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# See-through Visualisation for Training and Assessing Unsighted Physical Examinations

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## Abstract

*Objective: Motivated by the limitations of being unable to provide feedback and adequately assess technical skills whilst training unsighted physical examinations, such as Digital Rectal Examinations (DRE), we present a see-through visualisation system that can be used with benchtop models widely available in medical schools. Methods: We use position and pressure sensors located on the examining finger and have implemented a Virtual Reality (VR) simulation learning tool consisting of registered 3D models of the benchtop, augmented with relevant surrounding pelvic anatomy. The proposed system was evaluated with six medical students and eleven consultants. Results: The system is stable, runs in real time, uses unobtrusive sensor coils and pads, is able to capture data from sensors at 40Hz and adequately translates and rotates the position of the examining finger aligned to the 3D models of the benchtop and surrounding anatomy. Both medical students and consultants recognised the educational value of being able to see-through and visualise surrounding relevant anatomy. Although novices are reported to be the group that could benefit the most from our system, it is crucial not to be over reliant on visual cues for too long and to develop a strategy for the adequate use of the see-through system. Conclusions: The proposed VR simulation system is intended to improve the experience of novices learning unsighted examinations by providing real-time feedback and visualisation, allowing trainees to reflect on their performance and permitting more adequate assessment of technical skills.*

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Viewing algorithms—I.3.6 [Methodology and Techniques]: Interaction techniques—I.3.7 [Three-Dimensional Graphics and Realism]: Animation, Virtual reality—I.3.8 [Applications]: Applications—

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## 1. Introduction

Simulation for training medical and surgical skills has been an important area of research during the last two decades since it addresses some of the challenges and limitations associated with training on real patients, including fewer opportunities to practice, random exposure to cases, safety and ethical concerns, among others [GSS12, DPW*14]. Advances in technology, perception and learning theory have facilitated the improvement of training tools, by providing more portable and realistic simulated physical clinical environments [BTD*15] and by designing virtual models that attempt to replicate visual (graphics) and tactile (haptics) cues commonly encountered in clinical practice [CMJ11]. Virtual Reality (VR) has played an important role in simulation by providing fully-immersive environments, whilst Augmented Reality (AR) has offered realistic situated learning experiences [LFR*06, KBSC14]. AR offers new educational opportunities by blending virtual overlaying elements with the physical learning environment [BGM16]. Mixed Reality (MR) takes advantage of both VR and AR by merging the physical and the virtual world with full co-existence. Although these techniques date back to the 1990s, their application in education is relatively recent and increasing, with research studies agreeing on the benefits, but with challenges associated to conflicting conclusions (e.g. cognitive load and ease of use) and pedagogical issues [AA07].

Simulation can be supported by computer-generated performance metrics and by other qualitative mechanisms to assess performance, as well as to facilitate timely feedback of experts and medical educators to trainees, with the aim of developing competence [NBK13, DPW*14]. This is particularly evident in training of surgical technical skills, whilst training of more generic clinical technical skills still relies on teaching anatomy and using traditional benchtop models, with assessment largely focused on the process of performing the technical skills, which may be problematic when learning palpation skills since they are difficult to learn [HCWI*08], resulting in palpation being mostly neglected in medical training simulators [UK12].

Unsighted examinations such as Digital Rectal Examinations (DRE) and Bimanual Vaginal Examinations (BVE) are even more

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challenging to learn and teach since they depend entirely on the sense of touch, medical students receive no feedback or metrics on their technical skills, and assessment is typically limited to either diagnosing the right type of normal or abnormal findings on a benchtop model, or the communication skills of the trainee. Even though they are far from being realistic, benchtop models are widely used in medical schools, providing an opportunity for novices to practice the necessary steps of an unsighted examination, and rehearsing their communication skills during role-playing with simulated patients.

Related work on simulation has been proposed for a) learning imaging-based pelvic anatomy to overcome limitations of 2D sagittal images [DPO*03,HDH*09], b) understanding performance during unsighted examinations by using sensors embedded into benchtop models [BBS*09, WGK*10] or sensors attached to the examining finger(s) [GHDM*14], and c) haptics-based simulators [BPPW99,KNK*05,GMN*14,PUG01,MSVM06]. However, none of this research work has as yet been translated into improved training of unsighted physical examinations. Anatomy teaching usually takes place before learning the necessary technical skills; there is not much understanding as to how a DRE is actually conducted; and haptic-based simulators are still under development with a wide range of challenges to address.

