The Role of Haptics in Medical Training Simulators: A Survey of the State of the Art

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Abstract—This review paper discusses the role of haptics within virtual medical training applications, particularly, where it can be used to aid a practitioner to learn and practice a task. The review summarizes aspects to be considered in the deployment of haptics technologies in medical training. First, both force/torque and tactile feedback hardware solutions that are currently produced commercially and in academia are reviewed, followed by the available haptics-related software and then an in-depth analysis of medical training simulations that include haptic feedback. The review is summarized with scrutiny of emerging technologies and discusses future directions in the field.

Index Terms—State of the art, haptics, force feedback, tactile feedback, medical simulation, training.

1 INTRODUCTION

There is unrelenting pressure today to update and reform conventional medical practices, and patient safety in particular has been highlighted as a key issue to be addressed by medical process and technology [1]. Some of this is driving surgical management into innovative minimal access approaches, in turn, raising further challenges of training the increasingly complex skills required. Safe practice requires the operator to respond correctly to both visual and haptic cues. The operator’s deliberations then initiate and inform a range of motor actions, including very fine translational and rotational motions of tools, particularly, in challenging anatomy. As the spectrum of available techniques increases, so the limited number and availability of suitably trained practitioners becomes a significant problem. Medical simulators are therefore becoming more accepted as a tool for providing added value to the training process, and high fidelity haptics must be an integral component of such a tool. This paper provides a comprehensive survey of the current state of the art of haptics technology in this context.

Training based on an apprenticeship model has been used effectively by the medical profession for centuries. Learning involves the experience of errors, albeit under the guidance of an expert mentor. Yet performing an operation incorrectly through inexperience can lead to avoidable patient discomfort and complications. The latter can prolong a patient’s hospital stay or in the worst-case scenario can cause permanent damage or death. For example, a three-year study [2] by HealthGrades (Golden, CO, USA), an American healthcare ratings organization, found that medical errors resulted in over 230,000 deaths in American hospitals during the study period. In a different study [3] based on rates of cancer recurrence in 4,700 patients operated upon using keyhole techniques by 29 surgeons in seven hospitals throughout Europe and North America, Vickers et al. report that surgeons require 750 operations to perfect keyhole surgery procedures. It is not acceptable to make mistakes on patients when alternatives are available.

As technology has progressed, many different tools and techniques have been deployed to provide added value to the training process, such as using anesthetized animals or cadavers, or by practicing on mannequins or fellow students. However, the interactions that occur in an animal’s or cadaver’s tissues differ from those of living humans due to varying anatomy or absence of physiologic behavior, such as blood pressure. Not only are cadavers expensive, but procedures can only be performed once and a mistake can render the body useless to redemonstrate a procedure. This type of training also raises ethical issues. Mannequins of varying sophistication are becoming increasingly common to simulate part or all of a patient [4]. However, drawbacks of mannequins include limitations in their replication of physiology and that at best they have a limited range of anatomical variability. Barker [5] notes how students resort to training venipuncture upon fellow students as the plastic mannequin models don’t provide enough realism.

An alternative approach that is making an impact on the medical community is computer simulation enabled experiential training systems [6], [7], [8], which can train practitioners on a virtual patient while critically analyzing skills and providing feedback on the performed procedure. This feedback can then be used to refine the required skills until the operator reaches a target level of proficiency before commencing training with patients. Simulations can also
provide the user with an opportunity to practice difficult cases or to be exposed to those in which patient anatomy is unconventional before performing the procedure upon a patient. Such “mission rehearsal” can highlight operational and equipment difficulties that would otherwise be overlooked until they are encountered during the real procedure. Haptics devices are also being used to train operators of robotic surgery, e.g., the MIMIC Technologies (Seattle, WA, USA) da Vinci Trainer (but this class of applications is outside the scope of this survey).

Physical models require remodeling to simulate patient variability where a patient’s body habitus, (related to their quantity of muscle and fat) varies between different subjects. Virtual models offer the opportunity to simply modify the virtual patient using patient-specific data from one of the many 3D medical imaging modalities available in the hospital or to utilize the skills of the numerous well-trained medical illustrators who are capable with 3D modeling packages. This is a significant advantage of computer simulation over that of a cadaver or fixed anatomical models. However, when producing a realistic training simulation, the virtual patient must be displayed to the practitioner in such a way that they believe the simulation replicates a real situation so as to achieve “suspension of disbelief” [9]. Cadavers and mannequins have physical presence which a simulation lacks. Overcoming this lack of presence is an ongoing challenge of medical simulation research.

Of the human sensorial modalities (visual, auditory, touch, smell, and taste), two main modalities are currently used in simulation: visual and touch. Smell and taste will be included in the future with new products such as the ScentPalette from EnviroScent (Ball Ground, GA, USA). Auditory cues are sometimes used to alert a user to a fault, or for guidance and can be important for the correct learning of certain procedures using high-speed power tools, such as burr-based bone and tooth drilling. The visualization component is provided using either two-dimensional or three-dimensional displays and is well documented. The focus of this paper is to review the role of the sense of touch in enhancing a user’s perceived fidelity of computer simulations for medical procedures.

Haptics solutions are less mature than visual display technologies. In particular, haptics require bidirectional input and output, which is difficult to model accurately due to the large number of the different touch receptors involved. Haptics can be considered in two main categories: tactile feedback and force/torque feedback. Tactile feedback is sensed by receptors in and just under the skin’s surface allowing humans to detect if a surface is smooth or rough, hot or cold, as well as conveying pain. Force/torque feedback resists motion and/or rotation, for instance, stopping a person’s hand falling through a table top as they touch it. The biological receptors providing this feedback are in muscles and at joints allowing a person to know where their hand is in space, even with closed eyes (proprioception). Both tactile and force feedback can be crucial to the success of carrying out a medical procedure.

The term “force feedback” is often used in place of “haptic feedback.” However, these terms are not interchangeable. In a general case of proprioceptive feedback, where a person interacts with a simulated scene, both forces as well as torques must be experienced. This requires six degrees of force feedback but is not typically provided because of the higher cost of manufacturing devices that can provide torque as well as directional force feedback. In the following review, it will be made explicitly clear if torques are included when referring to feedback and devices.

Commercial haptics devices are available today, and many more have been fabricated in research laboratories. The majority incorporate only the force feedback component of touch (see Table 1 for a list of commercial manufacturers). Only a few solutions support tactile feedback, which is harder to reproduce as the biological processes of tactile receptors are not fully understood. Both categories are reviewed in Section 2: “Haptic Devices.” Section 3 focuses on software libraries that have been developed to interface with haptics hardware. A comprehensive evaluation of medical simulations involving haptic feedback is presented in Section 4. A brief summary of validation issues is then given and the paper ends with a discussion of current and future trends.

2 HAPTIC DEVICES

In 1965, Sutherland correctly predicted that the sense of touch would be added to virtual environments [10], allowing the user to feel virtual objects [11]. Burdea and Coiffet [10] in reference to [12], note how this became reality in 1971 and that many of today’s haptics devices still use this same robotic arm like arrangement. The typical “Haptic devices” as they are sold commercially provide a mechanical I/O device with which a user interacts. The device will track one or more end effectors in physical space and provide force and/or torque feedback (a bidirectional channel of interaction between a virtual environment and user). Devices that provide tactile feedback are more commonly referred to as “tactile devices” but are not widely available. Table 1 provides a list of the companies that manufacture multipurpose haptics devices together with the capabilities of each device.

