An Immersive Haptic-enabled Training Simulation for Paramedics

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***Abstract*—This paper describes the integration of haptics support into a virtual reality training simulation aimed at skills retention for paramedics. We focus on a chest decompression, a life-saving invasive procedure used for trauma-associated cardiopulmonary resuscitation (and other causes) that every emergency physician needs to master. It is not regularly performed by a paramedic, however, and therefore skills maintenance is a challenge. In our simulation, a virtual Russell PneumoFix-8 device is used to carry out the procedure and it is controlled with the 3D Systems Touch grounded force feedback device. We describe how this device has been integrated into an immersive virtual environment so that it or any other tool can be used at any location in the scene. Quantitative data has been obtained from an evaluation exercise carried out with 21 paramedics. The majority of these participants reported a good feeling of presence, according to the Spatial Presence Experience Scale. They indicated strongly that the use of haptic-enabled simulators that include the kind of interaction techniques implemented in our simulator would be beneficial for training and skills retention. The realism of using the simulator at a 1 to 1 scale was also highly scored. A System Usability Scale was also calculated and the results show that the simulator is close to an acceptable standard for usability but more work is needed. We will address this in future work.**

***Index Terms*—human-computer interaction, haptic device, virtual reality, skills retention.**

I. Introduction

Any healthcare professional will learn a variety of skills for the effective treatment of their patients and such skills are refined and mastered through their repeated use. However, skills retention can become a challenge if a particular procedure is rarely performed. This is certainly the case for a paramedic who may be called upon to carry out a life saving procedure that they have not used for some considerable time. Simulation-based interventions and refresher courses are therefore required at regular intervals, typically organised and delivered at a central location. For example, Au et al. [3] have identified the positive impact of such courses for resuscitation skills retention. Simulation-based interventions often require the use of expensive resources, however, such as custom-made mannequins that are designed for a particular procedure. We have been investigating the feasibility of using more affordable resources that use Virtual Reality (VR) that can be deployed at the work place of a paramedic, providing them with a training opportunity whenever they have time available. VR supports a high level of immersion, and more variations of the training scenario than would be possible if using a mannequin. Our first prototype demonstrated the potential of this approach [13], [14].

This paper describes our recent work to enhance the support for haptics within our VR training simulator for paramedics, called ParaVR. Haptics pertains to the sense of touch and covers both tactile and force feedback. The use of haptics in a training simulator is not new [7] and there are many examples in the medical domain [6]. If used correctly, haptics will improve learning by increasing the immersion of the paramedic within the VR scenario and provide realistic force feedback as they interact with a virtual patient.

We focus on a chest decompression, a life-saving invasive procedure that every paramedic needs to be able to carry out. It involves inserting a special type of needle (called a Russell PneumoFix-8) into a predefined location on the chest. Haptic feedback is crucial when training this technique, as the paramedic is guided largely by their sense of touch whilst making the insertion. A grounded force feedback haptic device such as the 3D Systems Inc. (Rock Hill, South Carolina) Touch is the most suitable for this task - see Figure 1. Through the manipulation of the end-effector stylus, the user can move the virtual tool used in the procedure (input) and feel the forces applied to the virtual tool as it is inserted into the chest (force output).

In the next section we summarise related work and discuss the limitations of using a grounded force feedback device as the main mechanism for interaction in immersive VR environments. Section 3 provides the detail of our ParaVR implementation and how it has been adapted with a new approach for supporting haptics devices. Section 4 presents the results of a validation study carried out with paramedics at three local ambulance centres. The paper concludes with a discussion and plans for future work.

II. Background

In the past five years, cost-effective Head Mounted Displays (HMDs) for immersive VR have become readily available. They are typically used in combination with two hand controllers that can be tracked, or more recently by directly tracking the users hands. HMDs can be tetherless and contain an in-built computer for running the VR application. Those HMDs connected to a host computer (wired or wireless) can take advantage of the full computational power of the host PC's graphics card and CPU. Support for haptics has been limited to tactile feedback with the hand controllers being made to vibrate as the user interacts with objects in the virtual scene.

