

The Design of a Haptic Simulator for Teaching and Assessing Spinal Anaesthesia

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Abstract

Through an interdisciplinary design process we have created a haptic simulator to mimic the physical and sensory environment surrounding the performance of spinal anaesthesia. Our simulator utilises existing haptic toolkits to reproduce tissues and surfaces in a realistic way. It simulates needle insertion with audio and visual (2D/3D) feedback occurring during the actual procedure. The overall simulation system is designed for being an integral part of an existing curriculum and offers excellent potentials in assessing procedural skills in a safe and controlled environment.

Keywords: Haptics, Virtual Environments, Simulation, Medical Training, Medical Assessment

1 Introduction

The nature of medical training is undergoing major change world wide. The reasons for this include alterations in doctors work practice, patient expectations and new employment legislation e.g. the European Working Time Directive. It is less acceptable that doctors in-training practice their procedural skills on patients. One solution is to simulate medical procedures using advanced computer technology, such as Virtual Reality (VR) and haptic feedback. Haptic refers to technology that interfaces the user via the sense of touch with computer-generated sensations using robotic equipment (Srinivasan and Basdogan, 1997). The medical procedure known as spinal anaesthesia was selected as the subject for investigations and simulator development.

This paper describes how existing technology and some specific technical solutions have been utilised for rapid prototyping of a simulator, creating a promising platform for teaching and assessing medical procedural skills and a potential tool for assessing other, relevant competencies associated with the procedure of spinal anaesthesia.

Through an interdisciplinary design process (Klein, 1990), the simulator was developed involving medical doctors, interaction designers, psychologists and system developers collaborating closely throughout the process.

1.1 Procedure of Spinal Anaesthesia

Spinal anaesthesia involves injecting a small amount of local anaesthetic through a needle inserted between the spinal vertebrae, below the end of the spinal cord into the surrounding spinal fluid. The local anaesthetic quickly blocks the patient's sensations below the point of injection providing excellent operating conditions for surgery on the lower part of the abdomen and legs.

Almost always, the procedural skill of spinal anaesthesia is learned by watching a more experienced practitioner and subsequently performing the procedure on a patient under close supervision. Clearly this process has disadvantages. The patient can be put at risk by having a potentially hazardous procedure performed by a trainee. The training opportunities are limited by the type and number of patients who are suitable for the procedure of spinal anaesthesia during the time of the training.

1.2 Design Criteria from Literature

The criteria presented in this section are derived from simulators designed for spinal anaesthesia, lumbar puncture and epidural anaesthesia. These three procedures enjoy common factors i.e. anatomical area, sensory experience and location of needle insertion.

Several VR simulators have been used for training in epidural and lumbar puncture. One of the earlier explorations was made by (Singh et al. 1993). This work has followed by several others (Gorman et al, 2000; Dang et al, 2001; Magill et al, 2003; Wilson et al, 2004; Färber et al 2007). However, the work these papers describe does not take the overall curriculum into account during the design process, an issue addressed in the general simulation literature (Gallagher et al, 2005; Reznick et al, 2006; Dawson, 2006).

From these previous simulators important criteria can be derived that should influence the design of a haptic simulator for lumbar puncture, spinal and epidural anaesthesia. These are: reliable and robust reproduction of the human tissues, interactive visualisations of relevant anatomy, providing needle insertion and the possibility to create different procedure-related scenarios (variation in anatomy etc.). These design aspects also correlates to suggestions occurring in the medical simulation literature in general (e. g. Issenberg et al, 2005; Reznick et al, 2006).

1.3 Design Criteria from Determinant Study

To identify the educational aspects associated with the procedure, key determinants of teaching and learning spinal anaesthesia were identified by the authors using questionnaires and focus group discussions of experts and trainees (Kulcsár et al, 2008). One important determinant identified was recognition of certain characteristic sensations as spinal anaesthesia is performed. Both experts and trainees agreed that acquiring the ability to recognise these sensations was a significant element of learning to perform spinal anaesthesia. Several clinicians firmly believed that the only way to acquire this skill is by recurrently performing (or practicing) spinal anaesthesia on patients i.e. learning by doing.

