A Subset of Mixed Simulations: Augmented Physical Simulations with Virtual Underlays

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ABSTRACT

Most of us have appreciated Mixed Reality (MR) in the form of the virtual "yellow first down line" when watching football on TV. However, MR technology was previously confined to a few pioneering groups and was not readily available. Simply defined, MR integrates the virtual and physical worlds to generate new environments where real and virtual objects are collocated (share the same space) while augmenting our capabilities to interpret, understand, practice, learn, train or teach. MR technology is becoming affordable and finding its way into simulation giving rise to a new field we call Mixed Simulation. We present in this paper five new mixed simulators with physical exteriors and virtual underlays: central venous access (CVA), ventriculostomy, radio frequency lesion, spinal instrument implantation and regional anesthesia. We exploited advances in the capabilities, cost and/or sensor miniaturization in medical imaging, tracking technology, 3D printing (rapid prototyping) and 3D graphic cards to develop and deploy compact, inexpensive mixed simulators that are anatomically authentic, i.e., exact physical and/or virtual replicas of the actual individuals used as models. Sub-millimeter accuracy, miniaturized tracking sensors monitor and record every move, twist and turn of a tracked needle during the simulated procedures, facilitating after action review or even self-debriefing (when instructors are unavailable) and automated scoring algorithms (immune to inter-rater variability) that include tracking and grading of near misses. Mixed simulators offer the potential for improved training and debriefing for military and civilian applications; e.g., the CVA simulator improves learning outcome in residents and can provide civilian reservists unfamiliar with subclavian venous access (common in military trauma medicine and combat casualty care) training prior to frontline deployment to care for warfighters.

ABOUT THE AUTHORS

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INTRODUCTION

Traditionally, simulation could be classified (and some would argue, polarized) into two broad categories, physical or virtual with much debate, for example, comparing the virtues of mannequin patient simulators to screen-based simulators. Generally speaking, physical simulation is best suited for learning psychomotor skills and team training exercises while virtual simulation excels at imparting cognitive knowledge and provides flexibility in displays. As a striking example, mannequin patient simulators still simulate cyanosis (skin turning a bluish hue as a result of lack of oxygen) poorly at the time of writing while in a virtual simulation simulating cyanosis in a patient depicted on a display monitor is a truly trivial task.

Recent advances in the capabilities (resolution, accuracy, computing power, etc.), cost and miniaturization of medical imaging, tracking technology, 3D printing (rapid prototyping), 3D graphics cards and laptop computers have made possible compact and relatively inexpensive simulators where virtual elements can be precisely registered to their physical counterparts or neighbors.

In looking for a name and taxonomy for simulations that collocate virtual and physical components, we were inspired by the taxonomy that Milgram and Kishino (1994) developed for mixed reality *displays* (see Figure 1).

Figure 1. Mixed reality and the reality-virtuality continuum (Milgram and Kishino, 1994)

While simulators also make use of displays (primarily an output to the user), the former must also provide means for user input, that is for simulated interventions through an interface that allows a learner or trainee to interact, generally in real time, with different parameters, for example, to manage or mitigate a developing crisis or to perform a procedure.

Some simulators such as screen-based computer based trainers are primarily virtual. There is no physical or tangible representation of an object or person such as a wounded warfighter or weapon of mass destruction (WMD) casualty (Subbarao et al., 2005). Interventions are generally mediated (indirect), rather than direct. Direct intervention is using one's own hands to intervene or the actual instrument like a syringe and needle to administer drugs. A common device for mediated intervention is a pointing device such as a mouse or trackball that allows the learner to place the cursor on icons representing for example a syringe or drug, click the pointer to select a given drug if there is an array of drugs and use the keyboard or click and drag a slider along a slider bar to enter the amount of drug to be administered.

Other simulators such as mannequin patient simulators are primarily physical. There is a tangible mannequin that represents the patient. Clinical signs such as palpable pulses at the radial, carotid and femoral arteries can be directly felt via the trainee's own senses, such as the sense of touch. Cardiopulmonary resuscitation is performed by the trainee directly applying his or her hands to the mannequin's sternum and forcefully pushing down to perform chest compressions. Drugs are administered via actual liquid-filled syringes with attached barcodes that contain the identity and concentration of the "drug" (usually tap water) in the corresponding syringe. The trainee pushes the syringe plunger the requisite amount to expel the appropriate dose of drugs and the volume of liquid expelled from the syringe is calculated via a digital scale or a flow meter downstream of the syringe (Lampotang et al., 1999a).