Providing force feedback within immersive VR is more of a challenge. There are force feedback gloves in development such as those from VRGluv (Atlanta, Georgia) but such products are still in their infancy. The main option currently available is to use a grounded force feedback device such as the 3D Systems Touch (formerly called the SensAble Technologies PHANToM Omni). This device has been available in different forms for over twenty years [12]. It offers six degrees of freedom for input gestures, and three degrees of freedom for force output (up to 3.3 N). However, the work space of the Touch is constrained by the physical movement possible of the end-effector stylus, which is 16 cm x 12 cm x 7 cm (W x H x D). The challenge is to integrate such a device seamlessly into a potentially much larger virtual work space. One approach is to change the Control-Display Gain (CDG) so that small movements of the haptics end effector are mapped onto much larger movements in the virtual space. Li et al. [11] have shown that this will reduce task completion time at the cost of task accuracy and could negatively influence user confidence in completing the task.

Another approach is called the "bubble" technique [8] and is used to relocate the device work space, which is displayed visually using a semi-transparent sphere (the bubble). When the end-effector is located inside the bubble, its motion is position controlled with direct mapping of the end-effector's motion to the location of the bubble. When outside the bubble it is rate controlled and uses a faster coarser positioning of the bubble. Force feedback is applied when crossing the surface of the bubble. However, this feedback comes from the technique itself and does not feel realistic. It can alter the users' perception, which is not desirable in medical simulation. Also, the bubble technique does not perform well when using it in immersive VR. The bubble, or the haptic work space, is never mapped to the user's point of view or head orientation. This can cause situations in which from the point of view of the user, they push the haptic stylus forward but the bubble moves from left to right.

Fig. 1. ParaVR being used. The paramedic wears an Oculus Quest connected to a laptop and interacts with the simulation using the Touch haptics device. In the virtual world he is kneeling over the crash victim.

If eye tracking hardware is available then gaze interaction can be used to relocate the device work space. Li et al.'s [10] gaze-switching workplace approach allows the user to gaze at a target in the VR scene for a predefined period of time, resulting in the device work space being relocated and locked onto this target. They obtained an improvement in interaction efficiency, kinaesthetic perception accuracy and overall user experience. However, it is noted that they used a CDG of 4 in this work and so the positional accuracy would have been reduced. Eye tracking hardware is starting to be integrated into high-end HMDs such as the HP Reverb G2 Omnicept Edition and HTC Vive Pro Eye, or can be purchased as an add on. This functionality is not yet available for the entry-level HMDs.

III. The ParaVR Simulator

ParaVR has been built using the Unity (Unity Technologies, California) software, leveraging on its support for VR HMDs, and the 3D Systems Openhaptics Unity Plugin. An Oculus Quest HMD has been tethered to the host computer (Windows 10 laptop PC with Intel Core i7-7700HQ CPU and NVIDIA GeForce GTX 1060 GPU) using the Oculus Link USB-C cable. An advantage of the Quest is that it does not require the installation of separate sensors for room scale operation. The 3D Systems Touch force feedback device is connected to a USB port on the host computer. Figure 1 shows all of the equipment being used.

A. Chest Decompression

The procedure that can be trained with this version of ParaVR is called a chest decompression. It is a procedure for treating tension pneumothorax, which can be caused by a head-on motor vehicle accident. It develops when an injury is such that air accumulates between the chest wall and the lung and increases pressure in the chest, reducing the amount of blood returned to the heart, causing shock. A large needle must be inserted into the pleural space to remove the air (called needle decompression). Then a chest tube is inserted to continue to drain air and allow the lung to re-inflate. Usually local anesthesia is used. A device called the Russell PneumoFix-8 has been designed for performing chest decompression and this is what we use in the simulator. It consists of a combined verres-tipped needle and 11cm catheter with graduated markings and allows for insertion without the need for a scalpel or skin incision. It should be inserted in the 2nd intercostal space in the anterior mid-clavicular line and perpendicular to the chest wall, just above the 3rd rib. Once the catheter tube is in position the needle is decoupled and removed in order to let the air flow in and out the chest of the patient through the catheter.

B. VR Scene Set Up

At the beginning of the simulation, the ambulance has just arrived at the scene of the accident and the paramedic enters the simulation standing over the crash victim who is lying on the ground - see Figure 2. The need for a chest decompression has been diagnosed and the tools required have been placed alongside the victim. The paramedic must apply local anaesthetic and then proceed to deploy the Russell PneomoFix-8 correctly. The input device for each of these steps is the Touch device. The vital signs of the crash victim can be displayed and will change dynamically as the procedure progresses.