In this paper, we propose a see-through visualisation system based on sensors technology that allows medical students and tutors to observe performance whilst conducting a DRE on existing benchtop models, as well as to understand the relative position of surrounding anatomical structures. Our aim is to provide a system that is able to enhance the current learning experience, facilitate feedback, and improve the assessment of unsighted examinations. The proposed system utilises benchtop models widely available in medical schools and is informed by research involving position and pressure sensors [GHDM*14]. We first describe the visualisation system and the characterisation of finger movement during the simulation, as well as the anatomical and clinical scene 3D modelling. This is followed by a pilot evaluation study with medical students and clinician educators, a discussion of our findings, conclusions and future work.

## 2. Methods

### 2.1. Visualisation system

Based on previous work for visualising and analysing palpation skills [GHDM*14], we developed a learning tool in the Unity games engine (Personal Edition 5.3.3f) that allows a medical student to see-through while conducting an unsighted examination on a benchtop model (Fig. 1). We chose Unity as the main development platform due to its multiplatform support, low hardware requirements, and native support for virtual reality (VR) (Oculus VR SDK 0.8). We implemented a multi-threading system as a native plugin in C++, integrating Ascension's 3D Guidance API to incorporate the trackSTAR electromagnetic tracking system (Ascension Technology Corporation, Shelburne, VT, USA. 3DG revision 36.0.19.7), and the PPS API supporting the FingerTPS pressure measurement system (Pressure Profile Systems, Los Angeles, CA, USA. PPSDaq API). Unity then acts as a bridge between the real-time sensors plugin and the 3D visualisation. Our visualisation system can be used by a medical student wearing the sensors while seeing through, or by a clinical skills tutor or medical educator to observe and/or assess the skills of the student wearing the sensors (Fig. 2).

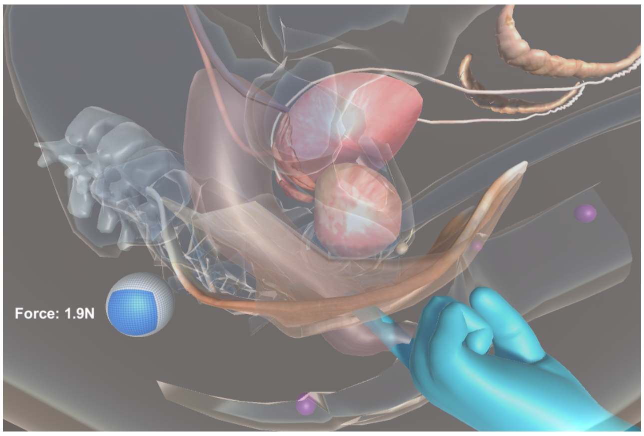

**Figure 1:** *See-through visualisation of pelvic anatomy whilst performing a Digital Rectal Examination on a benchtop model using position and pressure sensors on the examining index finger.*

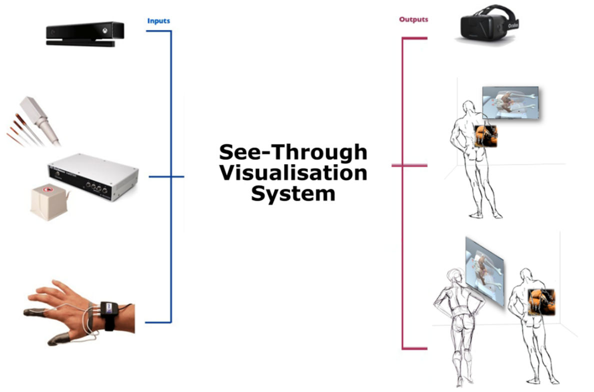

**Figure 2:** *See-through visualisation system. A medical student wears a position and a pressure sensor on the examining index finger and is able to see-through (screen or VR head mounted display) whilst conducting a DRE on a benchtop model. Alternatively, the view can be hidden from the student so that a medical tutor can provide feedback on performance or assess the student's skills. The user can also navigate through different layers of the anatomy using gestures with the non-examining hand.*

The proposed tool supports two modes of output visualisation: via a regular Liquid Crystal Display (LCD) or via a VR headset for better immersion with different user interfaces, namely a keyboard and mouse, or a gesture-controlled interface, respectively. Both interfaces allow a user to change the type of prostate as per the benchtop model, to toggle transparency of the benchtop model, and to add or remove layers of pelvic anatomy via a 2D dock (Fig. 3) on a screen or in 3D space within VR.

