Mixed Reality Manikins for Medical Education

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Creating 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 sensors and actuators that control the manikin behaviors and responses.

We describe how applying standard techniques from the fields of Virtual and Mixed Reality can significantly expand manikin functionality, at relatively low costs. We describe a working prototype of a Mixed Reality Manikin, with technical implementation details and one complete scenario. Also, we discuss a number of extensions and applications of our technique.

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 conditions. 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.

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 [1] 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 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 selected locations, 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.

The paper is organized as follows. In the next section, we review related work in the area of applying MR and AR methods to medical education. In section 3, we describe our MR manikins, including hardware and software com-

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ponents, with a special attention to implementation of virtual hands. One complete training scenario is described in section 4, followed by discussion of possible extensions and applications of our method.

2. Related work

Medicine and medical education are a fertile ground for VR techniques to grow, for an important reason: the cost of human error is high. In the last few years, medical VR 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) [3] and a palette of new interface metaphors and display techniques, including *MagicLens* [4] and *Virtual Mirror* [5]. 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 [6]. Another example of visual augmentation is a system described by Bichlmeier et al., that allows surgeons literally see into a living human patient, using a Head Mounted Display and CT scans of the patient [7]. Besides hand-held displays [4, 5, 6] and Head Mounted Displays [7], video projection of 3D content onto curved surfaces was successfully employed, for example, in Virtual Anatomical Model developed by Kondo, Kijima and Takahashi [8]. The authors used a human shaped surface as a screen for displaying internal organs, dynamically adapting the view for the user's position and orientation, and the shape of the screen [9]. Although the projection is monoscopic, due to motion parallax, the projected organs appear as if they lie inside the torso shape.

Visual overlays of medical imaging data such as CT scans and ultrasound scans [10] onto human patients, were among the first applications of Augmented Reality [11]. In addition to visual display, other input modalities were explored, including the sense of touch [12]. SpiderWorld VR system for treating arachnophobia, described by Carlin, Hoffman and Weghorst [13], exemplifies 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.

One of the recent developments in mixing VR with tactile-based interfaces was presented by Lok and Kotranza [14]. Their system integrated a physical tangible model of a human breast with a life-size virtual patient, displayed on a screen. The virtual patient communicated with a student performing a breast examination for cancer, showing signs of distress and anxiety. This work mostly focused on improving student communication skills. The authors reported that many students readily accepted the tactile modality in their interactions with the Mixed Reality Humans, as they named their touch-enhanced simulator. Students naturally used gentle stroking and touching motions to calm the "patient".

Following the classic AR taxonomy by Milgram et al [11], both the SpiderWorld [13] and Mixed Reality Humans [14] belong to the 'mostly-virtual' side of the virtual-to-real continuum of environments. As discussed in the Introduction, our goal is to enrich and expand hands-on experience that medical students have when working with human manikins. Thus, our work lies closer to the 'mostly-real' end of the range, taking advantage of the realistic appearance and rich tactile feedback provided by the manikins.

Traditional (i.e., non-VR) medical simulators, including human manikins, are also evolving rapidly. Manikins become more sophisticated and begin to take advantage of methods from the VR field. For example, the latest 3G model of SimMan line of manikins [1], 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. This 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. Such virtual medication with proximity-based tracking falls in the same category as our method. However, the localization precision of RFID-based tracking is not sufficient for our purposes. Thus, we chose a more precise magnetic tracking solution [16], for user activity recognition and classification.

Reliable recognition of user activity is another important component of a successful medical training system, as discussed by Navab et al [15]. Pulse taking and drug administration actions, described above, are detected and processed by dedicated devices, such as pressure-sensitive elements and RFID antennas, installed in well-known locations. In order to recognize palpation, Virtual Anatomical Model simulator [8], also make use of pressure sensors implemented in hardware. Two sensors are used, one for simulated appendicitis and the other for cholecystitis, installed in lower and upper abdominal areas, respectively.

Our main contribution is a novel approach of processing tactile interaction in software. This approach effectively removes limitations on the number of touch-sensitive locations, and makes more medical scenarios available for simulation.

3. Mixed reality manikins

We already briefly described our method of making manikins touch-sensitive by echoing physical user-manikin interactions in the 3D domain. In this section, we present our system in full detail.

