Mixed Reality Manikins for Medical Education

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Abstract In medical education, human patient simulators, or manikins, are a well established method of teaching medical skills. The current state of the art manikins are limited in their functions by a fixed number of in-built hardware devices, such as pressure sensors and motor actuators that control the manikin behaviors and responses.

In this work, we review several research projects, where applied techniques from the fields of Augmented and Mixed Reality allowed to significantly expand manikin functionality. We will pay special attention to tactile augmentation, and describe in detail a fully functional 'touch-enabled" human manikin, developed at SimTiki Medical Simulation Center, University of Hawaii. Also, we will outline possible extensions of the proposed touch-augmented human patient simulator and share our thoughts on the future directions in use of Augmented Reality in medical education.

1 Introduction

Medical manikins are realistic looking life-size replicas of a human body, equipped with a large number of electronic, pneumatic and mechanical devices, controlled from a host computer. Manikins can be programmed to simulate a variety of condi-

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tions. The level of visual realism and physiological fidelity varies between models, but in general, manikins can provide a range of convincingly accurate responses to medical interventions. One medical manikin is shown in Fig. 1.

Fig. 1 *Resusci Anne*, a realistic life-size cardiopulmonary resuscitation (CPR) simulator, by Laerdal Medical Corporation. Image from the simulator manual, available online [19].

Most of manikins capabilities for interaction, including physical examination are implemented in hardware. All interactions between a human and a manikin are mediated by dedicated mechanical or electronic devices, installed in the manikin. For example, a SimMan line of products by Laerdal Medical Corporation [19] have touch sensitive elements installed at both wrists. These sensors allow a person doing examination to check a manikin's pulse by physically touching its wrists. The manikin "feels" that its pulse is being felt and responds by providing the pulse data to the host computer.

In addition to checking pulses, healthcare persons in training are expected to learn how to collect other data using physical examination techniques. Manual examination may be as simple as touching the patient at different locations and asking whether it hurts. Nevertheless, these techniques are not supported even in advanced manikins, because user hands are not part of the system. Figuratively speaking, manikins are not aware of their own bodies as tangible objects. To compensate for the absence of feedback from the manikins, it is a common teaching practice for an instructor to observe student examination techniques from behind a one-way mirror. If a student is palpating a simulated appendicitis and presses on the tender location, the instructor can provide a cry of pain using a microphone.

The need for such continuous and close human facilitation during the course of the exercise has many disadvantages. First, it requires undivided attention from the instructor, which makes it difficult to supervise more than one student at a time. As a result, manikin-based training is very resource intensive. Secondly, visual monitoring, even with video recording equipment, may not always capture all student actions, which reduces the quality of debriefing and performance evaluations. Finally, examination techniques may be subtle and require precise positioning of the student's hands on the patient's body. Such details are also easy to miss in visual observation alone.

All of these issues can be solved by making manikins sense where and how they are touched, allowing them to respond autonomously and keep logs of these events. We suggest filling this gap in manikin functionality by employing methods known from Mixed Reality (MR) and Augmented Reality (AR) fields. Briefly, to make a manikin touch-sensitive at arbitrary locations on their bodies, we reproduce real physical examination procedures in the 3D domain. The geometry surface model of the manikin and user hands are checked for collisions, which gives the location of points of contact. A gesture recognition process, running in real time, determines which examination procedure is currently being applied. With this information, the simulation software that controls the manikin's behavior is able to trigger an appropriate response function, such as a cry of pain in the appendicitis scenario.

In this chapter, we review the current state of the art in applying AR and MR methods to medical education. In Sect. 3, a detailed description of the manikin with tactile augmentation will be presented, developed in the SimTiki Medical Simulation Center, University of Hawaii. A special attention will be given to implementation and calibration of virtual hands. One complete training scenario will be presented in Sect. 5. Finally, we will explain our novel method for creating high-fidelity manikin geometry surface model in Sect. 6 and conclude with a discussion of possible extensions and applications of tactile augmentation. Sections 3 through 7 are largely based on our previous work [26, 27]; that material was revised and updated.

2 Augmented Reality in Medical Education

Medicine and medical education are a fertile ground for Augmented Reality techniques to grow, for an important reason: the cost of human error is high. In the last few years, medical AR applications experienced a rapid expansion, driven by advances in hardware (tracking, haptics, displays [2]), new concepts in user interface design, such as Tangible User Interface (TUI) [28] and a palette of new interface metaphors and display techniques, including *MagicLens* [20] and *Virtual Mirror* [23]. These advances made it possible to visualize invisible, obscured or abstract objects and data, such as a flow of gases in a Mixed Reality anesthesia machine simulator [24].

Visual overlay of medical imaging data obtained from living patients received much attention from the research community as early as in 1992. From Bajura, Fuchs and Ohbuchi [3]:

> ...Of special interest are recent efforts to apply such AR displays to medical imaging, by superimposing data acquired via imaging techniques such as ultrasound, CT scanning, etc. conformally onto the actual patient. (1992)

In 2007, using a Head Mounted Display and direct volume rendering of CT scans, Bichlmeier and colleagues presented a system, that allowed surgeons literally see into a living human patient [4].