By replacing "Real Environment" by "Physical Simulation" and adapting Figure 1 accordingly, we end up with Figure 2 that depicts a continuum from physical to virtual simulations. The picture on the right

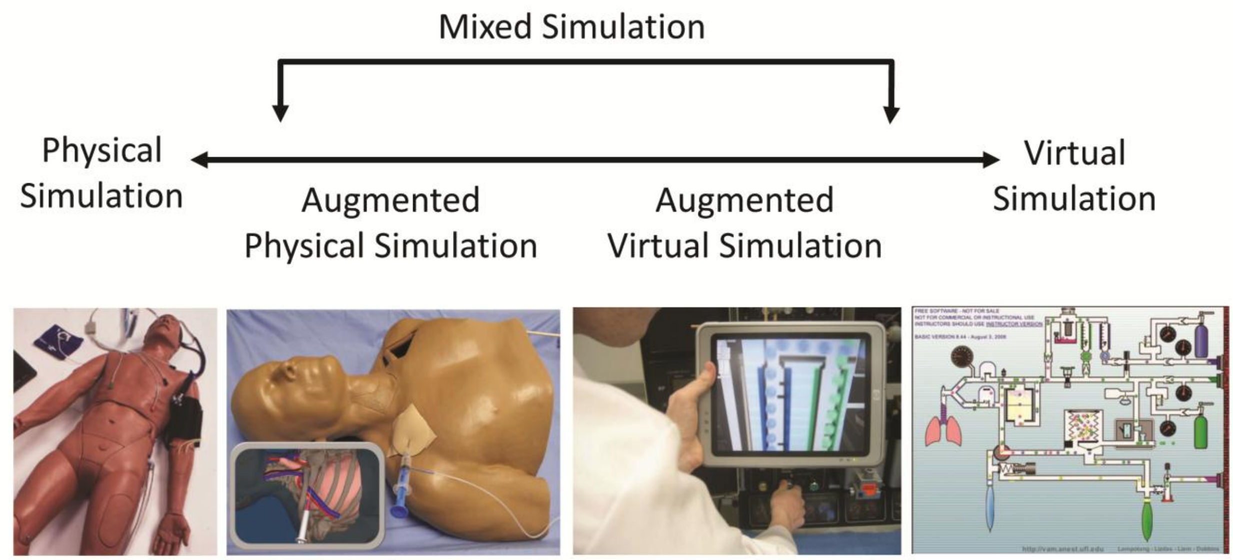


Figure 2. The physicality-virtuality continuum in simulation. The pictures depict representative simulators of each type, that were initially developed at the University of Florida over the last 3 decades, the latest being augmented physical simulators with virtual underlays (inset in 2nd picture from left).

depicts a purely virtual simulation, the web-enabled, screen-based Virtual Anesthesia Machine (VAM) simulation (Fischler et al., 2008). VAM is an example of transparent reality simulation where the plumbing of an anesthesia machine is made transparent and gas molecule icons flowing inside the pipes are not only made visible but are also color coded according to the local medical gas color code.

The picture on the left represents a physical simulator, a mannequin patient simulator such as the Human Patient Simulator (CAE Healthcare, Sarasota, FL) that actually consumes oxygen and volatile anesthetics (Lampotang et al., 1999b).

The simulations that combine physical and virtual simulations fall under the general category of mixed simulations as depicted in Figure 2. An augmented virtual simulation is a primarily virtual simulation that is augmented by a physical simulation or object. In figure 2, in the 2nd figure from the right, the Virtual Anesthesia Machine simulation is augmented by an actual physical anesthesia machine that functions as a tangible user interface (TUI) to the virtual simulation that is displayed on a tracked (infrared line of sight tracking) tablet computer that acts as a "magic lens" (Quarles et al., 2008a, 2008b).

Conversely, an augmented physical simulation is a primarily physical simulation that is augmented by a virtual simulation or components. The 2nd picture from the left in Figure 2 depicts the Central Venous Access (CVA) simulator that is representative of the subset of mixed simulations that is the general topic of this paper.

