CHAPTER 9

Haptics-driven healthcare training simulator systems

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KEY MESSAGES

- Most training simulations are vision-based only.
- Multidimensional training simulations are more effective and desirable.
- Touch is the second most important sensation for humans and is the only bi-directional sensation that humans possess.
- Haptics, which refers to the sense of touch, can significantly add to healthcare training simulations.

Overview

Real-time clinical material and patients for training are limited resources for healthcare students and effective training increasingly requires access to alternative realistic tactile experiences. One key factor in effective and sufficient training for healthcare professionals is to promote computer-aided virtual training simulations. These simulations provide repetitive and consistent training experiences and adopt vision and hearing to interact with the trainees. In many cases, this set-up is sufficient for a range of training scenarios. Nevertheless, there exist many other more complex forms of healthcare training that require not only vision and hearing, but also detailed tactile feedback to help with complex and fine-grained kinaesthetic movement and muscle memory. After all, touch is the second most important sensation for humans and is the only bi-directional sensation that humans possess.

In this chapter, we discuss the reasons and advantages of incorporating visual–haptic interactions for healthcare training simulations, and analyse the limitations of various existing haptic systems. We then demonstrate the current state of the art of haptics-driven healthcare training simulation systems through explanation of a few signature applications. With the prosperity of haptics research and applications, it is foreseeable that more advanced haptic training simulation systems will be available, and more healthcare professionals will benefit from such advances, thereby eventually providing a higher level of healthcare to society.

Introduction

The need to involve multiple human sensations, including vision and touch, in healthcare training simulation has been pushing the boundary of research and development work on haptics. *Haptics* refers to the sense of touch, the feedback from which can be interactively sensed through various haptic devices, electromechanical hardware that can provide force and tactile feedback to users. Coupled with the advances in interactive visual rendering, immersive virtual reality and augmented reality, haptic training systems are able to enhance the healthcare training experience and provide comprehensive training solutions for the healthcare community, particularly in invasive and interventional environments.

A number of key factors determine the effectiveness and practicability of a healthcare training simulator

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system. We discuss these factors here to highlight the necessity and advantages of incorporating haptics in healthcare training:

- *Immersion and realism* (see Chapter 10): This is an essential requirement of any training simulator system. Trainees should be easily able to identify the set-up of the training simulation and perform training procedures in the same or a very similar way to how they perform in real-life situations. Human sensations involved during the actual training should all be reflected in the simulation to immerse the trainees fully. Lack of immersion and realism may not only reduce the effectiveness of training, but also impose negative effects on the trainees and diminish their engagement.
- *Interactivity:* This is a core part of training simulator systems, as trainees gain direct and intuitive experience through interacting with the scenarios. Nevertheless, using a mouse and a keyboard for training provides significantly less interactivity than using actual touch sensations on injecting, cutting, grasping and rubbing the virtual scenario objects. Real-time interaction with the training system is both engaging and useful for improving the training results. Ideally the interface and tactile feel should replicate the clinical tools as closely as possible.
- *Repeatability:* A number of healthcare situations and conditions are rare, which makes the corresponding treatment difficult to repeat and pass on to others. Both traditional and haptics-driven training simulator systems can address this problem.
- *Measurable procedures and results:* Just as in the clinical environment, the training simulator system should be able to record what has taken place during the training and what the training result is. In addition, every slight interaction and movement during the training should also be recorded for easier analysis. Traditional training simulator systems are able to record movement, while haptics-driven systems are also able to both render and record the magnitude and direction of forces exerted at very high speed, typically 1 KHz.

From the analysis of these key factors, it is clear that haptics-driven training simulator systems have significant advantages over many traditional training systems, particular in invasive and interventional settings such as surgery.

Issues of haptics-driven simulator systems and their solutions

Although healthcare training simulation can benefit from haptics and its related techniques, there are still a few issues that need to be investigated further to evaluate their possible limitations. We discuss these issues in this section.

Device classification

Haptics, referring to the sense of touch, can be further classified as kinaesthetic and tactile. In many situations either term is referred to as haptics, which creates confusion and ambiguity. *Kinaesthetic* devices are more frequently used for training tasks that require the movement of muscles, such as surgical simulation, while *tactile* devices are mostly used for training tasks that require the relative movement of skin, such as palpation simulation. Furthermore, there have been a number of studies [1–3] trying both to combine feedback and to provide a higher dimension of fidelity for healthcare training. Most existing haptic devices are either kinaesthetic or tactile, and their number of haptic interaction points (HIPs), which are equivalent to the number of fingers, are usually much less than on the human hand. This reduction in functionality has confined the applicable domains for haptics.