In addition to visual augmentation, other input modalities were explored, including the sense of touch [11]. SpiderWorld VR system for treating arachnophobia, described by Carlin, Hoffman and Weghorst [7], is one of the earliest examples of using tactile augmentation for medical purposes. In SpiderWorld, immersed VR patients interacted with a virtual spider, which was co-located and synchronized in movements with a replica of a palm-sized tarantula, made of a furry material. During contact with a user hand, the visual input was receiving strong reinforcement from the tactile feedback. With a certain stretch of imagination, the SpiderWorld system may be considered as a very special case of augmented medical manikins.

2.1 Examples of Augmented Human Manikins

Human manikins with augmented sensory input for medical education have been developed in several research centers. We review three systems, which exemplify the most advanced visualization and interaction techniques to date.

2.1.1 The Visible Korean Human Phantom

Phantom is another word for a life-size anatomically correct replica of a human body, or one of its parts. The Visible Korean Human Phantom was developed by Bichlmeier and colleagues at the Technical University of Munich. The team created a method for fast direct volume rendering of CT data [17], which was applied for in-situ visualization of Visible Korean dataset, using a see-through Head Mounted Display [5]. As illustrated in Fig. 2, direct volume rendering allows to achieve correct depth perception of inner organs: they appear to be inside the body, rather than painted onto the surface of the phantom. Infrared camera tracking system provides accurate registration.

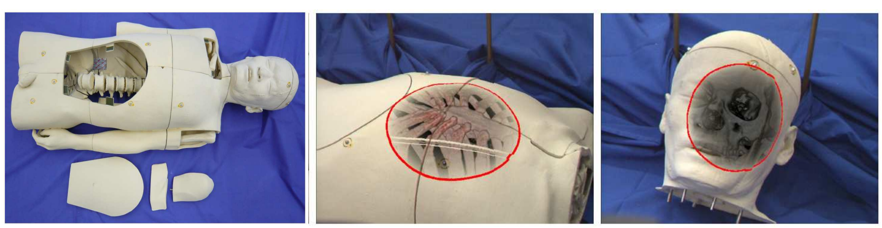
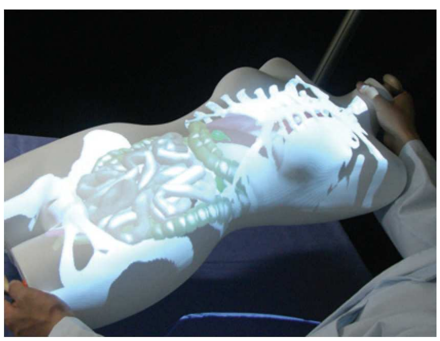


Fig. 2 *The Visible Korean Human Phantom*, direct view (left) augmented view (middle and right). Images courtesy of Christoph Bichlmeier, Technical University of Munich.

2.1.2 Free Form Projection Display Applications

As the name implies, the Free Form Projection Display (FFPD) technology allows to project virtual content onto curved surfaces, adjusting the image according to viewer's position [15]. Using FFPD, a research team at Gifu University, Japan, created Virtual Anatomical Model (VAM) [14], where virtual content (internal human organs) is rendered and projected onto a human-shaped screen. Electromagnetic motion sensor attached to the screen detects changes in its position and orientation, therefore, when the viewer tilts the screen, the image is also adjusted accordingly. Although the projection is monoscopic, motion parallax provides viewers depth cues, and the projected organs appear as if they lie inside the transparent manikin, as shown in Fig. 3.

In addition, the internal organs, stored in VAM as 3D geometry models, can be marked as fixed (bones) and movable (stomach and small intestine). When a viewer tilts the manikin, locations and shapes of movable organs are recalculated dynamically, using simulated gravity. As the result, the viewer can see how organs move inside the torso, interactively responding to direct manipulation of the tangible torso object. The improved VAM-based Dynamic Anatomical Model is described by Kondo, Kijima and Takahashi [13]. As the original VAM system [14], the Dynamic Anatomical Model uses FFPD for visual augmentation. A common term in AR community for Free Form Projection Display is Spatial AR [6].



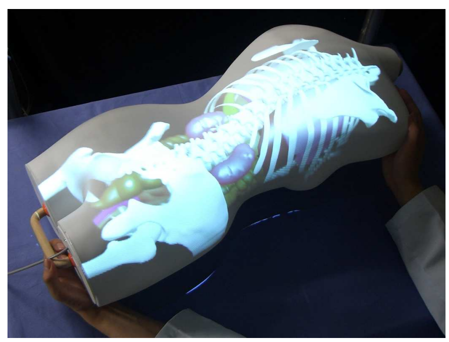


Fig. 3 *The Virtual Anatomical Model* uses real-time adjusted projection of internal organs onto human-shaped surface. Both the viewer's head and the manikin object are tracked in real time, which allows students to handle the display and examine if from different angles. Images courtesy of Ryugo Kijima and Yuzo Takahashi, Gifu University, Japan.