Within the subset of augmented physical simulators, we further focus the scope of this paper on those where the virtual component, typically representing anatomically correct soft tissues derived from medical imaging of actual individuals, is an underlay precisely registered to the external visible physical component, (also anatomically authentic) instead of an overlay like in the yellow first down line or the magic lens overlay in the augmented anesthesia machine (Quarles et al., 2008a, 2008b).

APPLICATIONS

Application 1: Central Venous Access Mixed Simulator

Background: During central venous access (CVA), a central venous catheter is typically inserted into the internal jugular (IJ) or subclavian vein. While ultrasound (US) guidance is recommended for IJ central venous access, subclavian vein access is almost universally performed without US, as a "blind" procedure. Clinicians rely on anatomical landmarks such as the sternal notch and the clavicle and heuristics to establish the entry point and trajectory to target the subclavian vein and a 3D mental model of the anatomy to safely steer the needle tip into the subclavian vein. It is difficult to get sufficient experience during training to achieve subclavian vein catheterization expertise, especially in civilian medicine.

"Use of subclavian central venous access is common in combat casualty care. A warfighter injured by improvised explosive device (IED) blast or gunshot would typically arrive with a cervical collar in place to a site where life-saving surgery can be performed. The requirement for adequate and secure central venous access in such critical situations, often to be placed while critical airway manipulations are occurring at the same time, mandates the use of the subclavian approach. Insertion of large-bore central access in the internal jugular vein in a critically injured individual would necessarily be delayed until the airway is secured by traditional endotracheal intubation through the mouth or by using a surgical technique; considerations of space at the head of the bed, and of sterility, would prevent simultaneous accomplishment of these functions. Furthermore, placement of an IJ line in a patient whose cervical spine is potentially unstable (thus, the cervical collar) is problematic. While airway management may take very little time, positioning the surgeon at the patient's shoulder allows him or her to place the subclavian line immediately (rather than *after* airway management is complete), and to be instantly available to provide surgical airway assistance if it is required." (personal communication, Commander Carl W. Peters, MD, 2012).

Thus, simulators can provide the opportunity for deliberate practice in subclavian central venous access to civilian reservists unfamiliar with the procedure prior to deployment to the frontline.

Motivation: At teaching hospitals, the incidence of iatrogenic (physician-caused) pneumothorax as a result of the needle tip unintentionally straying into the lungs during central venous access is a concern. In reviewing existing CVA procedural simulators, the cost of the disposable (a molded component with imbedded tubes filled with either red or blue ink - representing arteries and veins respectively - that leak and need to be replaced after repeated puncture) was a deterrent at our teaching hospital when contemplating a hospital-wide training program. We therefore set out to design an anatomically realistic simulator with lower operating cost that allows debriefing and provides an automated scoring algorithm.

Methods: We physically modeled the torso, neck and head of an actual human including anatomical landmarks such as the palpable sternal notch and the clavicle and selected ribs, as well as the feel of the skin and underlying tissue to user touch and resistance to puncture at specific regions where the needle is usually inserted. The remainder of the simulator was virtually modeled and registered to the physical component (the torso) with sub-millimeter accuracy.

The 3D physical model for the torso and neck and the vein, artery and lung came from CT and MRI scans of a colleague. The individual components (veins, arteries, lungs) from the MRI scan were manually reconstructed into separate 3D virtual objects with veins color coded blue, arteries red and lungs pink; see Figure 3.

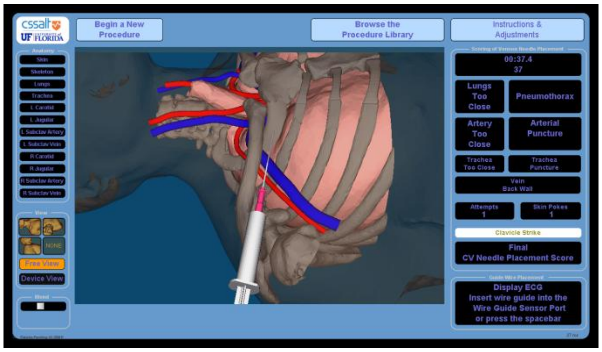


Figure 3. The virtual relevant soft tissues (veins, arteries, lungs) are displayed collocated to virtual representations of the physical needle, syringe and torso. Skin opacity has been set to transparent.