Some additional important determinants identified were: an explicit knowledge program for applied anatomy (enables learners to visualise the relevant anatomy), a case-based learning program and from a trainer's perspective a valid, reliable competence assessment procedure.

2 The Simulated Procedure

In the real procedure, the practitioner first inserts the thicker and shorter introducer needle to puncture the skin, selecting the skin puncture point and orientation of the introducer based on anatomical landmarks (spineous structure) identified by palpation with the other hand (i.e. non needle holding hand) and visual cues.

After that, the longer and thinner spinal needle is advanced through and beyond the introducer. The spinal needle is inserted all the way in to the intrathecal space, which lies inside the dura mater and contains the spinal cord surrounded by cerebrospinal fluid (the spinal needle is inserted at the lower part of the human back). See Figure 1 for a conceptual sketch of each layer. The local anaesthetic agent is injected into the intrathecal space. The simulator reconstructs all of these steps except the actual injection of the local anaesthetic and palpation. These particular parts of the procedure is left out because of technical limitations but will be implemented in the

future. Some doctors insert the spinal needle directly without first placing the introducer. The simulation also offers this option.

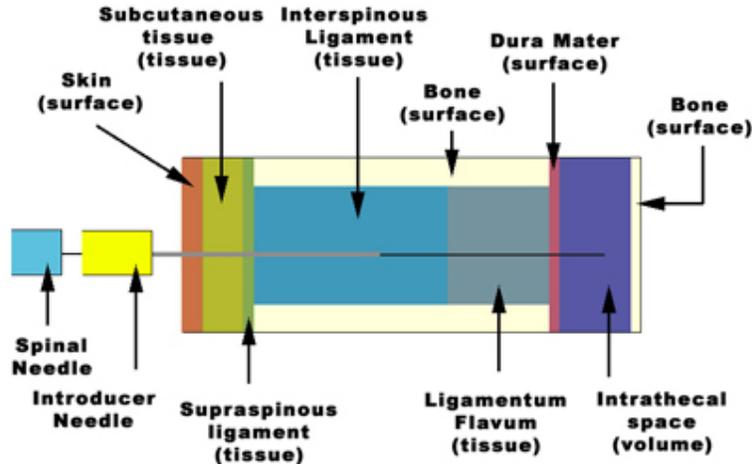


Figure 1. A conceptual, 2D cross-section of the human back showing each layer that the introducer and spinal needle has to penetrate. It also illustrates if the layer is modelled as a surface or a tissue (volume).

3 User Interface Design

The view for the user is a 3D model of the lower part of a human back. The simulated back is inside an enclosure of five surrounding walls to enable the user to see direction when navigating the spinal needle in the virtual environment.

In the top left corner is a 2-dimensional visualisation (Computed Tomography (CT) image) of the human back. Underneath is a menu providing choices, such as switching the needles, rotation of the human back and toggle audio feedback on and off. To facilitate easier selection, buttons are large. The buttons have haptic surfaces to provide feedback when touched and require a slight tap for selection. Figure 2 shows a screen capture of the interface and virtual environment.

Furthermore, all selections and actions in the interface/environment are performed with the haptic device. Using a mouse or a keyboard would likely result in a loss of immersion and possibly draw attention away from the task.

To create a more intuitive and realistic environment, an actual spinal needle is attached to the apex of the mechanical arm, allowing the user to go through the motion of insertion, penetrate and feel the different layers, thus providing the sensation of handling a real spinal needle.

The movement of the spinal needle, both in the clinical and virtual settings, takes place in a three dimensional space. In the latter setting, when using a normal PC-monitor it can be hard to judge the spatial relationship between objects. To make navigation easier, a SenseGraphics Immersive Workbench with stereoscopic glasses (www.sensegraphics.com), see Figure 2, was selected to create the illusion of seeing depth on the screen and enabling the creation of a shared workspace, i.e. what is displayed on screen is mapped over the force feedback device.