2.1.3 Mixed Reality Humans

Mixed Reality Humans (MRH), developed by Kotranza and colleagues [18], incorporate tactile modality into student-patient interactions, by means of using tangible user interface technology. MRH system was designed for teaching breast cancer examination techniques, focusing on improving student communication skills. An MRH combines a physical tangible object, in this case, a realistic replica of human breast, equipped with force sensors, with a virtual human patient. The breast object is mounted on a passive manikin, lying on a table. Students observe the scene through a Head Mounted Display, where the rendered image of the virtual patient is composed with video stream from a web camera, directed at the breast object, as shown in Fig. 4.

During examination, the MRH system processes student's motions and gestures applied to the breast tangible object, and the virtual patient provides appropriate responses, sometimes showing signs of distress and anxiety. User studies demonstrated that most students readily accepted the tactile modality in their interactions with the Mixed Reality Humans [16, 18]. Students naturally used gentle stroking and touching motions to calm the "patient". Following the positive results for breast cancer examination, the developers announced plans to extend the MRH patients to additional types of intimate examinations, where interpersonal doctor-patient communications play the most important role [16].

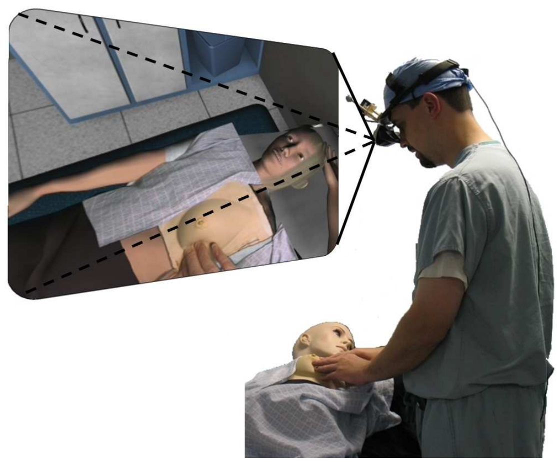


Fig. 4 *The Mixed Reality Human patient* undergoing breast examination. Image © 2009 Aaron Kotranza, used with permission.

2.2 Industrial Medical Simulators

Conventional (i.e., non-augmented) medical simulators, including human manikins, are becoming a "golden standard" in medical education, especially in training first responders. Manikins become more sophisticated and begin to take advantage of methods from the AR field. For example, the 3G model of SimMan line of manikins by Laerdal Medical Corporation [19], uses RFID tags for identifying syringes for the virtual administration of pharmaceuticals. This is done by attaching a labeled syringe to an IV-port on one of his arms. The dedicated IV-arm has an RFID antenna installed under the skin surface, which allows the manikin to detect the presence of the labeled drug and measure the administered amount, by capturing elapsed time while in contact.

However, new generations of manikins show trends in favoring hardware solutions, by installing more structural elements, such as pressure sensors and response actuators. As the result, use of dedicated devices inevitably increases production costs and does not provide enough flexibility for programming new teaching scenarios. For example, the Dynamic Anatomical Model simulator, the successor of VAM [13], is equipped with two additional pressure sensors for simulated appendicitis and cholecystitis, installed in lower and upper abdominal areas, respectively. These two sensors can recognize palpation actions in two locations only. Everywhere else, the manikin remains “touch-blind”.

Similarly, Resusci Anne CPR trainer, shown in Fig. 1, can only detect and count chest compression actions performed by a person in training. The rest of her body does not respond to any other physical intervention, which limits this particular model to simulating comatose or unconscious conditions. In general, limited capabilities for detecting and processing hand-to-body contacts, make even advanced manikins less useful in scenarios that require manual examination and immediate responses from the patient.

3 “Awakening” Manikins to Human Touch

The research project that will be described next, was carried out at the SimTiki Medical Simulation Center, University of Hawaii. SimTiki teaching curriculum is mostly based on Resusci Anne and SimMan lines of manikins, manufactured by Laerdal Medical Corporation (see Fig. 1). We set it our goal to improve the response from the available units by enabling their global “sense of touch”, in every part of their bodies.

The core idea is to make the examiner’s hands a part of the manikin system, by replicating the physical examination procedures in a virtual 3D space, co-located and aligned with the real manikin object. Within this approach, the manikin’s role is reduced to providing visual, tactile and audio sensory input, reacting to hand-surface collisions that are processed in software. The shape of the manikin and the examiner’s hands are modeled with required precision. Using motion tracking of the examiner’s hands, the system performs gesture recognition, and determines which procedure is being applied. Examples are: palpation, percussion, deep-press-and-release procedure, which all have characteristic motion signatures that can be reliably captured and recognized. Once the hand activity and location on the body are obtained, the system triggers audio responses from the manikin, according to the simulated medical condition. These responses are pre-recorded and can be easily re-programmed for each new teaching scenario.