We converted the CT scan of the torso, neck and head to a 3D model that was then used to create a full scale, anatomically correct, physical model via a 3D printer (zPrinter 310, Z Corporation, Rock Hill, SC); see Figure 4.

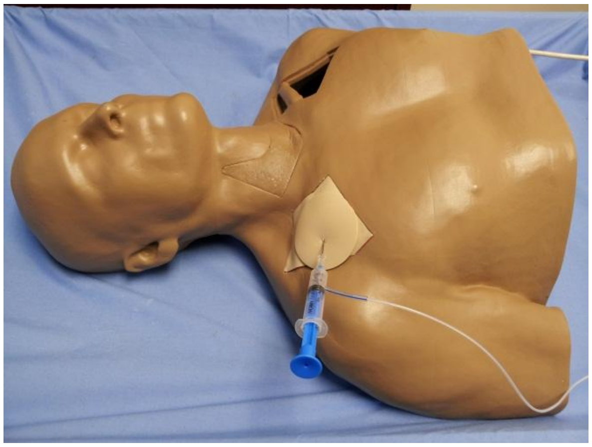


Figure 4. The physical torso in the CVA mixed simulator; an instrumented needle is inserted via a skin patch. The needle tip is tracked and recorded in 3D space while the user attempts to guide it to the subclavian vein.

The simulated skin is actually punctured by an instrumented 18 ga Raulerson needle from a commercial central venous access kit (TeleFlex Medical, Research Triangle Park, NC). A 6 degree of freedom (DOF) miniature magnetic sensor fitted inside the needle bore near the tip of the 18 ga Raulerson needle is tracked in real time by a 3D tracking system (Ascension Technology Corp., Burlington, VT) relative to the virtual 3D soft tissues surrounding the virtual subclavian vein, as it is manually guided by the user to the virtual subclavian vein.

A generic Windows 7 laptop interfaces with the tracking system and controls the simulation and displays the virtual elements during debriefing. We also implemented a scoring algorithm to automatically score performance at the end of a training session. A video of the venous access simulator is at http://simulation.health.ufl.edu/research/cvl_intro.wmv

Results: Surgeons not involved with development evaluated the simulator anatomy and judged it authentic.

The simulator was evaluated in a preliminary study with 28 anesthesia residents who each used the simulator 3 consecutive times. From Run 1 to Run 3, performance score (0 to 100 scale; lower score is better) for all participants was improved, on average, by 28% and a 71.9 seconds reduction in average time to achieve subclavian venous access was obtained.

We performed repeated measure ANOVA on the outcomes from the three waves of data collection with follow-up pairwise dependent sample t-tests. There were reductions in average time ($F=14.28$, $p<.0001$), the number of attempts ($F=10.77$, $p =.0001$), number of skin punctures ($F=6.59$, $p = .004$) and score as determined by the scoring algorithm ($F=14.59$, $p < .0001$). For all outcomes, there were significant differences between Run 1 and Run 2 and between Run 1 and Run 3 ($p < .05$), but not between Run 2 and Run 3. The increased success rate from 82.1 (Run 1) to 92.9% (Run 3) was not significant ($p = .08$).

Complication rates for pneumothoraces and subclavian arterial punctures were reduced from 11% to 7% and 13% to 7%, respectively.

On a five point scale (1=strongly disagree to 5=strongly agree), on average, participants agreed that the simulator was realistic (M=4.1) and strongly agreed that the simulator should be used as a training/educational tool (M=4.8). (Robinson et al., submitted for publication).

In preliminary trials, the skin insert could be used for at least 100 punctures. In contrast to existing CVA part task trainers, our simulator detects lung strikes, calculates and displays the margin of safety, i.e., the distance by which artery and lung puncture was avoided and offers recording and playback of the needle's path and an automated scoring algorithm.

The entire access procedure showing the 3D needle path relative to surrounding structures is captured and can be replayed for after action review (debriefing).

A mixed simulator to teach a procedure with potential for significant complications, i.e., subclavian vein catheterization, has been created and validated. It provides a unique new tool to allow novices to gain useful experience and confidence without risk to patients. The technology has been disseminated in the form of two CVA simulators that were supplied to a manufacturer of central venous access kits and have been used to educate clinicians in the US and overseas.

The CVA simulator has been used and will continue to be used to train University of Florida anesthesia, emergency department as well as interventional cardiology residents, fellows and faculty.