Device specification

Haptic devices vary significantly with reference to both their targeted applications and cost. The most commonly used haptic devices in current research and industrial projects are those desktop kinaesthetic haptic devices with a stylus and a single HIP attached, as shown in Figure 9.1. They have been successfully adopted in a number of healthcare training systems, but their capabilities are limited due to their models' simplified interactions compared with human hands. Based on this, there has been recent research on augmenting haptic devices, aiming for more intuitive interaction and better training results.

- Multimanual haptic devices (usually bi-manual devices) are intended for healthcare training simulations where both hands are required [4–6]. These devices usually consist of multiple single-point haptic devices, where each hand is considered as a single interaction point. In these devices, finger-level operations are usually omitted. Training simulations

(a) (b)

Figure 9.1 Examples of existing single-point desktop kinaesthetic haptic devices: (a) Phantom Omni from Geomagic (formerly Sensable); (b) Omega 6 from Force Dimension.

applicable to these devices include minimal invasive surgery, endoscopy and orthopaedic surgery (arthroscopy and trauma surgery).

- Multifinger haptic devices (usually between 2 and 5 fingers) are intended for healthcare training simulations where interfinger operations such as pinch, grasp and injection are highly regarded [7–9]. These devices usually omit dual-hand operations and are best suited for healthcare procedures focusing on single-hand operations, such as foreign body removal, epidural injection and lumbar puncture. Although some of these training scenarios actually require both hands to finish, many existing device set-ups focus only on the part where the main force feedback is rendered.
- Holistic haptic devices are more sophisticated configurations that are capable of providing both kinaesthetic and tactile feedback simultaneously. They can be significantly more useful in procedures requiring both kinaesthetic and tactile feedback, such as training simulation of a complex healthcare procedure involving palpation, injection, incision and suturing. One major challenge for holistic haptic devices is to identify the proper approach to integrate both types of feedback in the HIPs and associating the tactile feedback devices (usually an array of vibrators or pins) with the transformation of their corresponding HIPs.

Although research on these advanced haptic devices has been progressing, many projects are still at the prototype stage. With the growth of more accurate and capable haptic devices, the quality of healthcare training simulation systems is expected to be further improved.

Application examples

Since the early days of haptics research, healthcare training simulation has been one of the key application domains. Over the years, a number of haptics-driven healthcare training systems have been proposed, implemented and validated from both industrial and research facilities.

The key areas of existing haptics-driven healthcare training simulators are as follows:

- Minimal invasive surgery simulator systems, such as the insight ARTHRO VR [10] from GMV; the prototype system described in Nudehi et al. [11]; Laerdal's Virtual IV system [12], an intravenous catheterization learning and training system in IV insertion and phlebotomy; and the ImmersiveTouch [13], a training simulator for open and percutaneous surgeries. In addition, there are also a number of laparoscopic surgery simulator systems available [14–16].
- Endoscopic training simulator systems, such as the EndoscopyVR system [17] for gastrointestinal surgery and bronchoscopy; and the MicroVisTouch system [18] for microsurgery procedures such as endoscopic neurosurgery.
- Epidural injection simulator systems, such as the Yantric EpiSim system [19]; the Mediseus Epidural

system [20] from Medic Vision; and the work described in Dang et al. [21].

- Orthopaedic training simulator systems, such as the TraumaVision system [22] from Melerit Medical AB; the MAKO RIO [23] system from Immersion; and the lumbar puncture simulator system described in Gorman et al. [24].
- Dental training simulators, such as the Individual Dental Education Assistant [25] from IDEA International; and the Simodont Dental Trainer system [26] from Moog.

In recent years there has been new research effort in promoting healthcare training simulator systems. Some work focuses on the rendering and interaction algorithms for rigid (such as bone) and deformable (such as soft tissue) 3D models, while other work is more on specific medical training applications. We discuss this research in the following sections.

SimOptiX

A recent effort to push the limit of haptics-driven healthcare training simulator systems is the SimOptiX project, a haptically enabled optometry training simulator that features not only interactive training simulation using haptics, but also seamless integration with an actual slit lamp that optometrists and ophthalmologists use on a daily basis.

The simulator has undergone two major stages, with two distinct hardware configurations targeting trainees with different training requirements.