2.1 Force Feedback Devices

Commercial force feedback devices vary greatly in the degrees of freedom they offer, the size of their workspace, the force and torque they can apply, the shape of the end effector, and maybe most significantly, in price. Different types of actuation used in haptics devices include: shape memory metals, magnetic, piezoelectric materials, electro-rheological fluids, DC electric motors (the most common), pneumatic, as well as hydraulic actuation. There are many desirable properties of force feedback devices that will help to make a device more natural to use and enable optimal haptic interaction with a medical (and other domain) virtual environment (VE). Some of these properties are conflicting and so the advantages and disadvantages must be carefully considered in order to make an informed decision about the device of choice. For example, a device that is stiff will usually be made of metal and therefore have a large mass. This, in turn, can have an undesirable higher inertia than a lightweight plastic device.

Human haptic perception operates at a far higher rate than our visual system. The latter can be fooled into seeing continuous motion by displaying 25 to 30 interlaced images per second. However, providing artificial haptic feedback to
a user requires a significantly faster rate of “haptic image" update (around 30 times faster). This requires a significant amount of computational power for even simple models and has been a limiting factor in the development of haptics, only becoming a viable technology for simulation within the last 10 years [13]. The required refresh rate to provide realistic force feedback is commonly accepted to be at least 1,000 Hz. However, this refresh rate is widely debated. According to Burdea [14], a minimum refresh rate of only 300 Hz is acceptable. Conversely, a study by Booth et al. [15] using SensAble’s Premium 1.5 to deduce the minimum acceptable haptic refresh rate, suggests that “a minimum acceptable refresh rate must lie within the 550-600 Hz range." The necessary rate of update is dependent upon the stiffness of the surfaces to be simulated. A stiff contact between objects is better simulated by higher refresh rates, whereas lower refresh rates are satisfactory for softer objects. Additional methods can be applied to simulate touching stiffer objects such as combining vibrations with force to the end effector to represent the small vibrations felt upon object contact [16].

The end effector of a force feedback device is important to provide a meaningful interaction with the environment and the grasp used directly influences the force/torque that can be applied. Grasping geometry can be classified as a precision grasp or a power grasp [10] in reference to [18], with the user performing more dexterous or higher power tasks, respectively. Most commercial force feedback devices come equipped with generic end effectors, shaped like pens, balls, and tubes. It is increasingly more common for medical simulations to use modified end effectors, however, so as to increase the face validity of the simulation. For example, a syringe-shaped end effector can provide the extra validity needed to help a trainee nurse to suspend disbelief. On the other hand, such a modification may increase the cost of the simulator with no significant increase in training effectiveness in comparison to using an off-the-shelf stylus end effector. There are also examples of two commercial devices being combined to provide extra degrees of force feedback (DOFF) for a particular task. For example, Fig. 1 shows Simquest’s burr hole drilling simulation hardware in which two Novint Falcon devices are configured to give 5DOFF to a single drill handle. This approach requires specific design engineering expertise to develop the solution.

Other technologies for haptics devices have been investigated (e.g., Lorentz magnetic levitation [19]) that promise better haptic interaction fidelity in the future, but have not yet been incorporated into medical simulation solutions.

### TABLE 1
Commercial Force Feedback Hardware Manufactures and Devices

<table>
<thead>
<tr>
<th>Company</th>
<th>Devices</th>
<th>Degrees of Freedom</th>
<th>Degrees of Freedom</th>
<th>Workspace mm</th>
<th>Max Force Nm / Torque mMm</th>
<th>Stiffness N/mm</th>
<th>Price €/100</th>
</tr>
</thead>
<tbody>
<tr>
<td>SensAble</td>
<td>Omni</td>
<td>6</td>
<td>3</td>
<td>160 x 120 x 70</td>
<td>3.3 / 0</td>
<td>1.02</td>
<td>2</td>
</tr>
<tr>
<td>Technologies</td>
<td>Desktop</td>
<td>6</td>
<td>3</td>
<td>160 x 130</td>
<td>7.9 / 0</td>
<td>1.7</td>
<td>11</td>
</tr>
<tr>
<td><a href="http://www.sensible.com">www.sensible.com</a></td>
<td>Premium 1.0</td>
<td>6</td>
<td>3</td>
<td>127 x 178 x 254</td>
<td>8.5 / 0</td>
<td>3.5</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Premium 1.5</td>
<td>6</td>
<td>6</td>
<td>191 x 267 x 361</td>
<td>8.5 / 515</td>
<td>3.5</td>
<td>24 - 51</td>
</tr>
<tr>
<td></td>
<td>Premium 3.0</td>
<td>6</td>
<td>6</td>
<td>406 x 584 x 888</td>
<td>22 / 515</td>
<td>1</td>
<td>53 - 70</td>
</tr>
<tr>
<td>Force Dimensions</td>
<td>Omega3, 6, 7</td>
<td>3, 6, 7</td>
<td>3</td>
<td>160 x 160 x 110</td>
<td>12 / 8.0</td>
<td>14.5</td>
<td>14 - 24</td>
</tr>
<tr>
<td><a href="http://www.forcedimension.com">www.forcedimension.com</a></td>
<td>Delta 3, 6</td>
<td>3</td>
<td>3</td>
<td>360 x 360 x 300</td>
<td>20 / 200</td>
<td>15</td>
<td>22 - 40</td>
</tr>
<tr>
<td>NovInt</td>
<td>Falcon</td>
<td>3</td>
<td>3</td>
<td>101 x 101 x 101</td>
<td>~9 / 0</td>
<td>NA</td>
<td>0.2</td>
</tr>
<tr>
<td>Immersion Corp</td>
<td>CyberForce</td>
<td>6</td>
<td>3</td>
<td>304 x 304 x 495</td>
<td>8.8 / 0</td>
<td>NA</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>CyberGrasp</td>
<td>5</td>
<td>5</td>
<td>12 / 0</td>
<td>NA</td>
<td>NA</td>
<td>45</td>
</tr>
<tr>
<td>Haption</td>
<td>Virtuose</td>
<td>6</td>
<td>6</td>
<td>129 x 120 x 120</td>
<td>10 / 500</td>
<td>2.5</td>
<td>30</td>
</tr>
<tr>
<td><a href="http://www.haption.com">www.haption.com</a></td>
<td>6D Desktop</td>
<td>6</td>
<td>3</td>
<td>500 x 644 x 350</td>
<td>15 / 0</td>
<td>2</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>3D15-25</td>
<td>6</td>
<td>6</td>
<td>1060 x 900 x 600</td>
<td>35 / 3000</td>
<td>2.5</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>6D40-40</td>
<td>6</td>
<td>6</td>
<td>400 x 400 x 400</td>
<td>100 / 10000</td>
<td>NA</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td>INCA 6D*</td>
<td>6</td>
<td>6</td>
<td>Variable</td>
<td>40 / 5000</td>
<td>NA</td>
<td>80*</td>
</tr>
<tr>
<td>Mimic</td>
<td>Mantra</td>
<td>6</td>
<td>3</td>
<td>325 x 270 x 260</td>
<td>15.2 / 0</td>
<td>5.5</td>
<td>10</td>
</tr>
<tr>
<td><a href="http://www.mimic.ws">www.mimic.ws</a></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quanser</td>
<td>Mirage F3D-35</td>
<td>6</td>
<td>3</td>
<td>400 x 200 x 300</td>
<td>25 / 0</td>
<td>2</td>
<td>35</td>
</tr>
<tr>
<td><a href="http://www.quanser.com">www.quanser.com</a></td>
<td>HD2</td>
<td>6</td>
<td>5</td>
<td>530 x 300 x 500</td>
<td>19.7 / 1725</td>
<td>10</td>
<td>60 - 70</td>
</tr>
<tr>
<td></td>
<td>Pantograph:</td>
<td>2</td>
<td>2</td>
<td>270 x 240</td>
<td>10.1 / 0</td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>2DOF</td>
<td>3</td>
<td>3</td>
<td>270 x 240</td>
<td>10.1 / 255</td>
<td>3</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>3DOF</td>
<td>5</td>
<td>5</td>
<td>480 x 250 x 450</td>
<td>9 / 750</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>Moog FCS Robotics</td>
<td>HapticMaster</td>
<td>3</td>
<td>3</td>
<td>1000 x 400 x 360</td>
<td>250 / 0</td>
<td>10</td>
<td>43</td>
</tr>
<tr>
<td><a href="http://www.fcs-ca.com/robotics">www.fcs-ca.com/robotics</a></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MPR Technologies</td>
<td>Cubic 3</td>
<td>3</td>
<td>3</td>
<td>330 x 290 x 220</td>
<td>2.5 / 0</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td><a href="http://www.mpb-technologies.ca">www.mpb-technologies.ca</a></td>
<td>Freedom 65</td>
<td>6</td>
<td>6</td>
<td>170 x 220 x 330</td>
<td>2.5 / 150</td>
<td>2</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>F7S</td>
<td>7</td>
<td>7</td>
<td>170 x 220 x 330</td>
<td>2.5 / 150</td>
<td>2</td>
<td>29</td>
</tr>
</tbody>
</table>
2.2 Force Feedback Devices Summary