We are currently working on adding simulated ultrasound guidance to the CVA simulator.

In the remainder of this paper, we describe other anatomically authentic augmented physical simulators that use the same virtual underlay paradigm to address training in other "blind" or guided procedures.

Application 2: Ventriculostomy Mixed Simulator

Background: During bedside or emergent ventriculostomy, for example on a warfighter who has suffered brain trauma from an IED blast, a catheter is inserted into a brain ventricle, without imaging guidance, to drain fluid and relieve pressure building up in the brain.

Neurosurgeons rely on anatomical landmarks and heuristics to establish the entry point at the skull and a 3D mental model of the brain to safely and efficiently steer the catheter tip to a lateral ventricle.

Motivation: We designed a mixed simulator to provide practice to novice neurosurgeons to facilitate placing the ventriculostomy catheter tip into the ventricle in one pass without striking other undesired inner brain components. Accessing the ventricle in one pass, rather than multiple passes, is desirable because it minimizes the trauma that the catheter (fitted with a rigid stylet during insertion) causes to brain tissues on its way to the ventricle.

Methods: In the case of the ventriculostomy simulator, we physically modeled the scalp, skin, skull (including the harder inner and outer tables), dura, facial features,

Figure 5. Left: The mixed reality ventriculostomy simulator; a catheter stylet tracked in 3D space is inserted via a hole drilled by the learner through a disposable skull insert and steered to the ventricle. Right: The virtual soft tissues (ventricles, caudate, brainstem and other inner brain components) are displayed collocated to a virtual representation of the physical catheter/stylet. The scalp, skull and outer brain opacity have been set by the instructor to transparent, in this view. The ventricles are colored green in the display.

(including anatomical landmarks) and the feel of inserting a catheter through brain matter.

The remainder of the simulator (inner and outer brain) was virtually modeled and registered to the physical component (the skull) with sub-millimeter accuracy The 3D model for the skin, skull and the brain (outer and inner brain) came from CT and MRI scans of an actual human. The individual inner brain components (ventricle, caudate, brainstem, etc.) were manually dissected (i.e., identified and converted into separate, distinct 3D virtual objects); see Figure 5, right picture.

We converted the CT scan of the skin and skull to a 3D model that was then used to create a physical, full scale, anatomically correct 3D model of the skull via a fast prototyping machine (zPrinter 310, Z Corporation, Rock Hill, SC); see Figure 5 left picture.

The ventriculostomy needle tip and the ventriculostomy catheter stylet tip were both instrumented with magnetic sensors tracked in real time by a 3D tracking system (Ascension Technology Corp., Burlington, VT) relative to the virtual 3D structures of the inner brain.

We implemented a scoring algorithm to automatically score performance after a training session and a capture and replay function to facilitate after action review (debriefing).

The simulated skull is actually drilled using a hand drill and other hand tools provided in a commercial ventriculostomy kit (Bactiseal EVD Catheter set, 82-1745, Codman & Shurtleff, Inc., Raynham, MA). We designed and built scalp, skull and dura inserts that are used for right and left entry and then discarded. During a complete simulated ventriculostomy procedure, the trainee also tunnels the catheter below the scalp to minimize the risk of infection (Friedman and Vries, 1908) and sutures the catheter to the scalp. The disposable scalp/skull inserts can be readily removed with the catheter stitched in place on the scalp. The scalp, simulated with a different material than the skull, can be quickly separated making it straightforward to assess if a stitch accidentally punctured the catheter.

Results: The ventriculostomy simulator was used by more than 140 attendees at the 2011 and 2012 annual meeting of the American Association of Neurological Surgeons (AANS) and was well received. A study was conducted during the AANS meetings and a manuscript describing the positive results of the study is being prepared. Additionally, the ventriculostomy simulator is being used to train neurosurgery residents at the University of Florida. A video of the mixed reality ventriculostomy simulator can be viewed at: http://simulation.health.ufl.edu/simulation/ventric_sim.wmv.

Moving the camera view on a 3D environment can be helpful during after action review, for example, to appreciate how close or far away a needle is from a structure. For both the CVA and ventriculostomy simulators, we found during use that instructors were generally unfamiliar with the keyboard shortcuts needed to pan, tilt and zoom the camera view.