The first configuration is based on haptics with head mount display (HMD) and augmented reality (AR). It is targeted at optometry students, who mostly focus on isolated and repetitive training simulation sessions. The system consists of both visual and haptic pipelines, which run in parallel. In the haptic rendering pipeline, a standard Phantom Omni device is mounted next to the slit lamp, with careful hardware calibration on its location and rotation. In the visual rendering pipeline, a webcam captures the position and rotation of AR markers located on the eyes of a dummy head and visualizes the anatomy of a virtual eye through the HMD. All haptic-related operations will also be visualized during the training session. A number of key parameters for the immersive and accurate simulation of various optometry procedures have also been implemented in the configuration, such as the angle, distance and brightness of the head light, needle sharpness, eye separations for stereo vision and so on. Two typical training scenarios have been identified and implemented, including the needle-injection procedure and the foreign body–removal procedure. Different force-rendering algorithms have also been implemented to support the distinctive force variations during the procedures due to different tool choices. A small-scale user study was conducted and most participants are positive about the accuracy and immersion of this configuration [27].

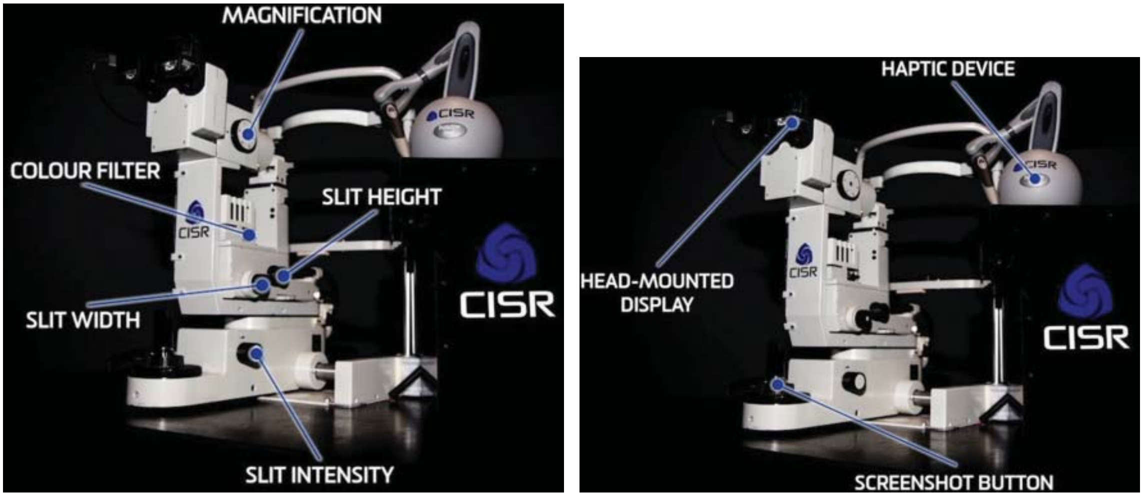
The second configuration is targeted at established optometrists and ophthalmologists to maintain and improve their procedural skills. This configuration is heavily involved with various absolute measurement sensors, which are electronically integrated into the slit lamp and replace many of its original optical pathway components. The integrated sensors are connected to the original control parts on the slit lamp and seamlessly translate user input into digital signals, which are reflected through multipoint haptic devices and visual rendering results. The detailed control layout is illustrated in Figure 9.2, and the actual system in action is demonstrated in Figure 9.3. Two rendering algorithms based on texture blending and masking as well as shading language were implemented [28], and their rendering results were compared to justify the visual immersions.

Based on this configuration, another user study has been conducted to validate its practicability as well as its comparative impressions with the first configuration. Results showed that a more natural user interaction interface, which in this case is the standard layout of control components on a slit lamp, could further improve the success rate and the immersion of the training simulation [29].

SimNeT

SimNeT is a haptics-driven needle thoracostomy training simulator system for tension pneumothorax, which is an emergency condition where excessive air accumulates in the pleural cavity following a lung or airway injury and exerts pressure on the lung, forcing it to collapse, as well as restricting cardiac output. Needle thoracostomy helps remove the air from the pleural cavity and prevents cardiac and respiratory failure. The key procedures of a needle thoracostomy are:

- Identify correct intercostal spaces through palpation.
- Identify different body components with distinct physical properties before needle introduction; that is, ribs are rigid while skin and lungs are deformable.