Choosing a commercial force feedback device for a specific application is not as simple as deciding upon the workspace required and selecting a suitable device in this category. Even the largest workspaces have multiple devices available. The requirement to have six degrees of force/torque feedback may mean the device will have a larger than necessary workspace. Budget restrictions can also limit the functionality that can be provided and often just three degree of freedom force-only devices must be used. An analysis of the task to be simulated should determine if the trade-off is valid. The force/torque capabilities of the device and the resolution of both position and rotation sensing also need to meet the requirements of the task. If a procedure requires millimetre translational precision while manipulating tools, a device with a coarser resolution than this would not be appropriate. Also the risk of providing too high fidelity of force/torque feedback can be as much of a problem as providing too little. A medical procedure where this scenario occurs is laparoscopic surgery. Here, the tools enter the body through tight introducers that severely limit the interactions felt during a procedure. Providing too little or too much feedback will lead to negative training.

Use of commercial haptic devices will enable easier replication of a simulator after its development. The production cost maybe lower if performing modifications to an existing device and such a device can be tested with already available software drivers. Production of a custom haptics device is an expensive and complex process only to be attempted by the experienced. In addition to the products listed in Table 1, there are some haptics devices available for specific medical procedures. Mentice is widely known for their minimally invasive procedure training solutions (MIST and VIST). Since acquiring Xitact (Morges, Switzerland), who specialized in the manufacture of medical force feedback interfaces, Mentice now market the Xitact IHP for the emulation of endoscopic instruments and the Xitact CHP for the simulation of interventional procedures such as cardiology, peripheral interventions and interventional radiology. Also at the low cost of the force feedback market, Logitech (Fremont, CA, USA) license and market many force feedback devices such as gaming joysticks (which have been used in some medical simulations). A now discontinued device, the 2DOFF Logitech Wingman Mouse [20] released in 1999, also showed promise as a low-cost force feedback device. At least one needle insertion simulation used this device [21].

2.3 Tactile Devices

Tactile information is conveyed by compressing, stretching or vibrating, and by varying the heat at the skin surface. Pasquero [22] provides in-depth information about the human tactile sense and a comprehensive list of 13 different tactile technologies. Note that the current limited understanding of human tactile receptors means that the design and optimization of tactile devices is a slow iterative process. Of the developed tactile devices, most are large and lack the portability necessary to be used in combination with force feedback devices for a true haptic interaction. To be useful for medical training purposes, a realistic feeling of touch identical to that felt during the actual procedure must be simulated. It maybe useful to simulate heat, conveying information on the patient’s temperature. This could be done with a temperature controlling glove [23]. No medical training simulation is yet known to incorporate this cue. A recent example of tactile technology used in medical simulation is work to simulate a palpation for the femoral artery in an interventional radiology procedure [24]. This has led to the evaluation of three tactile technologies: piezoelectric pads, micro speakers, and a commercial pin array device from Aesthesis (Salford, United Kingdom). These devices are suitable to be mounted onto a trainee’s fingertips or a force feedback device’s end effector—see Fig. 2.

Fig. 1. SimQuest’s burr hole drilling simulation hardware. Two 3DOFF Falcon devices arranged to give 5DOFF feedback to a single drill handle.

CompuTouch AS (Asker, Norway) have produced tactile devices that are small enough to be attached to a fingertip. These tactile displays have a tilting metallic plate interface that can be controlled by electromagnetic coils within the device. Various tilting combinations can produce the illusion of touching complex surfaces.

In an approach similar to that first taken by Caldwell et al. [25], another small portable tactile device consisting of a three by two array of pneumatic balloons has been developed by Culjat et al. [26]. The device has been designed to add tactile information to the controllers of the Da Vinci surgical system from Intuitive Surgical, Inc. (Sunnyvale, CA, USA). The conveyed tactile information is suitable for training purposes.
The term vibrotactile refers to a vibration sensation that is more global than directed tactile feedback. Vibrotactile devices are now common place in games consoles to alert a user to an action such as being shot or driving a car over a rough surface, and in mobile phones to alert the owner of a message or call when in silent mode. These devices comprise of a motor with an off-centered weight connected to the shaft. Some simulation solutions may find force feedback devices too expensive and opt to use vibrotactile displays to convey information such as operator mistakes or contact between two objects. A simulation adopting this approach is being developed for the training of ultrasound scanning [27]. The project uses the Nintendo Wii Remote controller, which incorporates 3D tracking and vibrotactile technology, as a virtual ultrasound probe.

The tactile sense is an important cue and as research provides methods of producing tactile stimulation at an affordable cost and in small enough devices to be mounted upon force feedback devices, the technology will become more widespread. Currently, these problems limit the applicability of this modality for common use in simulation.

3 HAPTICS LIBRARIES and MODELING

Several Application Programming Interfaces (APIs) have been produced to aid in the construction of haptically rendered virtual environments. They implement common methods of modeling forces, provide physics simulation, offer different methods of collision detection, and interface with most of the products listed in Table 1. However, they can be slow to support new advances and so it is often preferable to develop the core simulation routines separately. Licensing methods also vary. SensAble Technology’s OpenHaptics API is a commercial C++ library but it is free for academic use. OpenHaptics provides cross-platform support and with respect to programming it resembles the OpenGL graphics library. It only works with SensAble’s force feedback devices but these are the most popular products today.