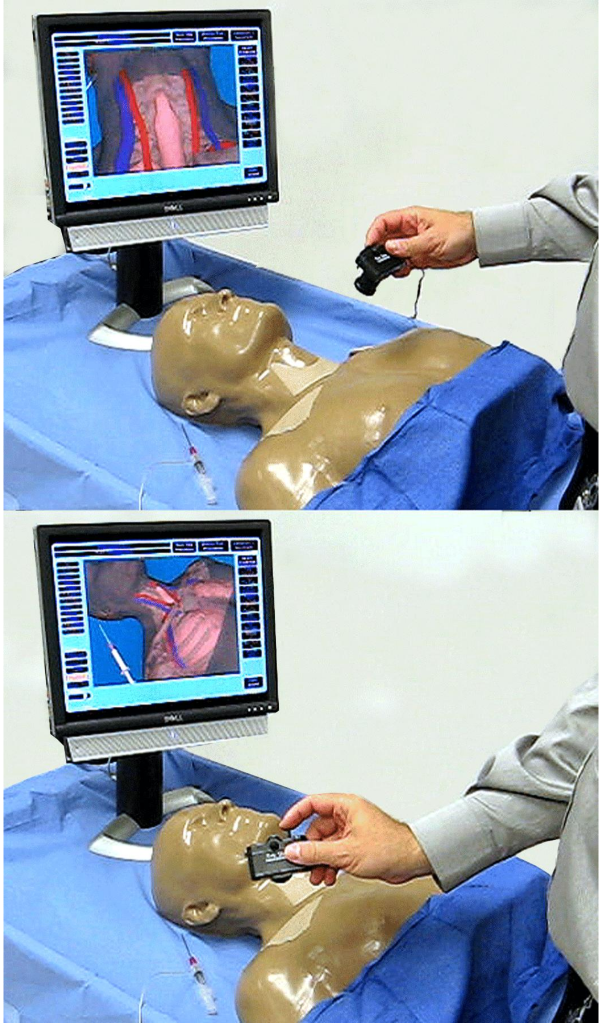


Figure 6. The tangible user interface (TUI) for manually controlling pan, tilt and zoom of the virtual camera view. The upper picture shows a zoomed-in view of the neck viewed straight on.

To create an intuitive and user-friendly way to control the camera view without a keyboard, we added a 6 DOF magnetic sensor to a physical toy camera that acts as a tangible user interface (TUI) to the virtual camera position and orientation. When moving the toy camera TUI in space with one's own hand, the camera perspective is observed to change in real time during both a simulated procedure or during replay of a previous procedure during AAR. Panning is done by translation of the TUI. Tilting is achieved by changing the TUI's orientation. Zooming is accomplished by moving the TUI closer to the torso. Whenever the user presses an instrumented shutter button on the toy camera TUI, the camera view follows in real time the TUI. The user releases the shutter button to lock the camera perspective and discontinue the camera view tracking the toy camera.

Application 3: Radio Frequency Lesion Mixed Simulator

Background: Radio Frequency lesion (RFL) is a guided procedure used to relieve trigeminal neuralgia, intense pain originating from the trigeminal nerve. A needle is inserted through the cheek muscle and then into the cranium via the foramen ovale under real time image guidance of the needle though fluoroscopy. Once the needle is in the trigeminal nerve region, and the location verified through stimulation, a radiofrequency lesion is used to destroy the part of the trigeminal ganglion which corresponds to the area of the pain, reducing or eliminating the pain.

Figure 7: The RFL mixed simulator. It comprises the phantom head, the electromagnetic tracker (the gray metallic plate underneath the phantom head) with electronic controller, and the computer that simulates the fluoroscopy unit.

Motivation: Neurosurgical residents are trained in the operating room by performing the procedure under the supervision of an attending surgeon. Especially during early training the resident physician uses significantly more operative time and fluoroscopic exposure in positioning the needle, increasing the risk from ionizing radiation exposure to both the patient and the staff. To allow the resident physicians to gain expertise in patient positioning, optimizing radiographic views, needle trajectory as well as providing an appreciation of the appropriate tactile feedback, a mixed RFL simulator was developed.