A fully assembled touch-augmented manikin is shown in Fig. 5. It includes an Anne Torso module (the top part of Resusci Anne), and a Flock of Birds motion tracking system from Ascension [1], with 4 feet tracking range. That area reliably covers the whole body of a human adult, by placing the transmitter unit in the center of the working space. For this project, two motion sensors were used, one for each hand, Velcroed onto sports gloves. The software module is implemented in Flatland, an open source VR engine [10], with added gesture-recognition capabilities, developed earlier for VR-Triage training system [25]. The system runs on a medium grade Vaio laptop, with Linux OS, 1.86 GHz CPU, and 1G RAM.

Fig. 5 Touch-augmented *Anne Torso* manikin, augmented with a tangible user interface. System components: the manikin object, laptop PC, Flock of Birds tracking system, speakers.

4 Virtual Hands

A virtual hand is one of the oldest metaphors developed for immersive VR applications [12]. It remains by far the most popular technique for direct interactions with objects in close proximity, which is exactly the case with human manikins.

Virtual hands are the most important and delicate part of the touch-augmented manikin, because users expect the manikins to be as sensitive and responsive as their own hands. High-end manikins have very realistic looking surface made of elastic skin-like material. Some models even mimic distribution of human soft and hard tissues under the skin. Thus, when a user touches the manikin, the sensation is very rich and life-like. As a result, users involuntary expect the manikin to reciprocate and "feel-back" the hand-surface contact event, with the same level of tactile fidelity and spatial resolution.

A carefully designed and implemented system for virtual hands control can create and maintain this illusion, by recognizing stereotypical physical examination gestures and making the manikin react promptly. As discussed by Navab et al [22], reliable recognition of user activity is a very important component of a successful medical training system. Below, we describe our implementation of virtual hands, focusing on features that are specific to our application.

4.1 Spatial Resolution Requirements for Hand-Surface Contact

During physical examination, the requirements for spatial resolution for hand positioning vary between simulated conditions and techniques used for their detection. In many cases, these requirements are surprisingly low.

For some cases, the area of hand localization may be as big as the whole abdomen (e.g., simulated peritonitis); for others, one quadrant of the abdomen (e.g., left upper quadrant for splenic rupture, right lower quadrant for appendicitis). These conditions are commonly diagnosed using palpation techniques, consisting of applying gentle pressure on the areas of interest. During palpation, the hands move in unison and are held in a crossed position. Palpation action can be captured in VR by placing a motion sensor close to the center of the user hand, and monitoring the mutual proximity of both hands and their collisions with the surface. In pilot tests, contact spheres the size of a tennis ball yielded reliable three-way collision detection (hand-hand-surface) for virtual palpation.

Other examination techniques need higher precision in localization of contact area. For example, when applying percussion, a non-dominant hand is placed palm down on the designated area, while the other hand taps over that area. The tip of the middle finger on the moving hand must hit the center of the middle finger on the resting hand. Thus, in order to detect percussion in VR, the system must be able to locate not only the user hands, but fingers as well.

This may be achieved by direct tracking of user fingertips with miniature sensors, such as used in Ascension Mini Bird 800 system [1]; their sensors are the size of a fingernail and weigh 1.2 gram only. The tracking range is 76 cm in any direction, which is more than enough for our purposes, provided that the hand is tracked separately with the standard Flock of Birds system, running in 4-foot tracking range. The fingertips locations may also be obtained with a CyberGlove [9]. This configuration, however, may be very expensive.

Instead of direct finger tracking, a simpler solution was chosen, based on an observation that each individual finger does not require tracking in full six degrees of freedom. During physical examination, fingers always (or almost always) move along with the hand and their individual range of motions is practically zero. In addition, only few fingers are actively used in direct hand-body contacts.

We implemented a two-step finger tracking solution. Each hand is tracked with a single motion sensor, attached with Velcro onto a sports glove (see Fig. 5). Magnetic tracking gives the general hand position and orientation, covering an area of 4 feet in each direction from the center of the manikin. By using an anatomically correct skeletal model of a human hand, the system infers locations of all virtual fingers needed to process the current hand activity. The virtual fingers are represented by small invisible cubic shapes, attached to strategically important joints of the hand skeleton such as end joints of each finger.

Thus, our hand tracking is implemented partially in hardware, using magnetic sensors, and then refined in software, using a hierarchical skeletal model of human hand. The skeletal hand model is also used for posing the virtual hands into different shapes, as shown in Fig. 6.

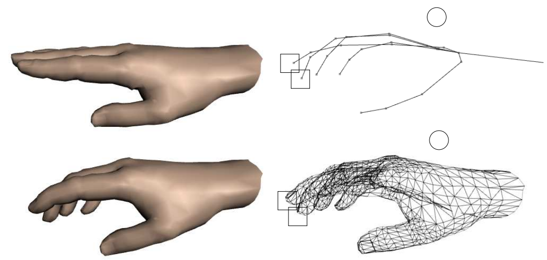


Fig. 6 Virtual hands in flat and neutral poses. Left: skin surface. Right: skeleton and wireframe views. Small cubes represent virtual fingertips, attached to hand joints for precise localization of contact points. The circles show where motion sensors are attached.