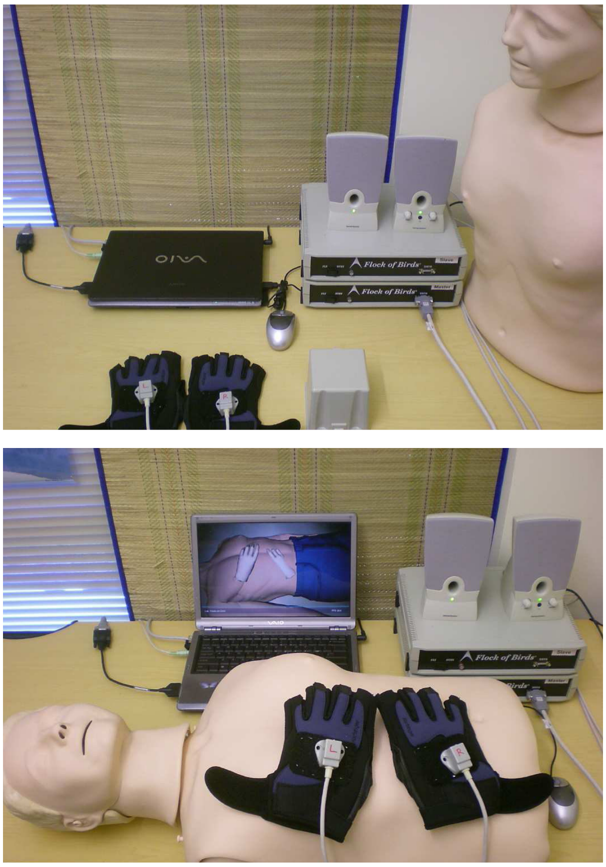

Figure 1. *Anne Torso*, a realistic lifesize CPR trainer, from Laerdal [1], augmented with a tangible user interface. System components: the manikin object, Flock of Birds tracking system with two sensors Velcroed onto sports gloves, laptop PC, speakers. Below: the manikin in working position for physical examination, with a debug view of the 3D models on the laptop screen.

3.1. System configuration

A mixed reality manikin consists of three parts: a tangible interface object (the manikin itself), a motion tracking system, and a software module which processes user input and simulates manikin's responses. These responses are pre-programmed according to specifications of the training scenario.

A prototype of our system is shown in Figure 1. It includes an Anne Torso, a lifesize female manikin for cardiopulmonary resuscitation (CPR) training by Laerdal [1] and a Flock of Birds system from Ascension [16] with tracking range of 4 feet in all directions. The software module is implemented in Flatland, an open source VR system [17], with added user gesture-recognition capabilities [18]. The system runs on a Linux laptop PC, 1.86 GHz CPU, and 1G RAM.

The 3D models of user hands and the manikin surface are shown for illustrative purposes only (Figure 1. During system use, students do not look at the screen – they work with the manikin directly, as shown in Figure 4.

3.2. Virtual hands

A virtual hand is one of the oldest metaphors in VR [19]. It remains by far the most popular technique for direct manipulations of objects in close proximity, which is exactly the case with human manikins. Virtual hands are the most important and delicate part of our system, because users expect them to be as sensitive and versatile as their real 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 user touch the manikin, the sensation is very rich and life-like. As a result, user 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 implemented virtual hand control system can create and support this illusion, by recognizing stereotypical physical examination gestures and making the manikin react promptly. Below, we discuss implementation issues, that are specific to our application.

3.3. Spatial resolution requirements for hand-surface contact

During physical examination, spatial resolution for hand positioning varies 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 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 detections (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 [16]; their sensors are the size of a fingernail and weigh 1.2 gram. The tracking range is 76 cm in any direction, which is sufficient for our purposes. Another solution is to track hands as solid objects and obtain the fingertips locations with a CyberGlove [20], fit to a skeletal model of the hand. This configuration, however, may be very expensive. We have experimented briefly with a budget virtual glove [21], which measures finger bending angles, and found it less useful, than expected. Among other issues, we encountered problems with stability of tracking, which was critical for reliable detection and processing of hand actions. Instead of direct finger tracking, a combined solution was chosen, described next.

3.4. Real hands, virtual fingers

In our system, we implemented a combined tracking solution. Each hand is tracked with a single motion sensor, covering an area of 4 feet in each direction from the center of the manikin. Magnetic tracking gives the general hand position and orientation. 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 attached with Velcro to the top of regular sports gloves (Figure 1) and then refined in software, using a hierarchical skeletal model of human hand (Figure 2). The skeletal hand model is also used to update the visible skin of each virtual hand, primarily for debugging and monitoring purposes.