(a) (b)

Figure 9.2 Illustration of the control layout for SimOptiX. The highlighted controllers were originally mechanical ones, but have been replaced by electronic sensors that feed the user input directly into the training simulation programming.

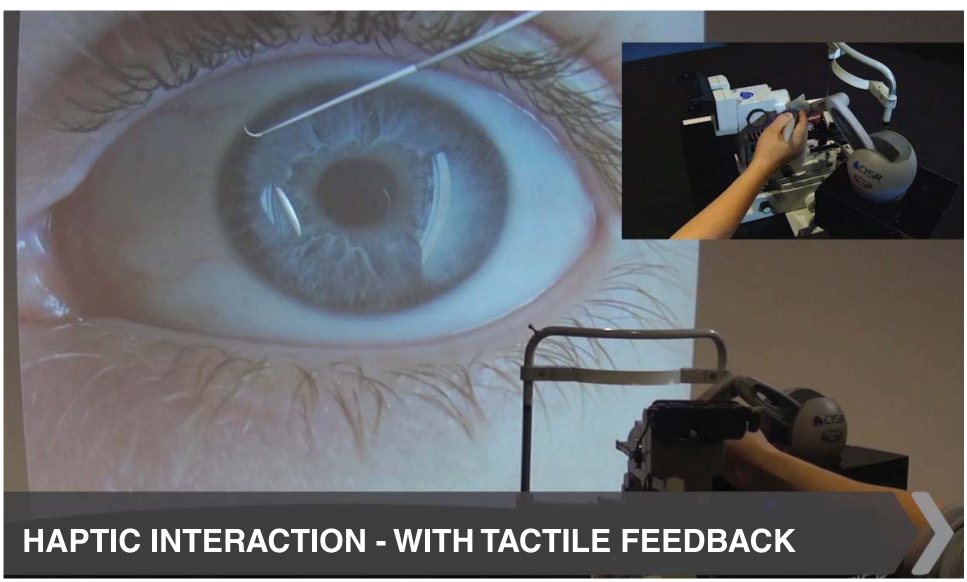


Figure 9.3 The SimOptiX system in action. Multiple cameras have been employed to shoot both system overview and detailed operations.

- Insert the needle between the intercostal spaces, without damaging either the ribs or the vessels and nerves attached to the ribs.
- Insert the needle into the pleural cavity at a certain depth, where excessive air can be aspirated while not damaging the collapsed lung.

One major challenge in this scenario is to render concurrently highly detailed objects in the scene, where the objects are a mixture of both rigid (representing ribs) and deformable objects (representing skin and lungs), and the objects include each other; that is, the lungs are within the ribs and the ribs are within

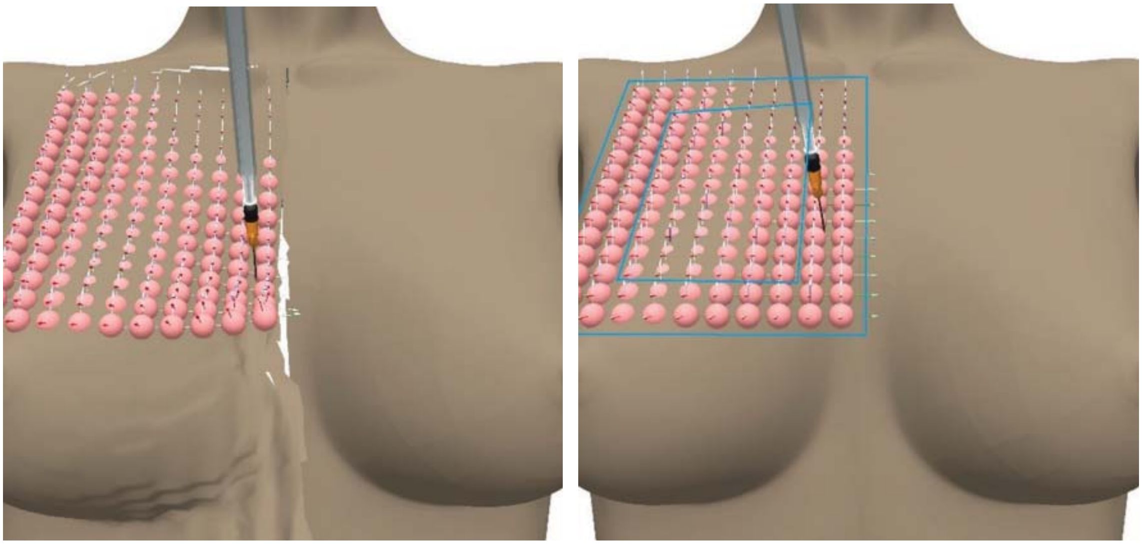


Figure 9.4 A comparative demonstration to the approach on avoiding deformation distortion on soft tissues during haptic training simulation: (a) how the deformation would look like without the technique for guarding the edges of the deformation patch; (b) with the technique.