Third party models have been used for assets such as the ambulance and other vehicles. An appropriate outdoor scene was created, including sound effects of passing traffic and general nature sounds to add an extra feeling of immersion into the scene. We have developed two models for the crash victim: an average male adult; and an obese male adult. This is to demonstrate patient variability and female and child models will be added in the future. Optionally, the crash victim's skin can be made transparent revealing the underlying anatomy. A marker showing the entry site can also be displayed. These are useful for reviewing the accuracy of performing the procedure and will typically be a part of a debrief discussion between the trainer and the trainee. The model of the Russell PneumoFix-8 was created to scale using the Unity editor. Further details can be found in [14].

C. Haptics Integration

The original ParaVR prototype experimented with using a Novint Falcon haptic device for controlling a needle and transmitting force feedback to the user when the needle goes through the skin. The Falcon was low cost ($250) but had only 3 degrees of freedom for input interaction, and a small work space (10cm x 10cm x 10cm). This made it unsuitable for controlling the orientation of the needle with its end-effector. As the Novint Falcon is also no longer in production, ParaVR is now using the Touch device (Figure 1). It is more expensive

Fig. 2. The initial ParaVR scene.

than the Falcon ($1,200) but is currently the cheapest commercially available option. We benefit from six degrees of freedom for interaction and a slightly larger device work space. It is well suited for simulating many medical devices as holding a stylus is similar to holding a needle, for example, and the stylus can also be replaced with 3D printed models of the real tools used in the procedure as we have done in previous work [4]. To use within Unity, we have deployed the 3D Systems Openhaptics Unity Plugin. It is freely available from the Unity asset store and it can be imported into the project directly from there. The plugin includes a manual for its utilization, some demonstration scenes, pre-built components and scripts to apply haptics effects to any object in the Unity editor. Details of the haptics rendering algorithm, including how collision detection is performed, are managed by the plugin.

The Touch still has a limited work space, however, as the movement of the end-effector is constrained by the length of the device's mechanical arm. This makes it difficult to integrate this kind of device as the principal mechanism for interaction in VR. This problem is often solved by applying a scale factor to the movements of the end-effector, resulting in a virtual work space bigger than the physical one. However, the spatial accuracy is severely affected, which is not acceptable in medical procedures simulators.

In this work a 1:1 mapping between the physical and the virtual work space is applied by default i.e. the Control-Display Gain (CDG) is 1. A representation of the virtual work space is always visible in the scene to help the paramedic identify those elements that will be touched (see Figure 3) and we implement a mechanism that allows the user to freely move the virtual work space to any location in the scene. In this way, the level of accuracy is not affected and the paramedic can interact with any part of the crash victim's body, and change

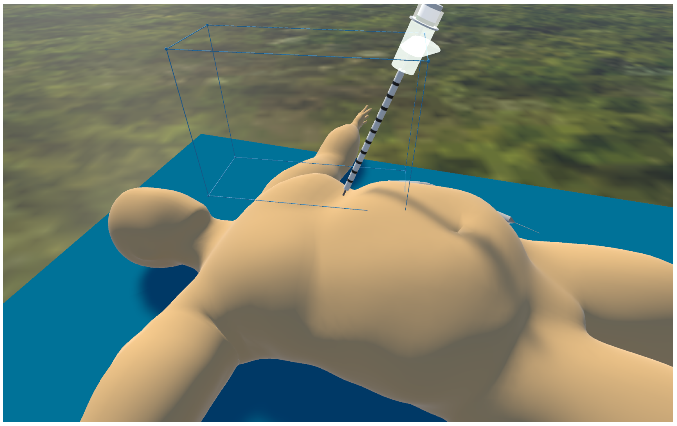

Fig. 3. The Russel Pneumofix-8 device being used on the obese adult male model. The wireframe cube represents the device work space in which haptics effects will be perceived.