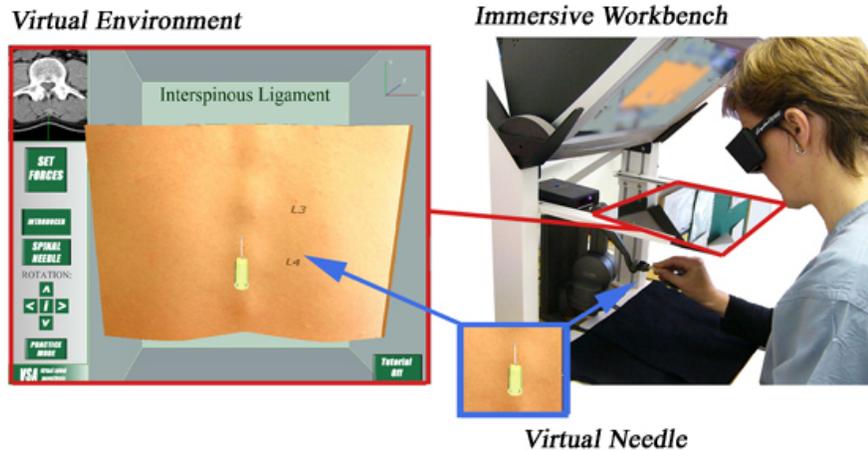


Figure 2. The movement of the haptic device corresponds to the movement of the needle in the virtual environment. An Immersive workbench is used to create intuitive interaction, where a mirror is used to display the virtual environment above the device.

4 Technical Aspects

For the implementation of the virtual anatomy and the force feedback properties, the software development environment H3D API (www.h3d.org) is used with the extension Volume Haptics Toolkit (VHTK) (Lundin et al, 2005).

4.1 Human Tissue Modelling

The needle insertion module is facilitated through a haptic device. The simulator utilises such a device, a Phantom Desktop (Sensable Technologies, www.sensable.com), which has been programmed to reproduce the sensations of needle insertion.

The simulation of the haptic feedback of the human back is divided into three different sensations: *surface tension*, *surface pop* and *volume resistance*.

Surface tension is modelled with a mass-spring system using the properties provided by the H3D API. The API's sensations are modified to create realistic stiffness and friction models of properties such as the density of skin which varies depending on age, obesity and other factors. It is also used to implement the pop sensation, which occurs for skin and dura mater. The haptic feedback from a surface is turned off when the user applies a certain amount of force with the needle; the needle penetrates the surface and moves into the next layer.

Once through the skin and into tissue, volume sensations are created to mimic this viscous environment. The Volume Haptics Toolkit is modified to facilitate the creation of multiple viscosities to parts of the human back thus creating the perception of penetrating a physical volume. The tissue sensations are generated by the equation [1], originally developed by (Lundin et al, 2005). The resulting force is represented as a point primitive (i) and calculated by the primitive position, its strength (s_i) and the proxy position.

Initially, each layer has default values set based on the perceptual experiences of the medical experts within the interdisciplinary design group for different cases. Other, more objective methods exist, for example using actual force measurement from a patient (Brett, 1997). However, the existing data for this is limited. In reality, these sensations can vary greatly from patient to patient depending on age, obesity and other factors. The method of using perceptual experience of medical experts allows the simulation to cover a wider range of patients. The

experts can within the simulation interactively adjust the parameters related to each surface and tissue sensation, customising the haptic properties of the back to different anatomic cases.

$$[1] \quad \vec{f}_i(\vec{x}_{proxy}) = \begin{cases} \vec{0}, & \text{if } \left| \vec{x}_i - \vec{x}_{proxy} \right| = 0 \\ s_i \frac{\vec{x}_i - \vec{x}_{proxy}}{\left| \vec{x}_i - \vec{x}_{proxy} \right|}, & \text{if } \left| \vec{x}_i - \vec{x}_{proxy} \right| \neq 0 \end{cases}$$

4.2 Needle Insertion Modelling

The haptic device used in this project has force feedback in 3 degrees of freedom. This means that it has force feedback at the needle tip, but the rotation around the needle tip, cannot be mechanically controlled. The real life situation, where the shaft of the needle is under pressure by surrounding tissue, is not possible to model with the current device. An alternative solution has to be developed. Once the virtual skin is punctured: i. the needle on screen is visually fixed along the insertion direction (when inside the back, the virtual needle maintains the initial direction of insertion) ii. the needle tip (haptic device) is fixed along the vector of the initial insertion direction using a haptic spring force (the haptic device can only be moved short distances sideways and cannot diverge from the insertion direction). The same technique is used for constraining both the introducer and spinal needle. When the spinal needle enters the introducer needle, the guide is turned on, fixing the spinal needle within the introducer direction. If a needle is withdrawn, the guiding force will turn off at the same place as it was turned on.

