an easier and faster method to calibrate the virtual model with them. One of the possible solution is to have users point to two opposite corners, allowing our application to detect the finger positions and automatically allocate the virtual objects based on the inputs.
Correct technique indication: Currently the visual bones change colour to red when too much force is applied to the physical device. However, there is no indication when the mobilisation techniques are correct. It is possible to make the bone colour change to green if the applied forces is within the threshold, indicating that the technique is correct.
Enhancing Sensory Feedback: Currently our application only displays bone models, lacking immersive training experience. In the future, we plan to implement a human body model, and target the lumbar spine within the whole spine. We will also integrate audio feedback so that when students apply too much force, the human model will provide a notification. Additionally, since most participants ignore the current instructions, developing audio instructions can be more effective.
Accuracy: To enhance the accuracy of spinal mobilisation in our MR application, we plan to conduct additional user studies with physiotherapy instructors and students. By gathering quantitative feedback and testing data, we can recalibrate the parameters in our functions.
Graph Analysis: Currently, students can only determine if the general pattern matches the benchmark without understanding the degree of similarity. To facilitate this, a rating could be given to students after each trial

to quantify their performance. Additionally, incorporating AI tools for the analysis of historical data could significantly improve learning outcomes. For instance, AI could help discover which part of the mobilisation deviates most from the benchmark thus require most improvement.

Evaluation of Learning outcomes: To assess the impact and effectiveness of our visual feedback method on educational outcomes, we plan to conduct evaluations for both short term and long term. These evaluations will help us understand how effectively our application enhances the learning of spinal mobilisation and could guide further improvements of the application.

7 Conclusion

We aim to demonstrate that our mixed reality (MR) system provides a safer and more efficient environment for learning spinal mobilisation, by offering real-time visual feedback on applied forces, customisation settings to simulate various back conditions, and a cost-effective solution that makes physiotherapy education more accessible. The development of this MR application addresses critical gaps in traditional physiotherapy education, providing immersive, real-time feedback and hands-on practice within a safe, simulated environment. Through the integration of visual and haptic feedback, our solution enables students to practice and refine their techniques with precision, reducing the limitations of peer-based training and enhancing skill acquisition.

User evaluations from physiotherapy students and professionals underscored the system's effectiveness, with participants highlighting its intuitive design and significant potential to improve learning outcomes. While the current application supports essential functionalities, future enhancements will focus on refining calibration processes, enhancing feedback accuracy, and adding new features to further elevate the training experience. This MR-based approach demonstrates substantial promise in revolutionising physiotherapy training, offering a scalable, interactive, and accessible platform that meets the evolving needs of medical education. Our work serves as a proof-of-concept and provide basis for future implementations. To fully realise its potential, it is crucial to conduct thorough evaluations of the system's short-term and long-term effects on learning outcomes.

Acknowledgement

We are grateful to Dr Antony Chacon and Dr Arzoo Atiq for their invaluable guidance and support throughout this project. Special thanks to Dr David Kelly from the Department of Physiotherapy, and to all participants involved in the user testing.

References

[1] Australian Institute of Health and Welfare. Back problems, 2020. Accessed: 2024-11-10.

[2] Barsom, E. Z., Graafland, M., and Schijven, M. P. Systematic review on the effectiveness of augmented reality applications in medical training. *Surgical endoscopy 30* (2016), 4174–4183.

[3] Birkfellner, W., Figl, M., Huber, K., Watzinger, F., Wanschitz, F., Hummel, J., Hanel, R., Greimel, W., Homolka, P., Ewers, R., et al. A head-mounted operating binocular for augmented reality visualization in medicine-design and initial evaluation. *IEEE transactions on medical imaging 21*, 8 (2002), 991–997.

[4] Canadian Musculoskeletal Care and Research. FSTT Technology, 2024. https://www.cmcc.ca/research/fstt-technology https://www.cmcc.ca/research/fstt-technology [Accessed: 2024-11-05].

[5] Chacon, D. A., Velloso, E., Hoang, T., and Wolf, K. Spinallog: visuo-haptic feedback in musculoskeletal manipulation training. In *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction* (2019), pp. 5–14.

[6] Downie, A. S., Vemulpad, S., and Bull, P. W. Quantifying the high-velocity, low-amplitude spinal manipulative thrust: a systematic review. *Journal of manipulative and physiological therapeutics 33*, 7 (2010), 542–553.

[7] Freburger, J. K., Holmes, G. M., Agans, R. P., Jackman, A. M., Darter, J. D., Wallace, A. S., Castel, L. D., Kalsbeek, W. D., and Carey, T. S. The rising prevalence of chronic low back pain. *Archives of internal medicine 169*, 3 (2009), 251–258.

[8] Garcia Fierros, F., Moreno Escobar, J., Sepulveda Cervantes, G., Morales Matamoros, O., and Tejeida Padilla, R. Virtual cpr: Virtual reality mobile application for training in cardiopulmonary resuscitation techniques. *Sensors 21*, 7 (2021), 2504.

[9] Herur-Raman, A., Almeida, N. D., Greenleaf, W., Williams, D., Karshenas, A., and Sherman, J. H. Next-generation simulation—integrating extended reality technology into medical education. *Frontiers in Virtual Reality 2* (2021), 693399.

[10] Interaction Design Foundation. User-centered design, 2024. Accessed: 2024-11-10.

[11] Kamphuis, C., Barsom, E., Schijven, M., and Christoph, N. Augmented reality in medical education? *Perspectives on medical education 3* (2014), 300–311.