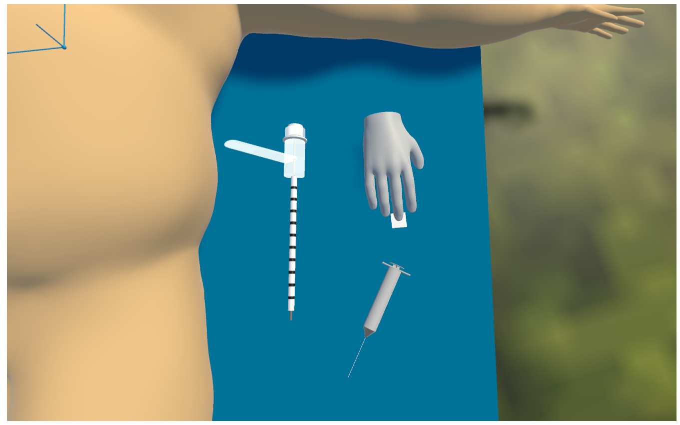

Fig. 4. The virtual tools needed for performing a chest decompression.

the tool needed in the procedure. A special relocation mode has been developed for this purpose. Within this mode the virtual work space is linked the the user's head movements so that using the VR headset the user can move their head towards the desired position to fix the work space in a new location. This does not require the use of eye tracking hardware.

Using a CDG of 1 by default ensures a realistic behaviour when manipulating tools within the simulator. However, the user can also increase or decrease the CDG value at run time. The higher the CDG value, the greater the freedom of movement. The lower the CDG value, the higher the accuracy in the movements. As modifying the CDG value modifies the size of the virtual work space, it is necessary to modify and adapt the representation of the work space in order to keep the user informed about the objects that can be interacted with.

Different tools have been added to the scene in order to allow the user practice the procedure in the correct sequence. The user can move their head and look at the set of tools available and select the desired one by pressing the buttons on the Touch stylus. The haptic feedback is also modified depending on the selected tool. For example, with the Russell PneumoFix-8 tool selected the needle can go through the skin and the user can feel the force effect of insertion while with the cotton swab tool the user can feel the surface of the body while cleaning the insertion area.

The simulation starts with the paramedic in a standing position near the crash victim. The crash victim can be selected at this point from all of the available models that demonstrate patient variability. The haptic device is placed on the floor near the paramedic, matching its position to the crash victim's body position. The paramedic should kneel down in order to grab the haptic end-effector and start the procedure. By default, the selected tool is a hand for exploring the crash victim's chest. In the tool set there is a cotton swab to clean the insertion area, a syringe with local anesthesia and the Russell PneumoFix-8 tool (Figure 4). The paramedic should select the right tool for each step. After the area is cleaned and the anesthesia is applied, the Russell PneumoFix-8 tool is inserted. Vidal et al. [15] determined the force at which a needle penetrates tissue is around 1.5N to 1.8N. This is within the range of the Touch device, which can deliver a maximum force output of 3.3N. Using the Openhaptics plugin, the force output is defined as a fraction of the maximum force (between 0 and 1) and so 0.45 is equivalent to 1.5N. This value has been distributed into the stiffness and pop-through parameters for the average adult male model, with values of 0.40 and 0.05 respectively. The resulting effect when the needle pierces the skin feels realistic. Patient variability can be introduced by changing the values of these parameters and more force is required when using the adult obese male model. Also, if the needle touches one of the ribs it will be felt by providing a high force feedback. At the final step, when the Russell PneumoFix-8 tool is in the desired position inside the chest of the crash victim, the paramedic can decouple the catheter and the needle in order to extract only the needle and keep the catheter in place.

IV. Evaluation

An initial evaluation of the simulator has been performed by twenty one paramedics from three regional ambulance centres (Welsh Ambulance Services NHS Trust headquarters, Wrexham Ambulance and Fire Service Resource Centre (AFRSC) and Newtown Ambulance Station). To maximise the availability of participants, four sessions were organised across three different days. A total of 9 male and 12 female paramedics were recruited with an age range spanning from the mid 20s to the over 50s. All the participants except one declared no previous experience in using virtual reality and none had previously used a haptics device. We also screened for colour blindness and stereo blindness. Following the first two sessions, the way in which tools were selected was made slightly simpler to use. This was not a significant change and therefore data collected across all sessions are equivalent and comparable.

A. Simulator Set Up

The demonstration environment was prepared identically at each of the three locations. It consisted of a Windows 10 laptop computer (with an Intel Core i7-7700HQ CPU and

Nvidia GeForce GTX 1060 graphics card) connected to the 3D Systems Touch haptic device and an Oculus Quest VR headset. A cushion was placed near the haptic device indicating the position at which the paramedic should kneel so that they are alongside the crash victim in the virtual world. The Touch device is placed on top of a small box so that it is at an optimal position for the intended usage in the chest decompression scenario. These can all be seen in Figure 1, which shows one of the paramedics using the simulator.