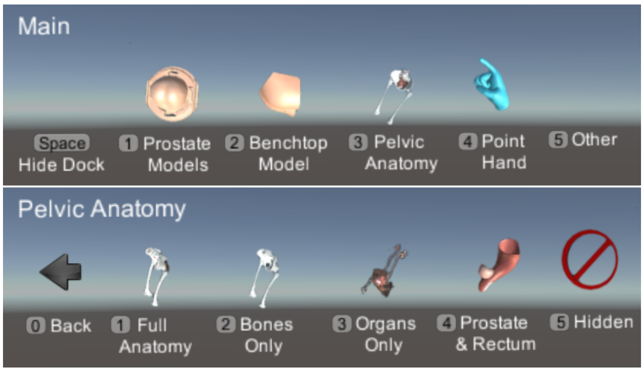

**Figure 3:** *2D Dock user interface.*

### 2.2. Position and pressure sensors

We use an Ascension 3D Guidance trackSTAR electro-magnetic tracking system with a mid-range transmitter that is mounted behind a Limbs & Things Rectal Examination Trainer Mk2 benchtop model (Limbs & Things Ltd., Bristol, UK) (Fig. 4c)). The position of the examining index finger is tracked by a 6DOF 3DG Model 180 sensor coil located on the nail, and a second one on the proximal phalange of the finger (Fig. 6a). A capacitive pressure pad (Pressure Profile System FingerTPS) is then located on the pad of the examining finger before wearing clinical gloves.

Similar to our previous work [GHD*14], registration between the virtual and physical benchtop models is done using the Iterative Closest Point (ICP) algorithm of four landmarks that are captured sequentially when the user touches these locations on the physical benchtop model with the tracked finger (Fig. 5).

### 2.3. Simulation

Our simulation loop reads the current position (vector) and orientation (quaternion) of the tracking sensors, in addition to pressure data (scalar). It then converts position and orientation from the coordinate system of the Ascension tracking system ( $x^A$ and $q^A$) into the coordinate system of Unity ($x^U$ and $q^U$) (Eq. 1-2). To calibrate the orientation of the sensors on the finger, we ask the user to extend and point his/her index finger (wearing the sensors) towards the mid-range transmitter (behind the DRE model), we save the distance $d_e$ between both sensors and compute an initial rotation $q^i$ by multiplying the rotation of target orientation $q^t$ to the inverse rotation of the orientation read from the sensors $q^{r^{-1}}$ (Eq. 3). The calibrated orientation $q^c$ is computed by applying $q^i$ to the last orientation read from the sensors $q^U$ (Eq. 4).

$$x^U = \begin{bmatrix} -x^A_y & -x^A_z & -x^A_x \end{bmatrix}^T \tag{1}$$

$$q^U = \begin{bmatrix} -q^A_y & -q^A_z & -q^A_x & q^A_w \end{bmatrix}^T \tag{2}$$

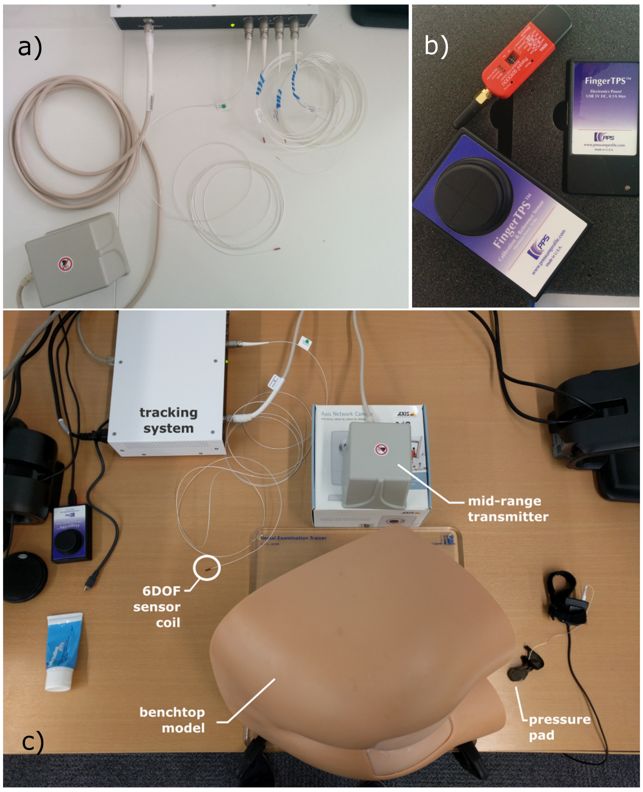

**Figure 4:** *Position and pressure sensors used for DRE on a benchtop model: a) Electromagnetic tracking system (Ascension 3D Guidance), b) pressure sensing toolkit (PPS FingerTPS), and c) mid-ranger transmitter located behind a DRE bench-top model.*