4.2 Activity recognition and hand processing loop

The key element in our ‘real-hand, virtual-finger’ solution is based upon real-time activity recognition. The system analyzes user hand location, orientation and velocity, as reported by the Flock of Birds, and checks for collisions with the 3D geometry model of the manikin. With this information, the system infers the current user activity and updates the hand pose accordingly. For example, when one of the hands is found to be resting on the manikin’s abdomen (the hand collides with the surface and its velocity is close to zero), the corresponding virtual hand assumes a flat pose (Fig. 6, top left). When the user hand is moving freely, its virtual counterpart is set to neutral pose (Fig. 6, bottom left).

Presently, the system recognizes the following examination procedures: percussion, shallow and deep palpation, pulse check, press-and-sudden-release gesture. On every cycle of the main simulation loop, the system goes through the following routine:

1. For each hand, check for collisions between its bounding sphere and the 3D model of the manikin; if no collisions are detected, set hand pose to neutral and return.
2. Check the hand orientation and velocity (both relative and absolute); determine the intended action and update the hand pose accordingly; update location of all virtual fingers;
3. For each virtual finger, involved in the current activity, check for collisions between the manikin surface model and the finger shape; if no collisions are detected, return;
4. Process collisions and evoke appropriate functions to simulate manikin response.

In section 5, one complete example will be described in detail, including a code sample for the simulated abdominal pain.

4.3 Hand Calibration and Alignment with Manikin Model

Hand calibration is performed for each new user, after he or she puts on the gloves and straps the motion sensors onto them. During calibration, users are asked to put their hands in a 'praying' position and keep them in this pose for five seconds (Fig. 7, left). During that time, the system measures the distance between the tips of virtual middle fingers, shown as little cubes, and translates the virtual hands in Y position until these two points coincide. This step accommodates users with different palm thickness. During the next step (Fig. 7, right), virtual hands are translated along Z-direction, adjusting for finger length. Translations are performed for both hands, in the coordinate system of the corresponding motion sensor. The calibration process takes a few seconds and is fully automated. A five second long interval ensures that the system collects enough samples for a specific hand positions and computes a useful average value.

Hands-to-model alignment is performed once per system installation, after the manikin is placed in a working position and the magnetic transmitter is installed in its close proximity, as shown in Fig. 8. In this particular case, the transmitter is placed under the examination table. The alignment procedure registers the virtual hands with physical location of the manikin and the magnetic transmitter, which defines the origin of the tracked space. In order to align the hands with the manikin model, the user must touch a dedicated spot on the manikin surface with one of the motion sensors, making a physical contact. The system captures the offset between the current location of the sensor and that virtual landmark. Then, both hands are translated by that offset, making contact in 3D space. If the visual monitor is used, users can see their hands 'snap' onto that dedicated location. For that purpose, we use the manikin's navel, an easy-to-find and centrally located feature.

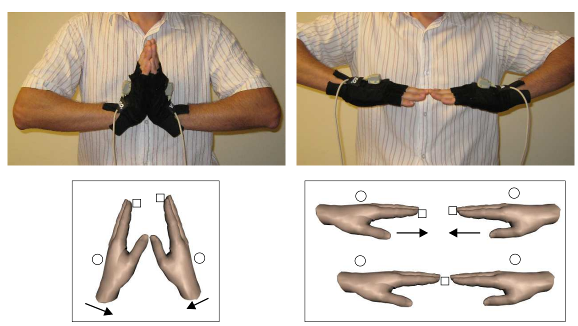


Fig. 7 During calibration, virtual hands are adjusted to accommodate thickness of user palms (left) and the length of their fingers (right).

5 A Pilot Study: Simulated Abdominal Pain

The first functional touch-augmented manikin was presented to public at the Medical Simulation Workshop organized by SimTiki Center at Asia Pacific Military Medicine Conference held in Singapore in April 2008 [29]. The audience of the workshop were mostly medical educators and health-care providers. The simulated patient was programmed to have abdominal pain, randomly assigned to different locations. In some cases, the simulated patient was pain free. Workshop attendees were invited to examine the patient, using percussion technique, and decide whether the patient was non-tender (healthy) or tender (had abdominal pain). One of the sessions is shown in Fig. 8. For that scenario, we used a very simple model of the manikin abdominal surface, a union of nine spheres, shown in Fig. 9; simplified code is listed in Fig. 10. The tender zone was randomly assigned to one of the spheres. When a user tapped on a non-tender location, the system responded with a neutral ‘knock’ sound, indicating that the tapping event was detected, but the location is not sore. When a painful zone was encountered, the program played back one of the prerecorded sounds of pain. At this moment, most participants stopped and declared the examination complete.

Fig. 8 The touch-augmented manikin was first presented at Medical Simulation Workshop held in Singapore Medical Training Institute, April 16th, 2008. A young cadet is performing percussion of Anne Torso manikin, searching for sore spots.