the chest. Through the research and development of novel rendering algorithms, a framework that supports disjointed heterogeneous models whose bounding volumes are overlapping or inclusive has been successfully implemented. This allows the immersive rendering of injection through multiple layers of soft and rigid three-dimensional (3D) models.

The palpation procedure is implemented by an array of spherical nodes with interleaved physical properties; that is, certain rows of the nodes are defined as rigid to simulate ribs under the skin, while the rows between are softer to simulate intercostal spaces. To solve the local distortion of deformable skin, as shown in Figure 9.4, a technique has been implemented to guard the edges of the deformable patch and ensure that the skin deformation will not be propagated to the edges of the patch. To be able to validate the actual needle-insertion depth, an X-ray view has been implemented to allow users to switch instantly from the normal view and associate the current insertion status with the force feedback, as shown in Figure 9.5. Although this augmented functionality is usually not available in the real-time clinical setting, it is particularly important in training simulations and helps trainees establish the connection between invisible operation and force feedback. As needle thoracostomy can usually be done through both mid-clavicular and mid-axillary approaches, two training scenarios have been built, with a corresponding validation and scoring system to help trainees improve their skills over trials.

SimInc

SimInc (Interactive Surgical Incision Simulator) is an ongoing project that is specifically designed for the training simulation of surgical incisions. Although an incision is one of the most basic skills for various surgical tasks, every surgical incision can be different. This is because not only is every patient unique, tissue on different parts of a patient is also different. Situations can be further complicated by many other factors, such as the shape and sharpness of the scalpel used, the angle between the scalpel and the tissue, the speed of the incision and so on. A well-trained surgeon can significantly reduce the impact of the incision to the patient, lessening pain and allowing faster recovery and a more cosmetic scar.

SimInc adopts the GEL dynamics engine [30] and enables trainees to perform surgical incision tasks on different tissues, using different tools, and simultaneously to perceive the visual deformation and haptic