Chai3D [28], an open source library, includes both graphics (using OpenGL) and force feedback components and is written by academics in C++ to be platform-independent. It is a comparatively lightweight API but it allows extensions to be easily added (such as ODE physics engine support), and also offers support for a range of commercial force feedback devices.

The H3DAPI, is a haptics development platform including graphics support. It is available under either an open source or commercial license dependent upon usage. According to the development requirements X3D, C++ or Python can be used. The API is maintained by SenseGraphics and provides support for Force Dimension, Novint, Moog, FCS Robotics, and SensAble force feedback devices. A scene graph architecture is used to reduce the complexity of environment definition.

SensAble’s devices are the most widely supported of all the haptic manufacturers and some additional APIs that provide singular support for these are XVR by VRMedia (Pisa, Italy), and OpenSceneGraph (through an additional sublibrary called osgHaptics).

ReachIn market two commercial haptic API’s that support various device manufacturers. One, the self-titled “ReachIn API” is compatible with C++, VRML and Python with visual components rendered using OpenGL. The second is HaptX, a haptics only engine designed for the games market. Haptik [29] like HaptX also provides a basic abstraction layer for force feedback hardware. It is an open source library allowing a wide range of devices to be accessed through a common interface.

The VirtualHand API, formerly from Immersion and now from CyberGlove Systems LLC, is a C++ simulation development API for hand interaction. It supports CyberGlove’s gloves as well as their CyberForce system and various hand tracking hardware. MHAPTIC [30], is another hand interaction simulation environment catering for two-handed manipulation. It is not freely available.

Specific to medical applications, OpenMAF [31], is an open source framework for computer-aided medicine and is based on the VTK toolkit. Haptic feedback is not the main focus in this project but is provided through SensAble’s OpenHaptics interface. SPRING [32] is an open source, real-time soft tissue simulation platform developed by Stanford University. SPRING’s main focus is minimal invasive surgery and a limited number of force feedback devices are supported. SOFA [33] is a framework aimed at real-time medical simulation, and the development of new algorithms. Support for force feedback is expected in a future release. Mass-spring and FEM deformation models, fluid models, and a large array of collision detection features are already provided. GiPSi [34] is an open source framework
for developing human organ level surgical simulation. The structure of the API is designed to use more general models than those used in SOFA whose models must be tailored toward specific methods. ESQUI [35] is a platform-independent laparoscopic surgery framework, although it is intended that the system can be applied to any surgical simulation. Using XML style scene descriptions, the ESQUI platform advocates the Simulation Reference Markup Language (SRML) as a standard for information exchange between simulators. One commercial laparoscopic haptics device is supported at the time of writing, VSS [36] is also a framework in development for virtual surgery simulation offering a cross-platform object-oriented system with support for both haptics, GPU processing and semiautomatic segmentation.

One of the hardest problems in medical simulation is the modeling of tool and/or hand interaction with soft tissue. The collision detection parameters must constantly change as the surface of the soft tissue deforms. This deformation is due to the actions of many different material layers within the tissue whose properties are little known and typically too complex to model in real time. Simplifications are usually made to enable a sufficiently rapid response time. Bodily functions, such as respiration, changes in blood pressure, and contraction of muscles, will also result in tissue deformation. Moore and Molloy [37] provide a broad overview of deformable models for a wide range of disciplines. A more detailed survey by Nealen et al. [38] focuses on deformations for computer graphics animations where visual fidelity is the main goal, while Meier et al. [39] survey deformation techniques for real-time surgical simulation. There is little overlap between these two surveys, highlighting the different challenges faced between animation and surgical simulation such as: strict real-time behaviour, acceptable accuracy in modeling highly complex tissues, and the capability to cut models for surgical simulation. A comparison of techniques demonstrates the trade-off between computational efficiency and realism. More recently, Famaey and Sloten [40] provide a detailed review of the key continuum mechanical models for surgical simulators for minimally invasive surgery. This could be for patient assessment or guidance for an intervention. Palpation and general haptic response commonly require direct multifinger, multicontact tactile manipulations, a challenging task for a medical simulator to implement and so is usually ignored. When included, the manipulation is usually greatly simplified.

An early palpation example was a knee palpation simulation using a Rutgers Master force feedback glove interface [41], work that was later extended to simulate the palpation of subsurface tumors [42], [43]. More recent palpation simulations have been produced for prostate cancer using a SensAble PHANTOM [44] and of the heart using a custom haptics device [45]. A back palpation simulation, the Virtual Haptic Back (VHB) [46], [47] uses two PHANTOM 3.0 devices with thumb interfaces. In vivo measurements of the back compliance have been recorded to improve simulation accuracy [48]. This is the first stage of a planned palpation system of the entire human body.

Several palpation simulators are reported using the PHANTOM Desktop. Stalfors et al. [49] designed a remote diagnosis (telemedicine) simulator of malignancy in the head and neck area using a Desktop with a 3D surface model created from computed tomography (CT) data. An index finger palpation of thigh tissue using a Desktop is also presented by Chen et al. [50]. They discuss various deformation models for palpation and select a contact model based on Hertz’s theory from contact mechanics [51].

Two simulations of palpation for a pulse have been presented, one specifically for palpation of the femoral artery as part of an Interventional Radiology (IR) procedure [24] and the other for the brachial pulse [52]. Both simulations have erred on the side of affordability using low-cost force feedback devices (the Falcon—see Fig. 2, and the Omni, respectively) with the former using an additional tactile component.

Immersion filed a patent in 2001 for a haptic interface for palpation of a pulse [53]. This haptic interface closely resembles their design of the Wingman Force feedback mouse [20] with minor amendments. The simulation has not yet appeared commercially.

A breast palpation simulation [54] developed by Gifu University uses the Haptic Interface Robot (HIRO) in combination with a finite-element soft tissue model. The user interacts with the device by placing their thumb, index, and middle fingers into thimbles on the tips of three robotic fingers. A different breast palpation simulator [55] uses a PHANTOM Premium, a 6 DOFF device. A third unpublished breast palpation simulation was performed by Stanford Robotics lab as part of their multipoint haptics interaction research. A video of their two-fingered interaction can be found on the Internet [56].

In the field of veterinary medicine, a rectal palpation training simulator for bovine fertility examinations has been developed at the Royal Veterinary College (London, United Kingdom) using a PHANTOM Premium 1.5 force feedback device with a thimble interface. The device is housed within a fiberglass model of a cow [57]. Other work from the same group includes a horse ovary palpation simulator, HOPS [58], and more recently, a simulation of feline abdominal palpation [59]. The latter requires a two-handed palpation with two Premium 1.5 devices. A cat
mannequin is also used to provide context and a tactile stimulus from the mannequin's fur. The developers state that the high-fidelity force feedback devices are necessary to convey the haptic cues required. Despite the high cost, all three of the simulations are used in the veterinary curriculum at the college, with the Premium devices swapped between the simulations accordingly.

The direct practitioner/patient contact in palpation requires simulating both force and tactile feedback. Although, commercial force/torque feedback can be simple and inexpensive to incorporate, the lack of commercially available tactile devices limits current solutions for palpation simulation.