Method: The simulator includes a phantom head, with anatomically correct bony structures and a silicone face to allow for needle insertion, a virtual fluoroscopic unit, and an electromagnetic tracking system. The simulator allows the resident to position the patient's head while the virtual fluoroscopic unit, with foot switch control, provides computer radiographs simulating positioning in an actual patient procedure; see Figure 7. Once the appropriate radiographic view is achieved the resident can insert the tracked needle into the phantom's silicone face, with the needle being projected into the virtual fluoroscopic view; see Figure 8. The simulator is able to track the needle providing feedback as to the location relative to the appropriate target as well as identifying errors if inappropriate targeting is achieved. The amount of fluoroscopic time expended i.e. dose received by the patient, is tracked and reported. The resident experience closely parallels that in an actual patient procedure without the radiation exposure to the patient and clinical staff as well as providing the requisite hand eye coordination training critical to this type of surgical training.

Results: The RFL mixed simulator reproduces all the features of RF lesion procedures with imaging visualization similar to that of a real fluoroscopy unit: anatomical details and real-time response of the system to the surgeon's actions. X-ray exposure time and targeting accuracy are computed and used as a benchmark to assess the student's ability.

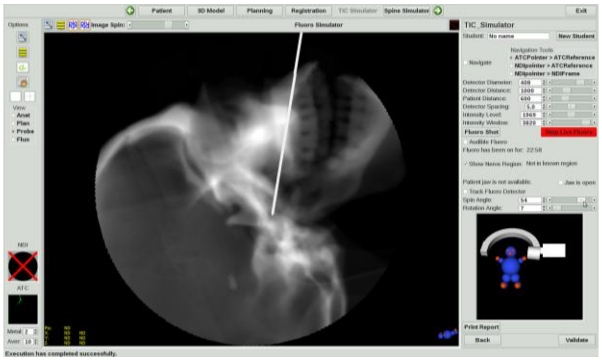


Figure 8: Combining the positions of the fluoroscopy unit, the phantom head, and the needle, the computer selects the closest radiograph projection and superimposes the shadow of the needle (white line) on top of the radiograph.

The RFL mixed simulator is used to provide University of Florida neurosurgical residents training in the RFL procedure with no risk to a patient and no radiation exposure to themselves or others. Once this training is completed, the student can continue his or her training in the OR with more confidence and less risk to the patient and ancillary personnel.

Application 4: Spinal Instrument Implantation Mixed Simulator

Background: Spinal instruments are implanted under open surgical, radiographic and image guided protocols.

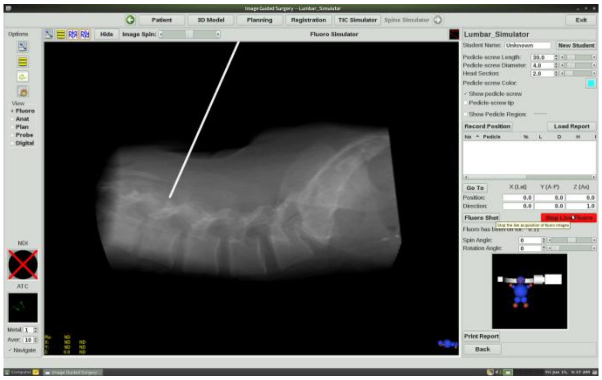
Motivation: Like in the RFL procedure, exposure of the patient and surgical staff to excessive ionizing radiation when a novice is learning to implant spinal instruments is a concern.

Methods: The spinal instrument simulator is a mixed simulator that allows for training and evaluation of implantation of spinal instruments under open surgical, radiographic and image guided protocols. The system is built around a physical model of bony anatomy derived from individual patient CT scans and reproduced using a 3D printer.

Figure 9. A view of the display of the mixed simulator for spinal instruments implantation. The bottom right picture shows a 3D image of the spine.

The physical model of the spine, embedded in a phantom torso, is registered to an image guidance program using electromagnetic tracking. The system allows instrumentation using free hand, tracked and guided instrumentation. The system contains a virtual fluoroscopic simulator that provides virtual x-ray projections (radiographs) at any arbitrary angle while projecting the surgical instrument into the fluoroscopic view; see Figures 9 and 10.

Results: The system provides metrics on appropriateness of instrument placement, i.e. assessment of screw location, time to instrumentation and radiation exposure utilized and is being used to train University of Florida neurosurgical residents.