Informal observations of the participants gave us very useful feedback:

The concept of touch-enabled manikins was well received. Over thirty medical professionals participated in the exercise. Practically all of them accepted the ‘magic’ of performing live percussion on a plastic inanimate object. Only one person lost interest during the exercise and quit; the remaining participants continued with the examination until they were able to decide on the patient’s condition.

Calibration must be done for all users. The default placements of virtual hands on the tracker may work adequately for the developers, but for most other users, these settings need adjustment, as described in 4.3.

Variability of motion. The percussion technique apparently allows for certain variations in hand movements. Some users tapped very fast and their motions failed to register with the system, which expected the hitting hand to stay within a certain speed range. This suggests that the gesture recognition system could benefit from a training phase, when each new user gives a few sample strokes. These samples can be captured, measured and memorized by the system.

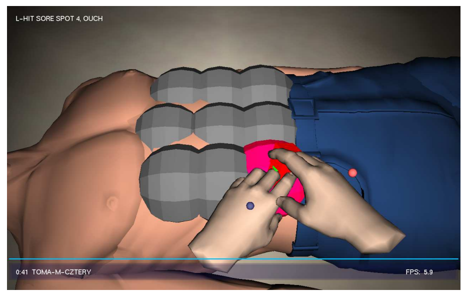


Fig. 9 Simulated abdominal pain scenario. A tapping event detected, at the lower right zone in the abdominal area. The human male shape is displayed for reference only.

```
OBJECT  *LH;        // left hand object (tracked)
OBJECT  *RH;        // right hand object (tracked)
OBJECT  *AO;        // abdomen object: union of zones
boolean  tapping;   // are hands tapping now?
OBJECT  *zone;      // current zone being probed
boolean  sore;      // is current zone painful to touch?

if(in_collision(LH, AO) && in_collision(RH, AO)) {
  //  both hands are touching the abdomen, check movements
  tapping = detect_percussion_gesture(LH, RH);
  if(tapping) {
    zone = find_closest_object(AO, LH, RH);
    //  touching sensitive zone, provide audio response
    if(sore = is_sore(zone)) {
      play_painful_sound();
    } else {
      play_neutral_sound();
    }
    if(debug) {
      // provide visual responses
      if(sore) {
        high_light_object(zone, RED);
      } else {
        high_light_object(zone, GREEN);
      }
    }
  }
}
```

Fig. 10 Simulated abdominal pain case algorithm.

6 Creating Manikin Surface Model

Anne Torso touch-augmented manikin is a successor of our first appendicitis simulator prototype, based on SimMan human manikin. The 3D surface model for the SimMan abdomen module, shown in Fig. 11, upper right corner, was constructed using the following steps:

1. Measure the physical extent of the abdomen module;
2. Approximate its surface by spheres, using Maya 3D authoring tool;
3. Export the spheres from Maya into the simulator;
4. Run the simulator, detecting hand-spheres collisions using the motion tracker.

Steps 2-4 were repeated, varying the number, locations and sizes of the spheres, until reported collisions with the virtual hand matched the physical contacts between user hands and the abdomen module closely. The whole process didn't take a very long time. However, when we had to go through the same routine again, building a surface model for our second manikin, Anne Torso, it became clear that this process must be improved.

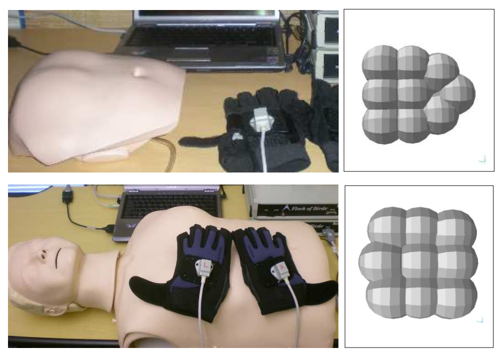


Fig. 11 3D surface models of SimMan abdomen module (top) and Anne Torso (bottom), approximated by spheres.

6.1 Improved Manikin Surface Model

A simple union of contact spheres appeared quite sufficient for simulated abdominal pain scenario. However, other medical conditions and examination techniques may require higher precision in localization of hand-surface contact points, as discussed in section 4.1. Therefore, a higher resolution representation of the contact surface may be required. There are many commercially available devices that can produce a high-fidelity 3D mesh of a physical object. Examples of the most affordable devices are: NextEngine desktop scanner and DeltaSphere 3D Laser Scanner (see [8] for more details). The 3D model of the tangible human breast object, used in Mixed

Reality Human project (see Section 2.1.3, Fig. 4), was also created by a laser scanner [16]. However, use of specialized scanning devices may not provide the best cost-effective solution.

In order to optimize and automate the process of manikin surface modeling, we developed a new technique, which effectively turned the motion tracking equipment into a home-made surface scanner. The main idea behind our method is to approximate the working area of the manikin by a heightfield over a plane. In order to build the heightfield in 3D, a user moves one of the motion sensors over the area of interest, such as the manikin's torso. The tracker finds the closest vertex on the heightfield grid and snaps this vertex vertically to the current location of the motion sensor. The process happens in real-time and is monitored visually. To improve the positional sensitivity of the motion sensor, which has a roughly cubical shape of 25 x 25 x 20 mm, we placed it at the center of a Ping-Pong ball, as shown in Fig. 12. This new enclosure allows tracing of surface features smaller than the original footprint of the sensor. The scanning process is described below step by step.