$$q^i = q^{r^{-1}} q^t \tag{3}$$

$$q^c = q^U q^i \tag{4}$$

Since the position sensors are located on the fingernail and above the proximal phalange (Fig. 6a), a position $x^{U'}$ is computed by translating $x^U$ along the $y$ axis of the quaternion a distance $d_h$ (distance between the nail and the pad of the finger) to account for different finger sizes (Eq. 5). Flexion of the finger is computed based on the distance $d_f$ between a point $x^E$ projected a distance $d_e$ along the direction of the $z$ axis of the proximal phalange $x^{U'}_1$, and the sensor on the tip of the finger $x^{U'}_0$ (Eq. 6-7 and Fig. 6b). Distance $d_f$ is then used to compute the angle of both joints of the skeleton of the finger (Eq. 8).

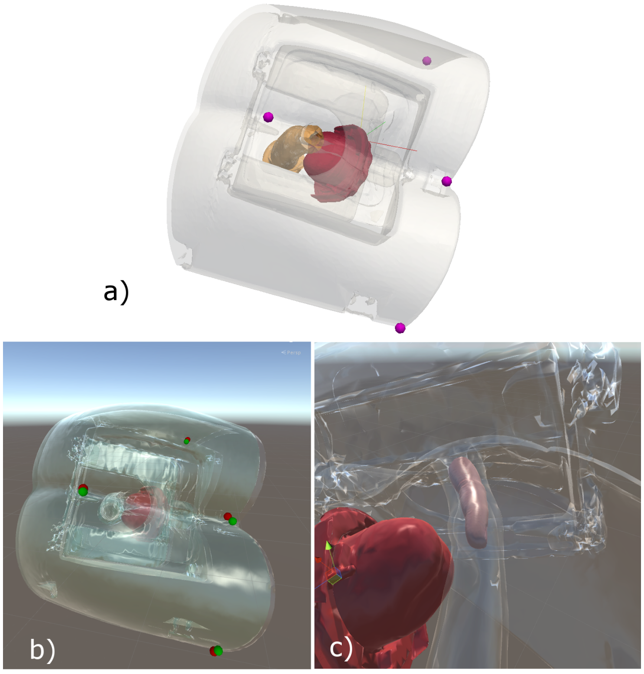

**Figure 5:** *Registration of virtual and physical benchtop models: a) four landmarks (in purple) that are touched on the physical benchtop model with the tracked finger, b) example of a registration (landmarks of virtual 3D model in green and landmarks touched with the sensors in red), and c) demonstrating how the finger is aligned within rectal walls of the benchtop model.*

$$x^{U'} = x^{U} - d_h \begin{bmatrix} 2(q_x^c q_y^c - q_w^c q_z^c) \\ 1 - 2(q_x^{c2} + q_z^{c2}) \\ 2(q_y^c q_z^c + q_w^c q_x^c) \end{bmatrix} \tag{5}$$

$$d_f = |x_E - x_0^{U'}| \tag{6}$$

$$x^{E} = x_1^{U'} - d_e \begin{bmatrix} 2(q_x^c q_z^c + q_w^c q_y^c) \\ 2(q_y^c q_z^c - q_w^c q_x^c) \\ 1 - 2(q_x^{c2} + q_y^{c2}) \end{bmatrix} \tag{7}$$

$$Joint_{A,B} = \begin{bmatrix} 0 & -\frac{90}{1.7} d_f & 0 \end{bmatrix}^T \tag{8}$$

We propose a simple visual cue in the form of a 'stress ball' to visualise the pressure applied on the anatomy. Pressure data is rendered using a sphere that deforms (squeezes) depending on the amount of pressure read from the capacitive-based pressure sensor (Fig. 7). To squeeze the sphere, a force is applied at the centre of its blue face, with a magnitude equal to the pressure read from the sensor in a direction towards its centre.