As the evaluation took place during the COVID-19 pandemic, we implemented the following safety procedures to reduce the risk of transmission to participants. Hand sanitiser was used upon entry and all participants and researchers wore a mask throughout the session. However, it was necessary for some to pull down the mask below the nose whilst in the VR headset to avoid fogging. VR equipment and surfaces were cleaned after each use, including the use of a Cleanbox [1] to further sanitise the VR headset. At any one time the number of people in the room being used was limited to within the total deemed acceptable for social distancing.

Before starting the evaluation the simulator was described to the paramedics including what they are going to see in the scene, what a haptic device is and how they can use it to interact with the elements in the scene to perform the procedure.

The two buttons on the Touch stylus are used to lock the haptic work space into the desired position, relocate the haptic work space, or select and use a different tool. A small black dot is used as a reticle to indicate to the user where they are looking. In the initial implementation, when the reticle is at the center of the work space the user could double click the lower of the stylus buttons to switch to relocation mode. This switching process was simplified after the first testing session to only require a single button click and without the need for the reticle to be in the center of the work space. Once in relocation mode, the work space can be placed anywhere in the scene by orientating the headset to look at the desired position and adjusting its distance by pressing and holding the appropriate stylus button (one moves it further away and the other moves it nearer). Once the work space is in the desired position it can be locked by clicking the same button again. Tool selection is performed when in relocation mode by orienting the headset so that the reticle is on the desired tool and then clicking the stylus button. Out of relocation mode, the needle of the Russell PneumoFix-8 device can also be decoupled from the catheter by clicking the second button. In addition, the CDG value -and the size of the work space- can be modified when out of relocation mode by pressing and holding the buttons. However, in this scenario the CDG was always kept at 1.

The instructor can select which model to use for the crash victim (average male or obese male). At the start of the VR session, the paramedic is asked to stand next to the cushion and to put on the VR headset. They are then immersed in the accident scene and experience the sights and sounds of the environment. The paramedic has been briefed that they need to perform a chest decompression and once they kneel down they can begin the procedure. The simulation then follows the steps described in the previous section. When carrying out the procedure, assistance was provided to the paramedic on which stylus buttons to press. The instructor can also make the skin of the patient transparent revealing the bones of the skeleton as a further aid for selecting the correct entry position.

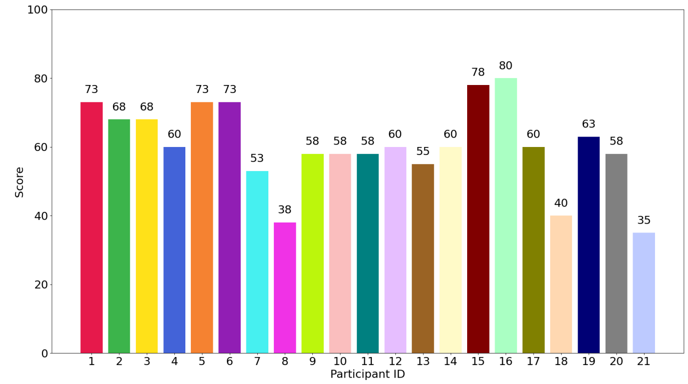

Fig. 5. SUS score by participant.

B. Results

After completing the simulation task, the paramedics filled out a questionnaire to rate their level of agreement with a series of statements using a 5 point Likert scale. The questionnaire included the ten statements of the System Usability Scale (SUS) [5], the eight statements of the Spatial Presence Experience Scale (SPES) [9] and five specific statements addressing the quality of the interaction technique. All data collected is accessible in [2]. The goal was to get initial data on the face validity of ParaVR. Figure 5 presents the resulting SUS scores from each participant, and Table I lists the interaction technique specific statements with the average score obtained from the 21 paramedics. The results of the SPES are divided into Self-Location (SL), addressing how the paramedic felt inside the simulation, and Possible-Actions (PA), addressing what they could do inside the simulation. The average for all participants are SL: 3.55 ($\sigma = 1.08$) and PA: 3.58 ($\sigma = 0.81$). This gives an overall average score for Presence of 3.57 ($\sigma = 0.89$).