1. *Grid generation.* A regular grid of quadrilaterals is created in Maya and is used as a template to build the height-field. The dimensions and density of the grid are adjusted to match the size of the object to be scanned.
2. *Sensor-grid alignment.* The motion sensor is placed on top of the object that must be scanned (Fig. 12, left); the system captures the sensor location and shifts its rest position to and above the center of the grid. This calibration procedure is implemented as a single key-stroke command. This step is identical to hand-to-model alignment, described in Sect. 4.3. At this moment, scanning is initiated.
3. *Surface scanning*. The user moves the sensor along the surface of the object in continuous sweeping motions and the system updates the height-field interactively, at the frequency of the graphics loop. On each cycle, the closest vertex is found and snapped vertically to the current sensor position. The process continues, until all vertices are elevated and the height-field is complete.
4. *Run-time operations on the mesh.* During scanning, the mesh can be saved, reset and convolved with a low-pass filter.

Using this technique, we were able to create a 3D scan of the SimMan abdomen module in less than 2 minutes, using 20x20 grid.

Fig. 12 Scanning SimMan abdomen module: sensor alignment (left), scanning in progress (middle), completed mesh (right) Grid size 40x40 cm, 20x20 points. Scanning time: under 2 minutes.

The second model scanned with this technique was the Anne Torso manikin, shown in Fig. 13. For Anne Torso, the density of the base grid was doubled (40x40 points) and an enhanced plastic Easter egg sensor enclosure (5 x 3 cm) was used. The eggshell shaped sensor enclosure naturally conforms to high, medium and low precision scanning modes illustrated in Fig. 14. Users can switch between resolution modes simply by touching the surface with the appropriate side of the egg. The motion tracking system detects the changes in orientation of the sensor, and scanning modes are toggled as directed.

Multi-resolution scanning permits dynamic adjustment of both speed and accuracy to match the local geometric detail of the surface. This method requires each vertex in the grid to have a list of its neighbors. Such lists are commonly created during initialization of the grid. If all neighbors of a certain vertex are snapped to the same height, as shown in Fig. 14, scanning speed can be further improved by skipping recently snapped neighbors in the main search loop. In our implementation, we did not use this optimization, as the search time was not an issue. The system was able to update grids of sizes 20x20, 40x40 and 80x80 points at 25 frames per second, which was adequate to our purposes.

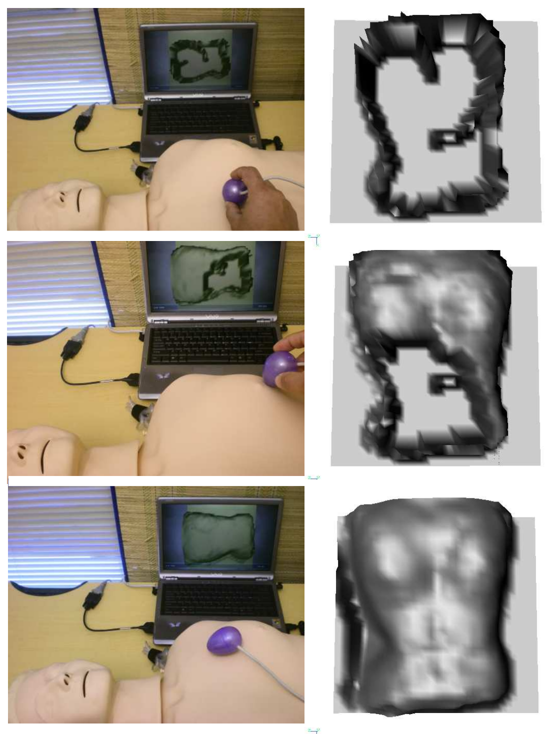


Fig. 13 Scanning Anne Torso: initial contour (top), intermediate shape (middle), and final mesh (bottom). The 3D mesh snapshots are shown as produced by the scanner, without retouching (see also Fig. 15). Grid size 40x40 cm, 40x40 points. Scanning time: about 8 minutes.

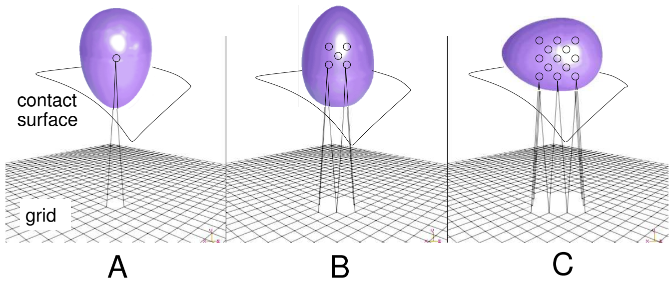


Fig. 14 A plastic eggshell provides three intuitive scanning positions: (A) contact with the sharp end moves one vertex; (B) the obtuse end moves the vertex and its closest neighbors (5 vertices per move); (C) contact with the elongated area makes the system to iterate on vertex neighbors twice (13 vertices per move).