### 4.2 Needle Insertion

The Mediseus Epidural simulator (Medic Vision) is a commercial example of a needle insertion simulation using force feedback. The simulation can be run from a laptop. It gives a vocal response if the user makes mistakes and produces an objective report for the student [60]. A relatively low-cost SensAble PHANTOM Omni is encased inside the system using a modified syringe end effector at a fixed insertion point. This transforms the three positional DOFF to one positional and two orientation DOFF. To reduce the cost, Medic Vision have been investigating replacing the Omni with a Novint Falcon device which would reduce the cost of this component by 80 percent. An alternative epidural anesthesia simulation is EpiSim from Yantric Inc. (West Newton, MA, USA), which was originally developed by MIT [61]. The simulator takes a high fidelity rather than low-cost approach, first using a SensAble PHANTOM Desktop before changing to use a 6 DOFF Premium device to provide better simulation fidelity [62]. An LCD screen is used to display fluoroscopic x-ray images of the lumbar region and a three-dimensional model of the needle, spine, and tissues. Simulation of variable tissue thicknesses accommodates for patient variability.

Novint have produced a custom grip for the Falcon in a commissioned project, incorporating a real syringe and fluid. It is expected that other simulation companies will take advantage of this low-cost hardware where appropriate.

Chinese acupuncture is another field in which needle insertion simulation is being employed for training purposes. A simulation by Heng et al. [63] uses two computers to split the computation workload and is displayed in stereo upon a mirrored immersive workbench display. A PHANTOM Desktop was used during testing but eventually an Omni was used with a customized needle end effector.

An initial step in many interventional procedures is the insertion of a needle or trocar, as an introducer for other tools. Most current commercial simulators for minimally invasive surgery (MIS) are built with the introducer already in place, e.g., the MENTICE Procedicus VIST—a simulator for vascular interventional surgery where forces can be applied to a real catheter and guidewire. Other commercial simulators for interventional procedures use a similar approach to reduce simulation complexity and cost. Immersion Medical produced a now discontinued intravenous access simulation device named the CathSim Accu-Touch System [64]. It contained a needle carrier with three degrees of freedom (DOF) movement, and one degree of force feedback. Movement consisted of pitch, yaw, and depth of insertion. Force could be applied along the depth of insertion vector, either while inserting or retracting the needle. This one DOFF allowed the simulation of a needle passing through different tissues. SimQuest developed the Virtual IV intravenous access training simulator, which was subsequently acquired by Laerdal (Stavanger, Norway). At present, the Virtual IV is produced by Immersion and has replaced the CathSim. The Virtual IV is sold by both Immersion and Laerdal.

A simulator for percutaneous vertebroplasty (a minimally invasive procedure performed to bind spinal fracture components) has been developed by the National University of Singapore [66]. The simulation is claimed to provide advanced feedback and requires a force feedback joystick, a Delta haptics device and a CyberGrasp glove. This MIS procedure requires the practitioner to deliver cement from a needle at a specified critical rate. A reflective mirror display is used for stereo visualization. The researchers have applied biomechanical models to model the bone needle insertion [67]. Future work aims to produce a cost viable version of the simulation.

A trainer for catheter insertion has been developed at the Center for Advanced Studies, Italy [68]. Using a head tracked stereoscopic viewing system and a PHANTOM, the solution was reported to be "sufficiently representative of a real catheter insertion" by a surgeon in the field but, not validated. The soft tissue component of the simulation uses an incremental viscoelastic model [69]. Forces are applied using a lookup table.

Simulations of ultrasound-guided needle puncture using two Omni devices have been implemented by Forest et al. [70], and Vidal et al. [65]. The latter simulator employs an immersive workbench. One of the Omni styluses is replaced with a custom, ultrasound probe shaped end effector, and the second Omni is used for the virtual needle—see Fig. 3. The simulation uses the graphics processing unit (GPU) to generate ultrasound-like images from CT data. This work is currently being developed and enhanced with the intention of producing a commercial biopsy simulator [71].

A commercial ultrasound training application for endovaginal scanning is being developed by MedaPhor (Cardiff, United Kingdom). This simulation is implemented using the H3D software and a single Omni force feedback device. Another endovaginal simulation VEUSim [72] is in development at Drexel University. A spine needle biopsy simulator incorporating visual and force feedback has been designed for training and task planning [73]. A 3 DOFF PHANTOM Premium with needle end effector is used in conjunction with a mannequin. The mannequin has a fixed entry point in the lumbar region which is used as a pivot point to translate the degrees of freedom in much the same way as the aforementioned Mediseus Epidural simulator. Only one puncture site is permitted. A 3D visual user interface allows the user to follow the needles movement toward a target lesion. It is not clear from the literature what validation studies have been carried out.

Lumbar puncture simulators have been developed over the last 15 years and demonstrate well how technology advances are aiding continual simulation improvements. An early (1994) lumbar puncture simulation produced using a
custom haptics device [74] suffered from low-bandwidth actuators that caused problems simulating stiff objects, and a large graphics delay that only allowing the procedure to be performed slowly. Stepping forward six years, a later simulator used a PHANTOM 1.5 device, a mannequin, and a more powerful computer with OpenGL support [75]. With a goal to produce a lumbar puncture simulator that was “effective, not cost-prohibitive, relatively simple to maintain, and truly usable,” results were said to be “encouraging” with one of the future goals to accommodate for patient variability. More recently, a lumbar puncture simulator using a 6 DOFF Premium force feedback device has been produced [76]. The six degrees of force feedback accounts for all of the possible forces/torques felt while inserting a needle and importantly if a user releases the needle while it is inserted, it will stay in the correct position and orientation. This simulator calculates needle tip resistance using CT density data and, in addition, models the forces acting on the needle shaft. This involves restricting rotation and transversal motion as well as increasing needle friction as depth increases. The tissue model is static with both a 2D and a 3D stereo view provided during the simulation. Testing was performed by users with varying medical experience, who concluded they could tell the difference between different tissues. The 6 DOFF was reported to facilitate “realistic needle behavior.”

Needles are also used in suturing for wound closure. The goal of one simulation [77] was to develop a realistic and economical haptics suturing simulator. However, the Premium 1.5 device used in this simulation puts a high price on the required hardware. The simulation is displayed upon a stereo-enabled mirrored display and the force feedback device is mounted upside down modifying the range of motion of the stylus—see Fig. 4. This configuration modification can be used to increase the usable workspace for specific tasks. A mass spring model was implemented to represent the deformable skin tissue. This simulation is now intellectual property of Verefi Technologies Inc. (Elizabethtown, PA, USA).

A device with 7 DOF positional capabilities and 4 DOFF was developed by Hing et al. [78] to simulate a needle insertion. The forces and tissue deformation involved in a needle insertion and removal were collected from a porcine specimen that was then used to validate a finite-element force feedback model. There is no visual feedback, and needle insertion and withdrawal velocity are unaccounted for. Work toward simulation of realistic tissue deformation is ongoing.

DiMaio and Salcudean developed algorithms to simulate visual and force output during needle insertion into a deformable tissue [79], [80]. The model calculations are performed upon mesh nodes in the tissue model. If nodes are in contact with the needle, they’re constrained. A rigid needle will constrain node movement along a single axis. Nodes may either stick to the needle or slip. As the physical behavior of the needle within the tissue is not known, the model for sticking and slipping has been produced experimentally. The original haptics device used in the simulation [81] has been commercialized by Quansar, and is named the Planar Pantograph Mechanism. It is a 3 DOF device allowing planar translation and unlimited rotation about a single axis. Quansar are also involved in providing a new force feedback device for Verres needle insertion [82]. The device has a syringe-shaped end effector but the technical details are unpublished.