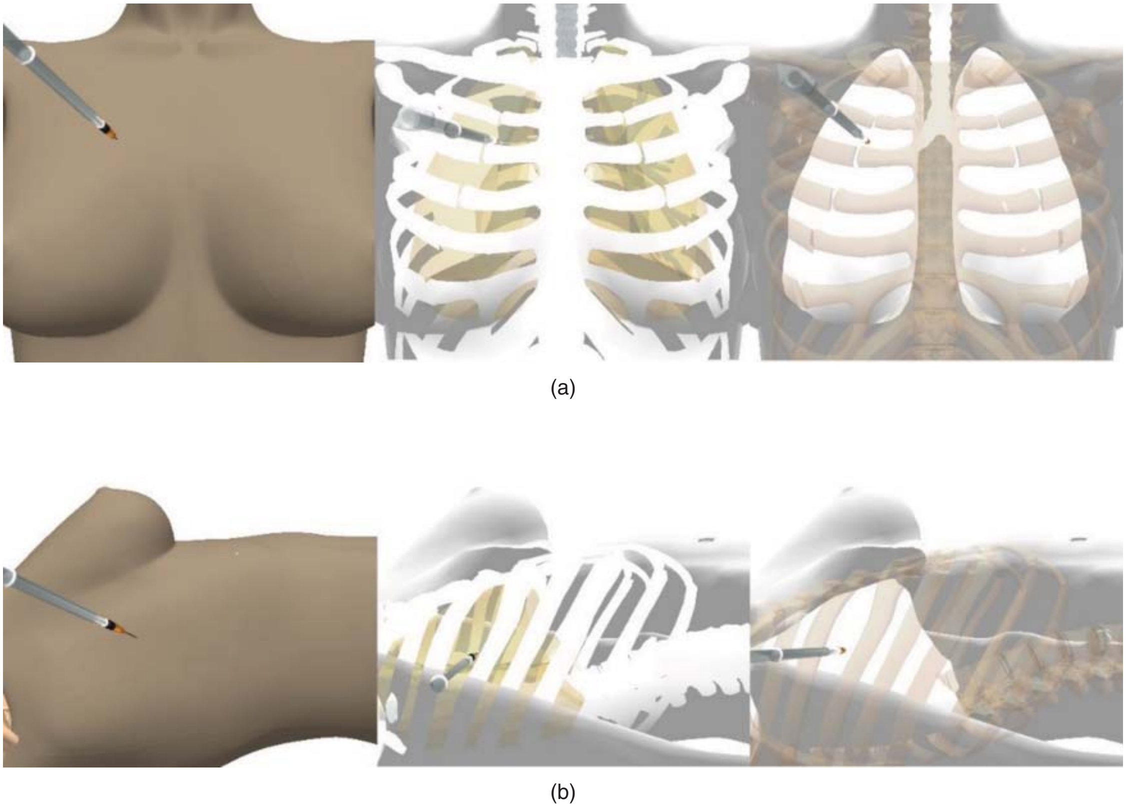


Figure 9.5 (a) X-ray view of multiple layered organs and tissues of pleural cavity for assisting trainees in validating haptic feedback with the actual organ/tissue touched. (b) Both mid-clavicular and mid-axillary approaches are shown.

incision force with every slight movement during the incision procedure. The identified and adjustable key parameters for the training simulator include:

- Tissue properties, such as skin elasticity and layered components under the skin.
- Scalpel properties, such as sharpness, blade shape and bevel angle.
- Operational properties, such as the velocity of the incision, and the magnitude and direction of the forces applied to the tissue.

Although incisions are usually short strokes, curved incisions are used in surgical procedures such as excision of skin lesions. To simulate such procedures, a curve-simplification algorithm has been proposed to convert continuous curves into three categories of grid-based split-line segments (horizontal, vertical and diagonal), which then splits the underlying deformation model accordingly and simulates the actual incision. Figure 9.6 is an initial demonstration of the interactive incision simulation (halfway and full-length incision), while Figure 9.7 illustrates the curve-simplification algorithm. Note that the actual simplification algorithm involves higher resolution of the grids and the simplified incision segments are much closer to the incision curve.

SimInc is targeted at the performance and result analysis of human-centred incision simulations. On the other hand, robotic surgery has been rapidly evolving during the past decades, and this focuses on the consistency of surgery performance and the reduction of human involvement during surgery. They may seem to contradict each other, but they are actually heading towards the same goal from different perspectives. Eventually, it is humans who design and implement algorithms for robotic surgeries, and there will always be unpredictable cases with which robotic surgery may not cope. In the future, human-centred surgical training may not be as important as it is now, but simulation training tools can always keep surgeons' skills up to

Figure 9.6 Different incisions based on the user's stroke through a soft body.

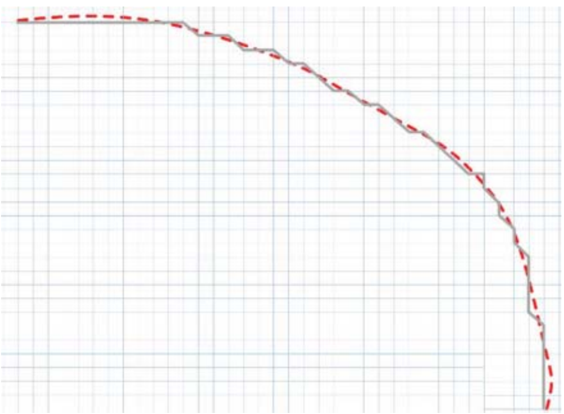


Figure 9.7 The interactive curve-simplification algorithm to render the user's stroke in grid-based segments. The actual simplification algorithm involves higher resolution of the grids and the simplified incision segments are much closer to the incision curve.

date and enable them to deal with difficult cases when necessary.

Conclusion and future work

Haptics-driven healthcare training simulations have been replacing traditional training simulations in the second decade of the twenty-first century, and this trend is still growing. The immersion of haptics into training content and its effectiveness in training results have helped healthcare professionals in a number of challenging scenarios. With the further development of hardware (especially multipoint haptics) and software (cross-vendor, extensible kinaesthetic and tactile communication frameworks), haptics is expected to play a more essential role in the healthcare sector. As patient-based training exposure becomes scarce, society still expects practitioners to become increasingly skilled. Haptics simulation modules allow healthcare students to gain valuable experience in a safe setting, while not putting patients at risk, thus helping to improve the quality of healthcare to the community.

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