Using multi-resolution scanning, a detailed surface model of Anne Torso module was created under 10 minutes, as shown in Fig. 13. Besides its speed, our semi-automatic surface scanner has the following features: it is cost-effective, requires no special skills nor equipment and is easy to learn and use.

In addition, the scanner naturally addresses the long-standing problem of distortions in the magnetic environment, that plagues many applications that use magnetic tracking. During scanning, these distortions are imprinted into vertex positions of the surface. Normally, these tracking artifacts are not welcome and may invalidate the resulting mesh, if used elsewhere (i.e., under different magnetic environment). However, if the mesh is known to be used with the same simulator at the same location, the distorted shape is perfectly preprocessed for correct hand/surface collision detections. The shape produced with our scanner is a reflection of the true surface of the physical object (a manikin) in the magnetic environment of the lab and its own inner ‘organs’. Creating a perfect surface model under distorted magnetic conditions would require complicated calibration of the tracker, to take magnetic distortion into account. Utilizing the same tracking equipment for surface acquisition effectively mitigates this problem.

In fact, we expected this feature to manifest itself in our system. Eventually, distortions were encountered while scanning the Anne Torso object, caused by magnetically active inner “organs”, asymmetrically located inside the manikin, as shown in Fig. 15. Distortions in the mesh are denoted by a circle. However, during model use, these distortions are not noticed by the tracker, because the sensor’s path in 3D space is also distorted in exactly same way. Full details on this technique, including the source code and discussion of possible extensions and limitations, were recently published [27].

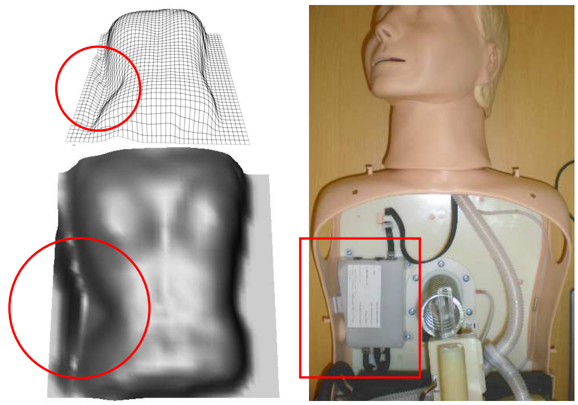


Fig. 15 Distorted area in the scanned surface, denoted by a circle. A 'postmortem' examination revealed that Anne was engineered asymmetrically: a large metal switchbox installed in her upper right abdominal area, caused distortions in the magnetic field.

7 Applications and Extensions

Mixing real and virtual elements in medical simulators, equipped with a motion tracker, yields a multitude of interesting extensions. Below, we list a few that immediately follow from the basic technique.

- *Tool tracking*. A stethoscope, reflex hammer, scalpel – all these tools may be tracked and processed for collisions with the manikin surface model in the same manner as user hands. Adding use of medical tools to training scenarios will expand manikin capabilities even more.

- *Instant programming of training scenarios.* By touching various areas on the manikin and recording appropriate voice annotations, an instructor can "teach" the manikin how to respond to different examination procedures, according to the simulated condition. These *location-action-response* mappings may be saved for later use. Programming manikin responses may be combined with tool-tracking, making manikin react differently when touched by a bare hand and a scalpel.

- *Non-contact interaction.* Tracking of user hands and hand-held instruments allows to process non-contact examination techniques also. Examples include: clapping hands to check hearing; make the patient's eyes follow a moving object; simulate pupil contraction as a response to a tracked penlight.

- *Measuring movements for performance evaluation.* Hand tracking provides a unique opportunity to measure user actions precisely. For example, in CPR training, the system can measure and log the location, rate and depth of applied chest compressions.

- *Multi-user capabilities.* Adding more motion sensors will allow several users to share the same working space and work with one manikin collaboratively.

8 Future

The next logical step in developing augmented manikins is integration with the native host computer, supplied by the manufacturer. Such integration may start with sharing log files that keep records of all user activities. Further steps may include access to manikin's actuators. For example, a 3G SimMan manikin has an "aggressive patient" behavior, when the manikin moves his arms violently, imitating hostile intentions towards the examiner. These extreme responses may be provoked by incorrect or clumsy user hand maneuvers, for example, by inflicting too much pain on a tender area while performing palpation.

Further exploration of video augmentation may open new possibilities in teaching medical science. Projecting pre-recorded didactic video material on the manikin's surface can show, for example, how fast a wound will heal, depending on the depth of a virtual incision made with a tracked scalpel tool.

We believe that advances in Augmented Reality, human-computer interaction techniques and medical human simulators will evolve together into highly realistic, multi-modal interactive system, capable of delivering life-like training experiences. We hope that the work described here will give researchers and practitioners some food for thought in their road towards this goal.

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