A needle insertion is commonly simulated using commercial force/torque hardware with frequent use of modified end effectors. A one DOFF can be used to simulate the penetration force but, 5DOFF is required for accurate simulation of needle puncture into an arbitrary location. Fixing the needles puncture location can reduce this to only 3 DOFF.
4.3 Laparoscopy

Laparoscopic surgery, or minimally invasive surgery, is a surgical procedure performed through small incisions, using long thin tools to perform a procedure within the body. A surgeon's view of the procedure is occluded by the skin and as such a camera is inserted into the patient along with the tools. Tool manipulation is unintuitive as the surgeon has to move the tool handle right to move the tool tip left, etc. The force/torque feedback is limited by the tight trocars through which the MIS tools enter the body. Orientation within the patient is also difficult to master and identifying the anatomy from a restricted camera angle is problematic. A practitioner needs training before performing an operation and several simulators are commercially available for this purpose.

There are more simulators available for training in laparoscopy than for any other medical specialty. Procedicus MIST, a simulator sold by Mentece was one of the first on the market. It was originally developed and sold by Virtual Presence (London, United Kingdom) as the Minimally Invasive Skills Trainer. The current version uses the Xitact ITP and IHP hardware devices. The ITP performs only tracking whereas the IHP also provides axial force and pitch, yaw, and roll torque feedback. The simulation software is modular, allowing basic skills to be tuned using an abstraction of the real-life task. For example, procedures such as suturing and knot tying are trained using a series of simple geometric shape manipulation tasks. Many evaluations have been performed on the product such as [83] and a complete list can be found on Mentece’s website [84].

Immersion Medical offers a laparoscopic simulator called LapVR that offers basic skills modules including the handling of some geometric objects and also includes training in more realistic environments. Tasks include camera navigation, cutting and procedural tasks of laparoscopic cholecystectomy. Each user’s progress can be tracked for evaluation of progress through the curriculum. A custom haptics device developed by Immersion is used.

LAP Mentor, a product from Simbionix (Cleveland, OH, USA) originally used the Xitact LS500 [85] hardware (which combined a computer and monitor along with two laparoscopic interfaces and a camera tool). The latest version uses new haptics hardware from Mimic Technologies. Simbionix also market a lower cost, portable version of this system designed to be run with a laptop—the LAP Mentor Express. The device supports an expanding set of modules including training of knot tying, suturing, and gastric bypass along with decision making and teamwork tasks.

The SurgicalSim Education Platform (SEP) is produced in a partnership between SimSurgery (Oslo, Norway) and Medical Education Technologies (Sarasota, FL, USA). Its basic skills module allows port placement, camera navigation, tissue manipulation, and suturing exercises. In addition to these basic operations, the simulation also includes gall bladder and embryo removal. Teamwork and decision making is also trained. The interface to the simulator provides no haptic feedback and uses electromagnetic trackers embedded in the handles of specially built laparoscopy tools. The tool shafts are inserted into an elastomeric sheet that represents the skin access portal. The deformable tissue interaction software is licensed to other medical simulation companies.

LapSim (Surgical Science AB, Goteborg, Sweden), is a laparoscopic simulator available with a choice of either the Xitact IHP or ITP interfaces. The simulation has two laparoscopic tool interfaces and a single monitor. The standard basic skills module deals with procedures such as suturing. Various add-ons are available such as the gynecological module. The simulation has been the focus of many validation studies [86] and links to these can be found on Surgical Sciences website.

Simendo (SIMulator for ENDoScropy) marketed by DeltaTech (Rotterdam, The Netherlands) provides a control interface without force feedback capabilities. Marketed as a simple simulator that does not try to tackle the complexities of a real procedure, DeltaTech recommend training on pigs for real-world training. The simulation is designed to train the practitioner’s basic tool skills only, much like the Mentece MIST, using tasks represented by geometric shapes. The simulation does not require a high-specification computer due to its simplicity and has undergone validation [87].

SkillSetPro (Verefi Technologies Inc.) is a laparoscopic training simulator combining camera navigation, suturing, and basic skills training software modules. The user interface is Verifi’s custom hardware derived from a SensAble Omni, which is embedded into a mannequin’s torso. The simulator incorporates trainee feedback and performance measurements that are “easily recorded and viewed.” Teamwork and collaborative surgery are also trained with the systems Head2Head module. Validation has been performed, but not as extensively as some of the other laparoscopic simulators [88].

The V5One system (VEST System One) produced by Select IT VEST Systems (Breman, Germany) is a virtual endoscopic surgical trainer using a custom built haptics interface and the KISMET simulation software developed by Forschungszentrum Karlsruhe (Karlsruhe, Germany). The KISMET software supports real-time interaction with deformable objects.

The VirtaMed (Zurich, Switzerland) HystSim is used for teaching hysteroscopy procedures and has been licensed by Simbionix. This system is the result of many years of work at ETH Zurich which entailed extensive attention to both physical behavior and visual appearance [89].

The Haptica ProMIS (Boston, MA, USA) system contains target simulations of a number of laparoscopic procedures that are used in combination with physical models and digital video cameras to produce an augmented reality display. This system does not include a haptics device but rather uses the real interaction of surgical tools with physical surrogate anatomy to provide haptic cues.

For effective simulation, tools that penetrate a fixed point of a mannequin structure can be attached to 3 DOFF devices. If simulations were to include trocar insertion a 6 DOFF device would be required. The frictional forces exerted on the laparoscopy tools as they pass through a trocar must also be considered as these may well prevent more subtle haptic cues being detected. No tactile feedback is present in laparoscopic surgery apart from at the tool/hand interface.

4.4 Endoscopy

A clinician feeding an endoscope into a patient will experience resistance between this flexible tool and the patient’s body. There have been several examples where endoscopes have been used with haptics in a simulator to
give an appropriate physiological response and accurate tool behavior, e.g., [90] a bronchoscope force feedback device, VIRGY endoscopic [91], and [92]. Commercial products for endoscopy include GI and URO Mentor from Simbionix and, Endoscopy AccuTouch from Immersion. Trifan and Stanciu [93] provide an up-to-date and comprehensive endoscopy simulation review. The decision of how many DOFF are needed for an endoscopy simulator is similar to that discussed in the previous section.

4.5 Endovascular Procedures
There are different disciplines of IR: one focusing on the peripheral vascular system; procedures focusing on the brain, possibly as therapy for strokes called interventional neuroradiology; and those procedures focusing on the heart, interventional cardiology.

Many procedures start with a needle insertion into the vascular system but current commercial simulators skip this step to reduce complexity and build cost. A guidewire and catheter are then manipulated within the vascular anatomy to navigate to the position of interest. This is a 2D visual (using fluoroscopic guidance) and tactile process, sensing small axial forces and torques at the fingertips while manipulating the wire. The acute training of wire guidance and the response to the fine forces felt while advancing a wire is crucial for efficient IR procedure training. An overexertion of force can have serious consequences and correct training to prevent this must be included in any IR training simulation.

Two early IR simulators were the Dawson-Kaufman IR simulator, designed by HT Medical for practicing angioplasty [94] and the daVinci/ICard IR simulator [95], [96].