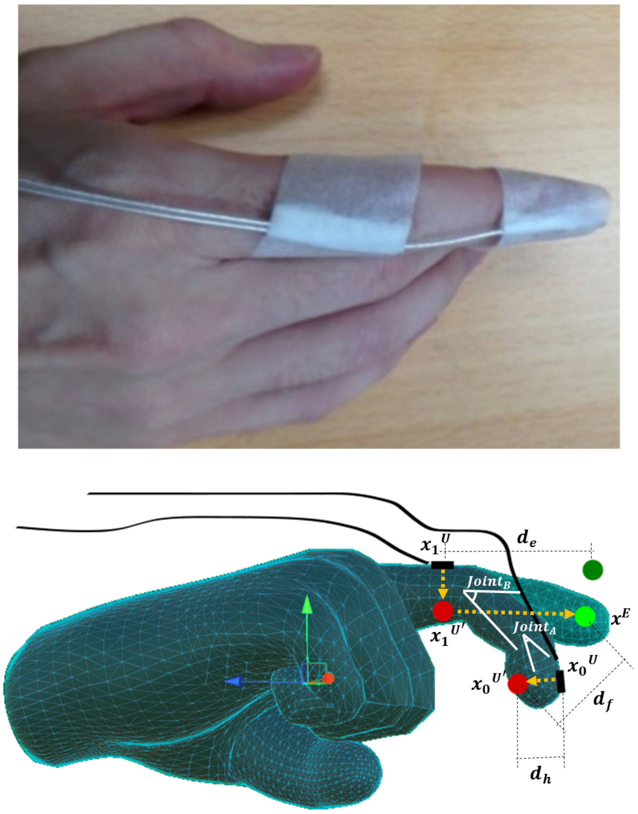

**Figure 6:** *Modelling the flexion / extension of index finger with two sensor coils: one on the finger nail and one on the proximal phalange.*

### 2.4. 3D Modelling

We modelled a clinical consultation room (Fig. 8a) in 3D using 3ds Max (Autodesk Inc., USA) with basic elements including a bed with a pillow and rolling paper, a sink, a wall-mounted towel dispenser and two bins (Fig. 8b). We then incorporated the 3D virtual models of the benchtop with a patient in the DRE position, including other relevant pelvic anatomical structures from a set of edited standard anatomical models (3DScience Zygote Media Group, Inc., American Fort, UT, USA) that included the rectum (aligned with the rectum of the benchtop model), bladder, seminal vesicles, bulbourethral glands, epididymis, spine and pelvic floor muscles of the levator ani (pubococcygeus and illiococcygeus).

### 2.5. Pilot Evaluation Study

We recruited a total of seventeen participants including medical students (N=6) and clinician educators from Urology (N=6), Family Medicine (N=2), General Surgery (N=2), and Colorectal Surgery (N=1). The pilot evaluation study took place in an office space at the Department of Urology, Tan Tock Seng Hospital, Singapore (December 2016). During the pilot, we asked participants to perform a DRE on a benchtop model while wearing the sensors on their examining index finger and visualising their own perfor-

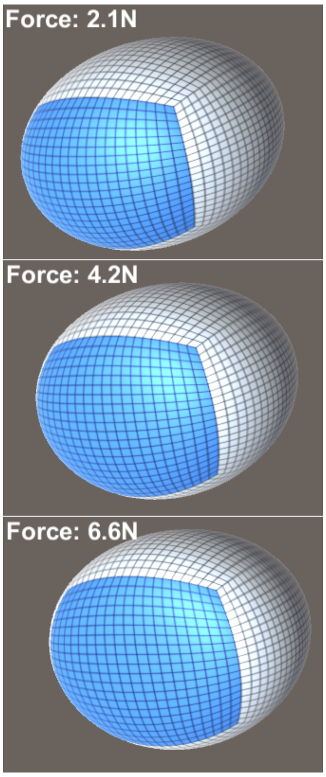

**Figure 7:** *Visualisation of pressure data. Three examples captured at different times during prostate palpation.*

**Figure 8:** *3D modelling of clinical consultation room.*

mance. The DRE was repeated three times so that the participant could observe his or her performance on a screen, initially with only the 3D models of the benchtop (Fig. 10a), followed by adding the surrounding pelvic anatomy (Fig. 10b), and then using a head-mounted VR display (Fig. 9). A semi-structured interview was conducted to investigate the perceived benefits of the see-through concept, perspectives of students and clinicians of augmenting the view with surrounding anatomical structures, and their opinion on using a VR head-mounted display, rather than observing their performance on a screen. All participants gave consent to participate, they were audio- and video- recorded and answered a questionnaire at the end of the study.