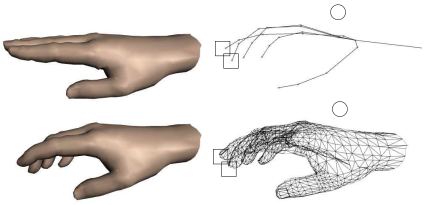

Figure 2. Virtual hands in flat and neutral poses. Left: skin surface. Right: skeleton and wireframe views. Small cubes represent virtual fingertips, attached to skeletal joints for precise localization of contact points. The circles show where motion sensors are attached.

3.5. 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 (Figure 2, top left). When the user hand is moving freely, its virtual counterpart is set to neutral pose (Figure 2, bottom left). Note a close match between the guessed shapes of virtual hands (flat and neutral) and the actual poses assumed by hands of a real user performing percussion, as seen in Figure 4.

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 4, one particular case will be described in detail, including a code sample for the simulated abdominal pain.

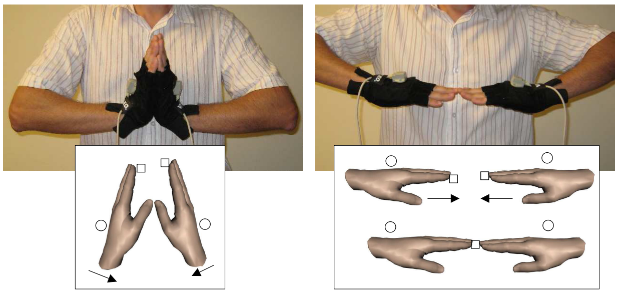

Figure 3. During calibration, virtual hands are adjusted to accommodate thickness of user palms (left) and the length of their fingers (right). The virtual hands are moved along specified directions, until virtual fingertips touch each other, to match the current user pose. Calibration also fixes the problem of unevenly attached motion sensors.

3.6. Hand calibration and alignment

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 10 seconds (Figure 3, left). During that time, the system measures the distance between the tips of virtual middle fingers, 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 (Figure 3, 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 ten second long iteration loop ensures that the system collects enough samples of specific hand positions and computes a useful average value.

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 Figure 1. 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 the virtual landmark. Then, both hands are translated by that offset, making contact in VR. If the debug view is open, users can see their hands 'snap' onto the dedicated location. For that purpose, we use the manikin's navel, an easy-to-find and centrally located feature. The system is now ready for use.

4. An example: simulated abdominal pain

A prototype of a mixed reality manikin was first presented to public at the Medical Simulation Workshop, Asia Pacific Military Medicine Conference held in Singapore in April 2008 [22]. 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 Figure 4. For that scenario, we used a very simple model of the manikin abdominal surface, a union of nine spheres, shown in Figure 5. 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 loca-

Figure 4. The 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.

tion 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.

Informal observations of the participants gave us very useful feedback:

The concept of mixed reality 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 3.6.

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.

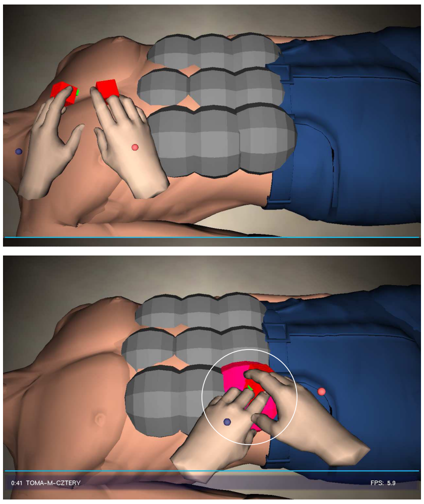

Figure 5. Debug view of user hands and touch-sensitive zones used in simulated abdominal pain case. Top: hands are idle, no contact, no action detected. Bottom: tapping event detected, hitting the lower right zone in the abdominal area, highlighted and circled.

```
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);
      }
    }
  }
}
```

Figure 6. An outline of the hand processing code for simulated abdominal pain case.

5. Improved manikin surface model

A simple union of contact spheres was 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 3.3.

In order to simplify the process of manikin surface modeling, we developed a new technique, which effectively turned the motion tracking equipment into a 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 system finds the closest vertex on the heightfield grid and snaps this vertex vertically to the current location of the motion sensor. The whole process happens in real-time and is monitored visually.