VIST from Mentice AB (Gothenburg, Sweden) is sold as a simulator for various endovascular procedures. VIST was developed from a simulation called the Interventional Cardiology Training System (ICTS) [97]. The development of ICTS started at MERL, the Mitsubishi Electric Research Lab (Cambridge, MA, USA) in collaboration with the CIMIT group [98] and a number of interventionalists. This work was subsequently brought to completion by Virtual Presence (Sale, United Kingdom) under contract to Guidant (Brussels, Belgium) and ultimately commercialized by Mentice. A more recent simulator using a hydraulic pulse generator for palpation, and an adapted Vascular Surgical Platform (VSP) haptics device from Mentice for catheter and guidewire manipulation, is being developed by the CRAIVE consortium in the United Kingdom—see Fig. 5 [99]. This simulator is aimed at training the Seldinger Technique for catheter insertion, which covers the initial steps of introducing a guidewire and catheter into the patient. A construct validation study is currently in progress.

Anderson and Raghavan [95] extended work from the daVinci simulation toward an IR simulator for cerebral vascular, peripheral vascular, and cardiac applications in collaboration with Kent Ridge Digital Laboratory in Singapore and the Johns Hopkins Medical Institution [100]. An earlier paper [101] describes NeuroCath, the cerebral vascular track of the simulator. The latest developments of NeuroCath are given in [102]. The system interface is a mannequin structure and the simulators focus is guidewire manipulation. Currently, actual cardiovascular IR instruments can be inserted into the guidewire interface, which tracks and provides force feedback to the user in conjunction with visual feedback. A vascular model and potential field catheter navigation method for the simulation are discussed in [103].

Modeling the response to a guidewire as it is manipulated within the vascular system is a complex research topic as both structures are deformable. Alderliesten et al. [104] test the reliability of their catheter simulation by comparing the simulated results to those of real wire manipulation in a phantom model. The reproducibility of guidewire propagation was also assessed. A straight and curved tip wire was modeled with a series of rigid segments. The static friction of the wire against the side of the vascular system (which had been previously ignored) was also considered [105]. The latest simulator from the SIM [106] group, EVE, is a neuroradiology training simulation [107]. Some features of the simulator include interactive fluid dynamics of blood flow [108], volumetric contrast agent propagation, and, real-time collision detection and collision response [109]. Current efforts are aimed toward integrating performance assessment and user guidance.

Other simulations of interventional procedures under fluoroscopic guidance include Simbionix's ANGIO mentor for interventional endovascular procedures. This includes two smaller portable versions of the product: the Mentor Mini and Express which can be run on a laptop and use the compact Mentice-Xitact endovascular interface device. Mentice also sell a compact version of VIST which uses this same interface device. The CathLabVR, simulator from Immersion, uses a custom haptics interface device.

The HERMES project [110] is a project to create a training system for coronary stent implants. The system uses a custom haptics device [111] and a finite-element method for soft tissue modeling of the artery [112]. The Catheter Insertion System (CathIL) [113] simulation adopts a mannequin approach. The mannequin is laid on an operating table.
to provide a simulation environment as close as possible to a real procedure’s environment. SimSuite (Denver, CO, USA) also produce a commercial training simulation.

4.6 Arthroscopy
A knee (or shoulder) arthroscopy procedure requires a small camera and specialized instruments to be inserted into the knee. In this procedure, the practitioner’s tools will interact with the soft surrounding tissue and the hard bone of the knee. Simulating realistic hard contacts is a significant problem [16] especially when combined with the need to simulate soft contacts next to the hard objects.

Arthroscopy simulators include the commercial product InsightArthroVR marketed by Immersion, created and manufactured by GMV (Madrid, Spain). The device uses an LCD monitor for visual feedback combined with two SensAble Omni devices with modified end effectors. The tips of the end effectors are manipulated within a knee or shoulder mannequin depending upon the procedure performed; giving the simulations good face validity. The simulator has undergone a recent validation study of face and content validity using a questionnaire style evaluation, and construct validity judged with a time metric on a small subject number [114]. A larger subject group needs to be studied along with a longer term transfer of skills study to draw any concrete validation conclusions.

Mentice sold an arthroscopic simulator called the Procedicus VA that originated from work at Prosolvia. It was acquired following the dissolution of Prosolvia and the subsequent creation of Mentice where the product was refined and commercialized. This simulator, which saw extensive use and publication as the first commercial arthroscopy simulator, is now being reengineered for future reintroduction.

Another commercial simulator is available from Touch of Life Technologies (ToLTech) (Aurora, CO, USA). This simulator has undergone extensive development under sponsorship and guidance of the American Academy of Orthopedic Surgeons. Two separate monitors are used, one for the virtual mentor and the second displaying the procedure. Force feedback is provided by two SensAble PHANTOM Desktop devices with modified end effectors. SensAble’s force feedback device’s have also been used in academic arthroscopic simulations [115], [116]. Heng et al. [117] provide illustrations showing that an off-the-shelf PHANTOM Desktop can’t be directly used in their simulation as its 3 DOF are not the correct degrees for the simulation. They have developed their own 4 DOF device which offers three degrees of force feedback.

Force feedback hardware has also been incorporated into a knee mannequin. Examples include KATS [118] which has undergone validation studies [119], OrthoForce [120], and the early work at MERL that used voxel-based haptic simulation approaches [115] coupled with a powered gimbal linked to a SensAble PHANTOM [121]. As humans can distinguish between the high-frequency vibrations that occur when two objects come into contact [122], Tenzer et al. [16] have tried to recreate the vibrations felt during the arthroscopy procedure to enhance the tactile fidelity of the OrthoForce device. Although the device has only been tested on a small group the results appear to be positive. Commercial haptics devices can be used for arthroscopy simulation if heavily modified. Frequently, custom devices are used. The tactile information involved with touching the knee above tool/hand interaction has not been simulated.

5 Simulation Evaluation and Validation
The fundamental perceptual issues while performing minimal access and other procedures are not fully understood. Evaluating simulations of such procedures is therefore nontrivial. Formal validation studies that focus on the use of haptics in medical simulation are scarce. The evidence, presented in this paper, suggests that surgical simulations incorporating haptic feedback provide a richer training experience than those that do not. The most complete validation studies to date have been performed upon the available Laparoscopic simulators (e.g., [123] and [124]). One study supports the use of force feedback during a tissue characterization task in a MIS setting [125]. It concluded that “subjects are more comfortable characterizing tissues when both vision and force feedback were provided.” Another study conducted using Immersion’s Laparoscopy VR suggests that for more advanced Laparoscopic tasks, the addition of force feedback in a simulation results in faster completion of tasks [126]. However, a recent review of haptic feedback in conventional and robot-assisted laparoscopic surgery [127] concluded that there is no firm consensus on the importance of haptic feedback in laparoscopic simulators.

Often, skills transferability is reported by demonstrating an improvement in the task of trainees who use the simulator over those who do not [128]. One evaluation of an endoscopic sinus surgery simulator [129] argues that a significant difference in performance between experts and novices demonstrates a similarity to real-world performance. It also advocates rating and comparing anonymous video of procedures performed by simulation trainees and a control group. A complete evaluation of transfer of skills where one control group does not use a simulator, another uses the simulator without haptic feedback and the third uses the complete haptic simulation has yet to be carried out. This has partially been addressed by Morris et al. [130] who demonstrated that recall following visuo-haptic training is significantly more accurate than recall following visual haptic or training alone, although haptic training alone is inferior to visual training alone. However, whether the latter would be true for an interventional radiologist, where reacting to haptic cues is a vital part of a successful procedure, has not been investigated.