## 3. Results

### 3.1. See-through visualisation system

The chosen position tracking system integrated into our system is very stable, runs in real time, with the mid-range transmitter and Model 180 sensor coils covering the necessary volume of the finger, whilst examining the rectal walls and prostate, as well as registering the virtual and physical benchtop models during calibration (namely touching of landmarks and finger orientation). The sensor coils are small and unobtrusive allowing the examiner to wear clinical gloves and use lubricant gel as per usual. Our implementation of a multi-threading plugin to communicate with sensors technology from Unity is stable, runs at 40Hz and supports up to four sensor coils (limitation of trackSTAR). The navigation of the system is intuitive and allows the user to easily change settings such as visualising only physical elements or augmenting the see-through view with surrounding anatomical structures (Fig. 10).

We visually confirmed that the physical setup was correctly aligned with the 3D models after registration and that the movements of the examining finger coincided with those of the virtual hand in our system, particularly supination / pronation and flexion / extension. Taking into account finger dimensions, we observed that physical touch visually matches when the finger collides with the 3D models of the prostate and rectum. We also observed that finger movements are better seen by having a see-through skin with a translucent rectum and illiococcygeus (Fig. 1).

### 3.2. Pilot Evaluation Study

When asked about how DRE is currently taught and assessed, participants referred to the following methods: on benchtop models during classes and during Objective Structured Clinical Examinations (OSCEs), whilst examining patients and articulating what they feel, and during clinical supervision and mentoring, although some participants recognised that they are not assessed well or officially assessed.

Anatomical structures that students are expected to be able to identify before performing a DRE on a patient include the prostate

**Figure 9:** *Pilot evaluation study involving medical students and clinician educators showing a participant performing a DRE.*

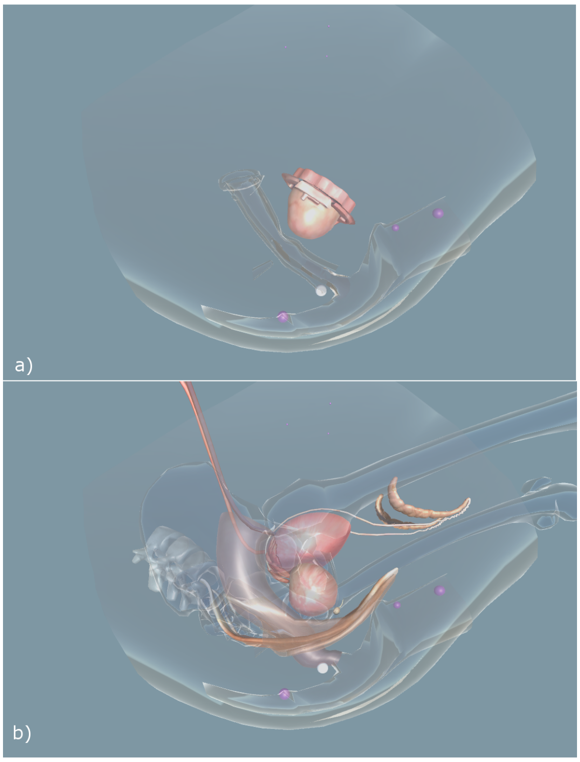

**Figure 10:** *Above: See-through view of the anatomy of physical elements of the benchtop model. Below: See-through view with surrounding anatomical structures.*

(size, consistency, surface, nodules, carcinoma, enlargement, median sulcus), rectal walls (including abnormal growths), anus, anal sphincter and seminal vesicles. Related to which anatomical structures are important to visualise, participants selected the prostate and rectum (17), followed by anal canal (15), anal sphincters (13), anorectal junction (11) and coccyx and bladder (10), with other structures selected by only a few participants.