4.3 Creating the Virtual Anatomy

The 3D model of the human back was modelled from CT-scans using commercially available 3D modelling software. The resulting model was adjusted and validated by the medical experts of the interdisciplinary design team. More sophisticated methods for extracting anatomy could have been utilised, e.g. (Wallin, 1991). However, extensive manipulation of this data would be required, as CT scans are not feasible to generate in the curved position (either sitting or lying) required by the patient for successfully performing the procedure.

The resulting model was agreed by the interdisciplinary design team to meet the required learning criteria, as discussed by others, such as (Scerbo and Dawson, 2007).

5 Learning Considerations

Providing learning considerations in the simulator is achieved through the iterative interdisciplinary design process involving medical experts, current methods of education in spinal anaesthesia and the results of the research of the determinants of the spinal anaesthetic procedure.

5.1 Visualisations

The texture of the virtual human back is solid by default and turns transparent only when the back is rotated or if the procedure is performed in an unsuccessful manner. The clinicians rely largely on their sense of touch when advancing the needle through the different layers; hence constant transparency would provide too much information during the learning process.

To get a better understanding of the relevant anatomy, the virtual back can be rotated both with and without the needle inserted, see Figure 3 (a). For example, if the needle is touching bone, it can be left in place and then rotated and viewed from different angles for exact observation of

how and where the misplacement occurred. From this information, the user can derive a greater understanding of the visuospatial structure for needle placement.

To enhance the visualisation (and understanding of the procedure) further, a 2D representation of the back displays where the needle is inserted and the point at which each layer is penetrated. This is done by mapping the xy-coordinates of the needle over a CT image of the back, see Figure 3 (b). Text feedback is also provided, so that the trainee can identify the layer in which the needle is located at any time.

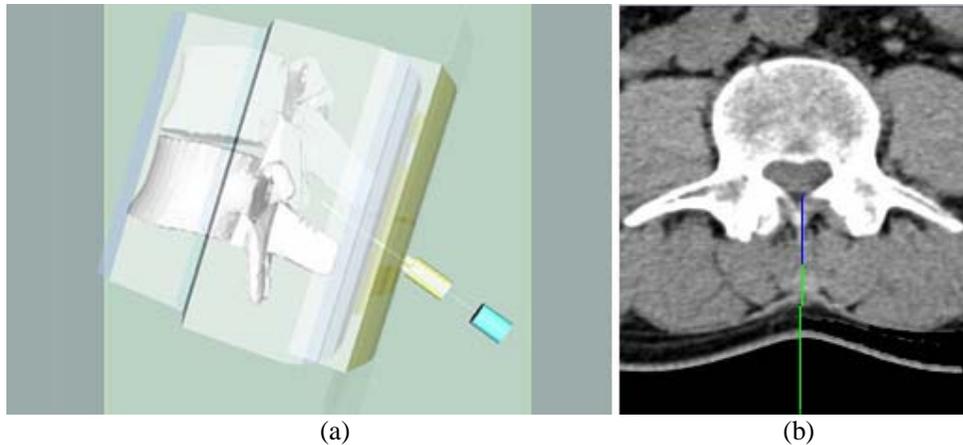


Figure 3. (a) The back can be rotated to investigate if the spinal needle is at the desired place: intrathecal space. (b) A 2D visualisation enables the learner to get a better understanding of the relevant anatomy.

5.2 Force Feedback

The H3D API and VHTK are able to recreate the sensations of performing spinal anaesthesia, providing excellent training opportunities for doctors in training. Especially important is that the simulation accommodates the real risk of touching bone if the needle is inserted at the incorrect skin puncture point or angle. The human tissue model provides this particular sensation, and if bone is touched, the user receives instant haptic, audio and visual feedback. Based on this feedback, the user can repeatedly attempt the procedure. It is important to remember that this training procedure can be carried out without compromising patient safety, allowing the trainee to practice skill acquisition in a safe and controlled environment.