Student Name: Unknown
Pedicle-screw Length: 30.0
Pedicle-screw Diameter: 4.0
Head Section: 2.0
Position: 0.0 0.0 0.0
Direction: 0.0 0.0 1.0
Spin Angle: 0
Rotation Angle: 0
Metal: 1
Aver: 10

Figure 10. A tracked physical needle (the white line) projected into a virtual fluoroscopic view where the virtual representation of the spine is collocated with a physical replica of the spine from a 3D printer.

Application in Progress: Regional Anesthesia Mixed Simulator

Background: During regional anesthesia, a needle tip is guided, usually under ultrasound (US) guidance, to the vicinity of a nerve so that anesthetics can be deposited to anesthetize the region that is innervated by the targeted nerve.

Figure 11. An anatomically accurate segment of spine created by a 3D printer for the regional anesthesia mixed simulator.

Motivation: Interpretation of the ultrasound image can be difficult for novices especially if (a) they are not familiar with the concept or interpretation of a cross-section (which is what an ultrasound image is) and (b) the complex anatomy of the spine. Misplaced needle tips can result in inadequate regional anesthesia and unnecessary pain to the patient.

Methods: We input CT scans from a volunteer to a 3D printer to build a segment of the spine; see Figure 11. The physical spine segment is then embedded in ballistic gel whose exterior has been molded to the shape of the back of the human model; see Figure 12. The virtual model of the spine will be registered with anatomical (sub-millimeter) accuracy to the physical model of the spine. Like in the other applications, a miniature magnetic sensor will be inserted into the bore of a regional anesthesia needle to allow 6 DOF tracking of the needle relative to the virtual and physical components. The nerves, lungs, arteries, veins, and ligaments around the spine will be purely virtual and anatomically authentic (based on the individual used as the model).

The regional anesthesia mixed simulator will also have a simulated ultrasound module because regional anesthesia is typically performed with US guidance. We are currently exploring the possibility of generating the US images in real time instead of using pre-recorded US images.

There are no results to report as this is work in progress. When completed, the regional anesthesia simulator will be used to train University of Florida residents, fellows and faculty as well as clinicians in private practice.

Figure 12. The physical spine segment embedded into ballistic gel.

CONCLUSION

Mixed simulators integrate physical and virtual components and have the potential to offer the best of both physical and virtual simulations while bridging the artificial divide between physical and virtual simulation. Augmented physical simulators with virtual underlays are a subset of mixed simulators and an emerging concept in simulation that has led to innovative technologies and new training capabilities in the simulators described in this paper. Unlike purely physical procedural simulators, such as those for central venous access, the ability to precisely track and record the path of a tool (the needle tip) facilitates playback and after action review, AAR, (debriefing), an important part of every simulation exercise.

The automatic capture of performance data in real time allowed the development of automated scoring algorithms, developed in consensus with clinicians and domain experts. The automated scoring algorithms coupled with the playback capability make possible self-debriefing (Boet et al., 2011) when instructors or experts (scarce by definition) are in short supply. The design of the simulators also enables collocated after action review (Quarles et al., 2008c) whereby the AAR is performed on the simulator and the trainee's performance (such as the needle tip trajectory and how close it came to unintentionally hitting the lungs) can be compared to the aggregate performance of his or her peers who previously used the simulator or to the performance of an expert. Collocated AAR can also include the trainee repeating a procedure while manually guiding a needle to follow the needle tip trajectory of an expert.

Future areas of development in augmented physical simulations with virtual underlays applicable to combat casualty care include trauma ultrasound examinations, analgesic nerve blocks and the placement of needles and chest tubes to treat penetrating chest wounds and re-expand collapsed lungs.

The CVA and ventriculostomy simulators are compact (each can fit into a single padded shipping case that meets airline weight and volume limits for checked luggage) compared to previous ventriculostomy simulators that used a CAVE system. They are also relatively inexpensive when taking into account their capabilities. In addition, the CVA and ventriculostomy simulators are turn-key systems that do not require a technician or our engineers to be present when the system is set up, used or dismantled. The time interval from the CVA simulator being in its shipping box to being up and running is about 7 minutes. The small footprint and the turnkey aspect lower the logistics challenge in considering deployment of these simulators in combat zones to provide point of care, on demand training.

The technology and its applications demonstrated in this paper were focused on healthcare due to the background and work environment of the authors. There is no apparent reason why similar commercial off the shelf (COTS) technology (that was used in this paper and has now become affordable and widespread) cannot be used in civilian and military applications of augmented physical simulators with virtual underlays.

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