When asked to rate different aspects of the see-through visualisation tool, on average, medical students rated it 'definitely agree' ($\mu$=4.5; $\sigma$=0.7) and consultants 'agree' ($\mu$=4.1; $\sigma$=0.4) on a 5-point Likert scale (1 - Definitely disagree; 3 - Neutral; 5 - Definitely agree), considering that the tool may be useful for demonstrating the position and movement of the finger, can help a trainee better understand DRE ('reinforce regional anatomy', 'appreciate structures felt', 'understand surrounding structures', 'orientation of the organs'), allows the trainee to reflect on his/her performance ('visualisation', 'rather than relying on a mental picture'), may help trainees to get adequate feedback on their palpation skills ('direct feedback'), and that it may be used for the assessment of performance during palpation of the rectal walls and the prostate ('trainer knows whether the student is doing correctly'). Overall, participants agree that both the ability to see-through ($\mu$=4.5; $\sigma$=0.5) and displaying surrounding relevant anatomy ($\mu$=4.1; $\sigma$=0.8) has an educational value, particularly for novices before practicing on real subjects. When asked about any aspects of the tool that might hinder learning, participants included the 'over reliance' of visual cues if used too long, 'cost and time to set up', and 'too much complexity [anatomy] could confuse [medical students]'. Participants had a lower level of agreement ($\mu$=3.8; $\sigma$=0.7) when asked about the educational value of using a VR head-mounted display, particularly by consultants. They also commented that a better benchtop model would be more beneficial and useful for the learning tool.

## 4. Discussion

There is increasing interest in the research community to incorporate the sense of touch to VR. So far, simulation tends to rely on rendering visual cues, but occluding the view of the physical world may limit the way of interacting with virtual objects. Whilst MR is promising since it fully integrates the physical and virtual environments, there is clearly an area of research that needs to be explored when augmenting the view of objects that can be touched in the physical world, with more virtual objects without recurring to active approaches to render touch such as haptics.

Modern sensors are unobtrusive to wear and reasonably affordable. Visualising the movements of the examining finger by means of the use of sensors whilst practicing on existing benchtop models allows medical students to reflect on performance and be subject to a suspension of disbelief. The movements of the examining finger and the palpated anatomy were observed throughout the whole examination, rather than observing only regions of the anatomy that have been embedded with sensors. Through a deforming sphere, we could visualise the amount of pressure applied on the anatomy. Further investigation is necessary to determine the best format to present pressure to trainees so that they may reflect on their performance. Providing users with immersive visualizations may be beneficial for the purpose of teaching, although this process brings additional challenges to the way they interact with the system. Related to the gesture-controlled interface, creating 3D buttons (2D dock) spatially located in 3D space seems more intuitive and easier to manipulate.

We were able to enhance the experience with more virtual anatomical structures as long as there was a correspondence between those structures that can be palpated in the real world, and those visualised during palpation of the anatomy with a virtual hand. It was evident that incorporating the surrounding anatomy and presenting it in a suitable manner had important benefits for novices who could then map what they learnt during their anatomy teaching sessions, and concentrate on the position and relative orientation of these organs whilst performing a DRE on a benchtop model, along with the necessary technical steps to adequately perform it.

Related to enhancing the learning experience, our proposed system allows tutors to give feedback by observing the performance of students and provides a more robust tool to assess competency based on observation of technical skills, complementing those that are currently assessed related to communication skills and decision making. Seeing through also implies a better understanding of what technical skills constitute adequate performance. Therefore, we envisage feedback and assessment to be provided by a combination of computer-generated metrics and observation of skills by tutors and experts. In spite of the advantages offered by the see-through approach, it is crucial to eventually hide that view from the learner, since the actual examination will not depend on visual cues.

## 5. Conclusions and Future Work

Our previous research about performance of unsighted examinations [GHDM*14] provided evidence to support use of a see-through visualisation system to improve medical students' learning experience. Therefore, in this paper we present a VR/MR simulation system that allows to better visualise the movement of the examining finger with the aim of facilitating feedback, reflecting on performance and allowing for more adequate assessment of technical skills. The educational value of the system was recognised by medical students and consultants.

The work presented in this paper will allow for the investigation of multi-sensorial experiences (physical palpable world with a visual virtual world) and their impact in learning outcomes [AA07]. We envisage further validation of the learning tool, with particular emphasis on the educational impact and transfer of knowledge (construct, concurrent and predictive validity) [BGM16]. We will also investigate the optimal timing within the curriculum to offer this see-through view, and when more sophisticated tools should be introduced to train the sense of touch with limited visual cues (similar to what they are expected to find whilst examining real subjects). We also expect to incorporate deformation of pelvic anatomy on palpation and study whether a visual plausible deformation model is enough, or a more accurate behaviour based on continuum mechanics is necessary.

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