[12] Loranger, M., Treboz, J., Boucher, J.-A., Nougarou, F., Dugas, C., and Descarreaux, M. Correlation of expertise with error detection skills of force application during spinal manipulation learning. *Journal of Chiropractic Education 30*, 1 (2016), 1–6.

[13] Meta. Hand tracking on meta quest, 2024. Accessed: 2024-11-05.

[14] Meta. Meta xr all-in-one sdk. Unity Asset Store, 2024. Accessed: 2024-10-24.

[15] Meta. Unity isdk hand grab interaction, 2024. Accessed: 2024-11-05.

[16] My Choice Osteopathy. Mobilization Techniques for the Lumbar Spine, 2014. https://mychoiceosteopathy.wordpress.com/2014/10/20/mobilization-techniques-for-the-lumbar-spine/ https://mychoiceosteopathy.wordpress.com/2014/10/20/mobilization-techniques-for-the-lumbar-spine [Accessed: 2024-11-05].

[17] NASA. Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. Human Systems Integration Division at NASA, 1988.

[18] Opdenakker, R. Advantages and disadvantages of four interview techniques in qualitative research. *Forum Qualitative Sozialforschung = Forum : Qualitative Social Research 7*, 4 (2006), art.11–.

[19] Park, S., Shin, H. J., Kwak, H., and Lee, H. J. Effects of immersive technology–based education for undergraduate nursing students: Systematic review and meta-analysis using the grading of recommendations, assessment, development, and evaluation (grade) approach. *J Med Internet Res 26* (Jul 2024), e57566.

[20] Petersen, E. J., Thurmond, S. M., Buchanan, S. I., Chun, D. H., Richey, A. M., and Nealon, L. P. The effect of real-time feedback on learning lumbar spine joint mobilization by entry-level doctor of physical therapy students: a randomized, controlled, crossover trial. *Journal of Manual & Manipulative Therapy 28*, 4 (2020), 201–211.

[21] rehabstudents. Maitland Lumbar PAIVM (skeletal model), 2010. https://www.youtube.com/watch?v=t0OCzavA6SY https://www.youtube.com/watch?v=t0OCzavA6SY [Accessed: 2024-11-05].

[22] Stanney, K. M., Nye, H., Haddad, S., Hale, K. S., Padron, C. K., and Cohn, J. V. Extended reality (xr) environments. In *Handbook of Human Factors and Ergonomics*, G. Salvendy and W. Karwowski, Eds. John Wiley Sons, 2021, ch. 30.

[23] SurgeonsLab. Mixed reality and Virtual reality, 2024. https://d1soyzazbrp5cn.cloudfront.net/assets/images/MixedRealityAndVirtualReality.jpg https://www.surgeonslab.com/ [Accessed: 2024-11-05].

[24] Unity Technologies. Arduino bluetooth plugin. Unity Asset Store, 2023. Accessed: 2023-10-6.

[25] vgis.io. Using qr codes (qr-based calibration) kb-ap043. vgis Support, 2023. Accessed: 2023-10-24.

[26] XCharts Team. Xcharts: A powerful and flexible charting library for unity. GitHub repository, 2024. Accessed: 2024-11-04.

Appendix A: Questionnaire before development

1. What is your age?
2. What is your gender?
3. Are you a Teacher or Student?
4. Are you familiar with spinal mobilisation?
5. What is your career area?
6. Are you familiar with extended reality?
7. What limitations does spinal mobilisation teaching currently face?
8. What improvements can mixed reality bring to traditional training models?
9. What kind of features do you want to see if we implement an extended reality application to simulate spinal mobilisation?
10. What are your expectations for the mixed reality application?
11. Do you prefer to interact with the digital simulator menu using hands or controllers?
12. Are there any ethical concerns when using extended reality in physiotherapy training?
13. Have you ever experience any cybersickness (motion sickness) when using mixed reality devices?

`https://q.surveys.unimelb.edu.au/jfe/form/SV_bDGEjPrYyeb1Q4S`

Appendix B: User Evaluation

1. How easy is it to generate a cube?
2. How easy is it to grab and move the cube around in virtual space?
3. How easy is it to match the virtual cube with the physical device?
4. How easy is it to open the menu?
5. how easy is it to click the button in the menu?
6. Generally how do you find the interaction with the menu?
7. How do you find the instructions?
8. Do you find the displacement (up down movement) genuine, correct and responsive?
9. Do you find the rotation genuine, correct and responsive?
10. Do you find the change of colour functionality helpful?
11. How easy do you think switch from SpinalLog to vARtebra?
12. Do you find the graph useful and could help student learning?
13. Any suggestions for the overall visual feedback?
14. Overall, how do you think this VR app would help you learning spinal mobilisation?
15. Any other comments?

`https://q.surveys.unimelb.edu.au/jfe/form/SV_b8c2ctZTWMyes5w`

Appendix C: User Evaluation Results

Results can be accessed using University of Melbourne accounts.

https://docs.google.com/spreadsheets/d/1iiFAyuEXzGjlj5p2XiivM287ZNKm-ayFGv4iuFpe_Ho/edit?u
sp=sharing

Affinity diagram:
https://miro.com/welcomeonboard/NkhTOGorbnNMUnB1N1d6YSs1NEU2MithOG03RmUzL0ZDN2ZralY4TE9hMU9jeD
BteXZrbldaNHBpdVNpTTN0WjdnMnpHY0FYUVhFcGc3bXpkRFVRS3NIVmdjbnZON3NKaE55MjZ4QWxQM0VBaWpsY3FYSC9Q
OVRUTG9hUDNQWVchZQ==?share_link_id=528577313420.