Each patient's anatomy is different. The simulation allows the assignment of different properties to each layer, thereby greatly increasing the range of training experience available to the learner.

5.3 Audio Feedback

Audio feedback can be turned on or off throughout the simulation. If the audio mode is on, explanations of the procedure can be played at the beginning of the simulation. While the user is performing the procedure, event driven audio feedback is provided. For example, when an error is made, suggestions can be played back to aid its correction. Errors such as touching bone, incorrect insertion point, incorrect needle angle and too many attempts are continuously tracked by the system.

Each time the needle enters a new layer, the user is informed of the layer the needle has penetrated. Throughout the simulation ambient sounds, such as those heard in a real operating room, are played, i.e. ECG, patient breathing etc.

5.4 Two User Modes

As one of the main aims of the simulation is to learn how to identify the intrathecal space (i.e. dural puncture), the simulation has two different modes. First, in *Practice mode*, the user can learn how to advance the needle through each layer with appropriate visual feedback (visualisations) and audio feedback (explaining voice).

Second, when the trainee has understood the concept of the procedure, *Trial mode* can be turned on. In this mode the intrathecal space is identified without any audio or visual feedback except for the landmarks as in *real life*. If the needle is placed correctly, spinal fluid appears to drain slowly from the needle, which is the *real life* clinical verification that the intrathecal space has been reached, see Figure 4.

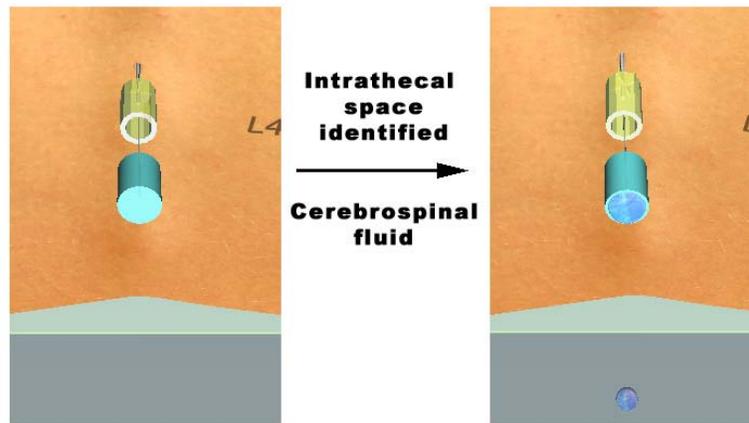


Figure 4. When the intrathecal space has been reached, spinal fluid drains slowly from the spinal needle.

6 Discussion and Future Work

The development and the choices of technology have been selected so additional learning objectives so far not included in the simulation can be implemented in a near future. For example, it can be extended with a greater variety of patient anatomy data, thus facilitating the inclusion of a case-based learning format.

A rigorous design process is currently taking place incorporating expert and trainee anaesthetists, to describe in detail the procedure of spinal anaesthesia in order to create a range of different scenarios and cases. A surrounding learning management system is under development to support a case-based learning format and facilitate the assessment of competencies not included in the simulator (i.e. ranging from overall medical knowledge to specific technical aspects, such as palpation).

The simulator is currently used in a long term study among a large number of medical trainees to validate the performance transition from the virtual training environment to the clinical setting.

7 Conclusion

The sensations experienced during the administration of spinal anaesthesia are difficult to teach, however, by utilising existing toolkits and a modified Phantom Desktop to create force feedback representations, trainees can learn to recognise and become familiar with them in a safe and controlled environment. The simulator also provides a range of interactive visualisations to help

the trainee understand the relationship between needle insertion, perceived sensations and the anatomy.

Furthermore, the simulator creates an excellent platform for a future competence-based assessment procedure aiming at covering the desired competencies of a practitioner as outlined by the Accreditation Council for Graduate Medical Training (www.acgme.org). Such a procedure is under current development by the authors (www.medcap.eu; Lövquist et al, 2008; Zhang et al, 2008) and will utilise the so called Competence based Knowledge Space Theory (CbKST) (Albert and Lukas, 1999) for performing the assessment logic.

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