Another trend is to use data acquired from empirical in vivo force measurements [131] rather than using a purely mathematical model. The measured forces can then also be used to compare simulation output against real-world data and reduce reliance on the validation of a simulator’s fidelity and accuracy by a subjective “it feels right” approach. Such a study has not yet been reported.

A good overview of the issues that need to be considered when assessing a surgical simulator can be found in [132]. The need for multidisciplinary collaboration to build an effective simulator is advocated. Other important points made are that it is advantageous to deconstruct tasks into simple steps, to have repeatability of procedures which will facilitate learning from mistakes, to provide objective feedback, and that it is necessary to integrate simulators into the education curriculum. There is often a trade-off between the fidelity of the simulation and it’s cost, and it is not always necessary to achieve ultrahigh fidelity in order to provide a training benefit. The current published evidence clearly demonstrates that VR simulation can improve intraoperative performance. The work surveyed above demonstrates that good use of haptics has an important role to play in achieving this goal.


6 Discussion and Conclusions

The particular requirements for haptics within a surgical simulator varies with the application but the common trends and issues identified above can be summarized as follows:

- How to use haptics and still have an affordable simulator? The cost of multipurpose force feedback devices has greatly reduced but custom devices often needed by surgical simulators are still expensive.
- The availability and development of tactile interfaces is still in its infancy.
- There are always technology questions to consider, with real-time response essential.
  - How many DOFF are needed? Is three DOFF sufficient as six or more is expensive?
  - What computational power is needed? Is dedicated processor required for the haptics pipeline?
  - Is the force range sufficient? Will the range cover the whole pathology and patient variability that the simulator will encounter?
- Multipurpose haptics devices are by far the most commonly employed, but do they compromise the fidelity of the simulation, particularly, when compared to custom-built haptics devices? However, software support for multipurpose devices is good with several haptics libraries now available. In many cases, new and novel algorithms are also being implemented to improve performance and fidelity of simulation.
- What is the objective of the simulation? Clinical skills or tool training? A higher fidelity is typically needed for the latter. In both cases, a more successful simulation is provided if a detailed task analysis has taken place.
- There is a marked lack of validation studies that can report on the benefit (or otherwise) of using haptics in a surgical simulator. The question of appropriate simulator metrics for the use of haptics remains open.

Inevitably, compromises are made when incorporating haptics into a medical simulator but nevertheless the technology has a growing and important role to play in the medical domain. This has been particularly the case for minimally invasive procedures and also when a tool such as a needle or surgical drill needs to be simulated. Open surgery and procedures where practitioners must grasp soft tissues directly with their hands remains a research challenge.

In a 2008 publication by economist Scheffler, the cost of training a new physician is estimated to be $1 million [133]. The true advantage of providing an effective training simulation is hard to evaluate. In monetary terms, effective simulation can reduce the time wasted in extended procedures due to inexperienced practitioners practicing during valuable operating time; the guidance needed from experienced practitioners; the medical errors (costly by requiring corrective procedures and through compensation claims) and the need of expensive cadavers. On an ethical level, a simulation that prevents medical errors that would have resulted in a patient death or disability should make the simulator indispensable, but in the real world of business, this is not an adequate enough justification unless it is possible to prove to providers and insurers that a simulator will reduce risk and so save money. Unfortunately, a direct linkage between simulator training and improved patient outcomes is difficult, if not near impossible to prove [134].

 Procedure variability between practitioners in a single department as well as between different hospitals will cause conflicting requirements. A procedure carried out by an expert should not be deemed incorrect because they don’t perform the procedure in the same way as the control experts. To incorporate this variability into any measurement and assessment approach, it then may be advisable to limit definitions of incorrect methods of performing a procedure (for example, defining an area not to be penetrated by the needle) to locality of specific anatomical structures. Such measures would be turned off when a simulation is used to allow the surgeon to try high-risk maneuvers in a safe environment and discover new techniques. Any limitations of a simulator should be made clear so as to avoid incorrect training that could engrain bad habits (negative training). An extreme example of this could be a simulation that allows the removal of the virtual patient’s heart without killing them. For such an extreme example, it is clear that the practitioner would not believe the simulator is correct and perform this operation in real life. However, more subtle simulator inaccuracies are harder to spot as being unrealistic. Although many simulations aim to recreate realistic representation of anatomy and physiology to develop skills that can be transferred to the patient [135], this may not be the most effective training method available. Validation studies of the MIST task trainer prove that manipulating simple geometric objects, i.e., not anatomically realistic, is a very effective tool for training basic MIS tool skills [136].

The ability to record metrics in a simulation offers advantages for trainee evaluation. A whole array of data is available to the programmer to process for evaluation and therefore needs to be carefully thought out. The metrics to be recorded should be defined in a task analysis preceding the simulator development and not as an afterthought. If the data recorded are the correct information and it is accurately correlated with expert judgment of performance, the possibility to use simulation for accreditation exists [135].

The availability of effective simulators will ultimately be defined by cost. The cost of force/torque feedback devices is slowly decreasing but the volume of sales needed to reduce cost significantly is currently beyond the scope of medical simulation. SensAble Technologies currently make the most popular choice of force feedback interfaces for medical applications. Their PHANTOM Premium devices are chosen for their high-quality response and their Omni device for its low-cost 6 DOF tracking and 3 DOFF capabilities. The games market has driven innovation in graphics cards and the GPU is now a powerful computation tool. Novint’s Falcon device augurs that force feedback may also be adopted by this market. This may then lead to more low-cost force feedback interfaces being available for simulation development.

Low simulation cost is usually high on the list of requirements during development of a commercial simulation product. Cost cutting on hardware in the early stages in an effort to save money, however, may obstruct the production of a simulation with sufficiently high fidelity. Analysis of a high-quality simulation can determine if the extra cost is worth the increase in fidelity and so producing a quality prototype simulation, validating this, and then reducing the fidelity to meet cost requirements while maintaining transfer of training effectiveness may prove
to be a better approach. For example, the low-cost Falcon device may well be sufficient for many tasks currently using PHANTOM devices (e.g., needle puncture) and we have seen evidence of this trend occurring, although such information is difficult to obtain from companies who do not want to reveal their intellectual property.

Comparing simulations and devices is extremely difficult as each product offers different features and the availability of evaluation results vary. For example, a basic real-world needle insertion is a five degree of freedom operation. It could be assumed that nothing less than a device displaying these many degrees of freedom could be used to produce a realistic simulation. However, realism comes at a cost and a near realistic affordable simulation maybe better than no simulation at all. It is not immediately obvious if the education value of a low-cost simulation offering only three degrees of force feedback is any better or worse than a higher cost solution offering the full five degrees of force feedback. No study has yet been carried out to show whether this is indeed the case.

Emerging technologies will continue to offer the potential of creating higher fidelity simulations, but should only be used where a clear training benefit can be proven. Haptics technologies have reached this stage and will have a pivotal role to play in the ability to maintain skills competence and reduce the need to train on patients.

References


This page contains a list of publications and a biography of a person named Dwight Meglan. The publications listed are focused on topics such as haptic feedback, surgical simulation, and robotic surgery. Dwight Meglan received his BSc degree in mechanical engineering and his PhD degree in biomedical engineering. He is currently a professor at the School of Computer Science, Bangor University, United Kingdom. His research interests include visualization and virtual environments, particularly in the areas of haptic feedback and surgical simulation.

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