V. Discussion and Conclusion

The SPES results shown above indicate that the simulation achieves good levels for both the SL and PA categories, so the paramedics actually felt as if they were in a real accident scenario and capable of performing the actions needed to successfully carry out the procedure. They commented on the use of multiple senses (vision, touch and audio) as all being contributing factors. Only one paramedic rated both SL and PA negatively (with averages of 1.25 and 1.75 respectively). Another participant rated SL negatively (1.25 on average) but PA positively (3 on average). The average score of the other 19 participants is 3.79 ($\sigma = 0.8$) and 3.71 ($\sigma = 0.71$) for SL and PA respectively, meaning that the majority had a good

TABLE I
INTERACTION TECHNIQUE SPECIFIC STATEMENTS SCORES.

Statement	Average score
I found it easy to move the haptic work space around the scene and train the procedure	3.86 ($\sigma = 0.85$)
Using the simulator at 1 to 1 scale is realistic	4.14 ($\sigma = 0.57$)
I found it useful to be able to relocate the work space so that I could interact with the patient's body and perform the puncture	4.19 ($\sigma = 0.75$)
Changing the size of the work space would offer more flexibility for using different tools	3.85 ($\sigma = 0.96$)
The use of haptic simulators that include this kind of interaction techniques would be beneficial for my education/training/skills retention	4.33 ($\sigma = 1.11$)

feeling of presence. There are almost no differences between the two categories showing that the simulator is balanced in terms of immersion and actions.

Despite the paramedics having no prior experience of using VR and being asked to perform a complex series of steps, they have given a favourable rating for the interaction technique that we have developed for using the Touch in a virtual environment. Almost every paramedic agrees or strongly agrees with the statement that ”The use of haptic simulators that include this kind of interaction techniques would be beneficial for my education/training/skills retention”. They also rate it as realistic in using a 1 to 1 mapping between the physical haptic stylus and the virtual tool, reinforcing our hypothesis that using haptic-enabled simulation in a medical procedure requires a CDG of 1 to be applied by default. The ability to relocate the virtual work space has also been found useful with an average score of 4.44 out of 5. However, in the first two evaluation sessions some paramedics struggled with the process of switching to relocation mode (placing the reticle in the center of the work space and then double clicking the lower of the stylus buttons). If the patient's body is in the middle of the work space it can block the indicator and they do not know where to place the reticle to make the double click. Thanks to the simplification of this switching process none of the paramedics who participated in the other sessions reported any difficulties in this process. Another limitation described by the paramedics is that sometimes it is not possible to keep the haptic stylus vertical when performing the insertion because it hits the mechanical arm of the device itself. The insertion starting point therefore needs to be selected carefully taking this limitation into account.

The scores from the System Usability Scale show that the system is close to an acceptable level for usability but more work is required. The average SUS score obtained from the participants was 60.12, whereas 68 is the threshold defined by SUS for achieving a good level of usability. Seven of the paramedics have given a score of 68 or better, and the maximum score given by one of the participants has reached 80. Ideally we would like to achieve scores of 80 and above. The other 14 of the paramedics currently rate below average. However, this was their first experience of using a VR simulator and the Touch device and several paramedics noted that they would get more proficient after some practice.

Verbal comments from the paramedics also indicated other areas where improvements should be made. The force felt when running the hand over the chest should enable the third rib to be identified without having to make the crash victim's skin transparent. This will require incorporating tissue deformation into our model. The force feedback also needs to be improved to give better fidelity for the insertion of the Russell Pneumofix-8. Although, the Touch device has been shown to be suitable for needle puncture procedures [15] and the maximum force output of 3.3N is sufficient, more data on the force needed for insertion of the Russell Pneomofix-8 is needed. Finally, the correct position of the Russell PneumoFix-8 could be displayed for comparison with the trainees attempt, and sometimes alternative insertion sites are used.

Summarising, a new virtual reality haptics-enabled simulator for training the chest decompression procedure has been presented. Our focus in this paper has been to investigate how to efficiently use the Touch haptics device in an immersive VR scenario such as this. It includes the first implementation of a new technique addressing the limited work space of this kind of haptics device such that it allows a flexible VR experience whilst maintaining a good level of accuracy. The simulator has been introduced to and tested by 21 paramedics and the results have shown that it offers good levels of immersion and face validity has been demonstrated. The haptic interaction technique has been positively rated and the usability of the simulator is promising given that none of the paramedics had previous experience with haptics or virtual reality, but more work needs to be done in this area.

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