Using this techniques, a detailed surface model of Anne Torso manikin was created under 10 minutes, as shown in Figures 7 and 8. Besides its speed, our semi-automatic surface scanning technique has the following features: it is cost-effective, requires no special skills nor equipment and is easy to learn and use. In addition, models created with this method are already ‘pre-calibrated’ for use with the magnetic tracker, because all distortions and irregularities in the magnetic environment around the working area are imprinted into the vertex coordinates of the model. Full details on this technique are forthcoming [23].

We believe, that high quality surface models, in conjunction with high resolution tracking may result in a new family of applications, such as acupuncture training.

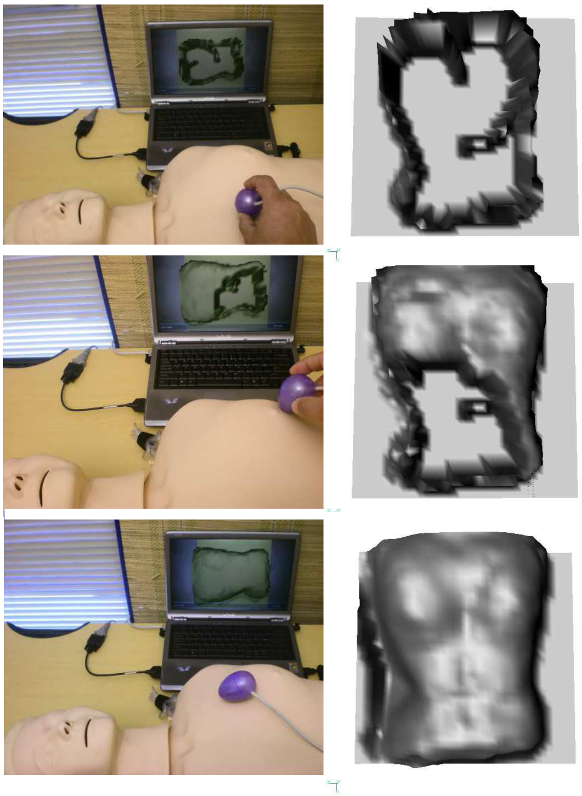

Figure 7. Scanning of *Anne Torso* with a magnetic sensor in a plastic enclosure: initial contour (top), intermediate shape (middle), final mesh (bottom). The 3D shapes are shown as-is, without retouching. Mesh size 40 x 40 cm, 40 x 40 points. Time taken: about 8 minutes.

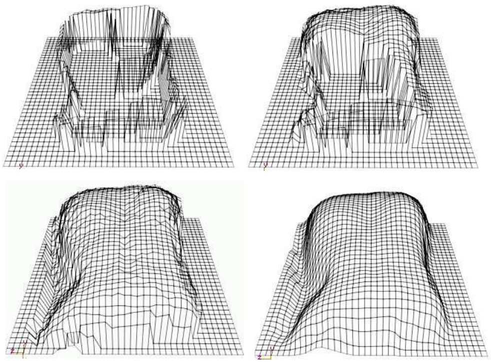

Figure 8. Wireframe views of the 3D scans of Anne Torso. The bottom-right shape is smoothed with a low-pass filter.

6. Applications and extensions

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

- *Tool tracking*. A stethoscope, reflex hammer, scalpel – all these tools may be tracked and processed for collisions with 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 his or her own vocal 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.
- *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.

7. Future work

The next logical step in developing mixed reality 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, inflicting too much pain on a tender area while performing palpation.

There are other interesting research areas related to multi-modal interactions with manikins. For example, a skin-like surface of manikin is suited well for projecting additional video material: blood, wounds, scars, etc, both in real-time and in fast-forward time scale, in order to show how a wound will heal, depending on the depth of a virtual incision made with a tracked scalpel tool.

Additional viewing modalities is yet another topic of future work, including simulated x-ray vision by projecting bone structures into the area of interest, following the results described by Kondo and Kijima [9].

8. Conclusions

We presented a new technique for adding touch-sensitivity to manikin simulators with the following features:

- Multi-purpose: a standard human manikin can be programmed to simulate a large number of medical conditions and examination procedures.
- Multi-user: adding more motion sensors will allow several users to share the same working space.
- Relatively inexpensive: a fraction of the cost of a manikin.
- Portable: may be shared between manikins.

With our technique, a human manikin simulator becomes one big tangible interface object, with programmable sensitivity at arbitrary locations and flexible responses to physical examination.

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