A Modular Interactive Virtual Surgical Training Environment

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ABSTRACT

Safe and successful surgical intervention requires careful planning and precise technical execution. The ideal surgical education and training environment would include repetition, reinforcement, review, and re-evaluation to speed the achievement of required performance levels, focus trainees on critical tasks, and promote the development of competent intraoperative decision making. In practice, students learn how to operate by practicing, under supervision, on real patients. This method subverts the desired objectives due to uncontrollable factors such as random patient availability and diverse disease presentation. An interactive virtual surgical training environment provides a promising alternative by potentially reducing medical error rates, improving the accuracy of intraoperative judgments, and increasing efficiency without the risk to living patients.

A good first step for creating a full surgical trainer is the development of a fractured femur simulator that provides medical personnel with hands-on experience in managing various types of fractures without risk to a human patient. This paper describes ongoing work to develop such a simulation, and includes a discussion of the following:

1. Development a of medical Haptic device tool kit.
2. Development of an instructional plan.
3. Creation of six training modules.
4. Assembly of an integrated system architecture for a full femoral procedure.
5. Assessing of the computational, force feedback, and display latency as well as haptic and visual fidelity to judge the overall ability of the system to replicate conditions in an actual medical procedure.

The modules are used to teach a student through a series of exercises that develop the cognitive and psychomotor skills required to perform the outcome procedure. We conclude by discussing how to transform this special purpose simulation into a general-purpose surgical training simulator.

ABOUT THE AUTHORS

Charles J. Cohen has been working in the fields of simulation, image processing, robotics, human-computer interaction, and artificial intelligence for over a decade. Currently, he is the Vice President of Research and Development for Cybernet Systems Corporation. He has been the project manager for many projects for the United States Armed Forces (Air Force, Navy, and Army), National Aeronautics and Space Administration, and other government agencies. Dr. Cohen's current research interests are in simulation, modeling, gesture recognition, image processing, estimation theory, system integration, visual communications, machine vision, and perceptually coupled systems.

Mr. Hay is a lead developer in Cybernet's OpenSkies group, specializing in graphics programming and simulation. He has had significant experience in the software industry including satellite diagnostic systems, genetic sequencing tools, Chrysler's original intranet site, administration software for Lawrence Livermore National Labs, educational virtual worlds, swarm UAV command and control software, and medical simulation technology. Ron has been a lead developer on Cybernet's OpenSkies Graphics, Simulation, and Networking engine, being involved in that system from its birth. When not writing software, he is occasionally seen running around the soccer field, trying not to hurt himself again.

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INTRODUCTION

Safe and successful surgical intervention requires careful planning and precise technical execution along with dynamic responses to observation of the surgical site during the procedure. In an ideal surgical education and training environment, repetition, reinforcement, review, and re-evaluation should speed the achievement of required performance levels, focus trainees on critical tasks, and promote the development of competent intraoperative decision-making. Such training should reduce medical error rates, improve the accuracy of interoperative judgments, increase efficiency, and improve patient outcomes at lower cost. In practice, surgeons in training learn how to operate by practicing, under supervision, on real patients. This subverts efficient and quantifiable attainment of the desired objectives due to uncontrollable factors such as random patient availability and diverse disease presentation. An interactive virtual surgical training environment would provide a promising solution to these problems.

Traditional surgical training programs seek to accomplish multiple goals including the acquisition of broad surgical knowledge, diverse operative experience, expert technical dexterity, and the ability to respond to unforeseen surgical or anatomical anomalies with extemporaneous creativity and flexibility in a psychologically stressful environment. Current training methods rely almost entirely on supervised practice on real patients and are subject to the vagaries of timing, patient availability, and disease presentation. Inexperienced trainees face the daunting task of performing complex and technically challenging procedures under the watchful eye of supervising surgeons who must continuously balance the paramount needs of patient care against the training requirements of the surgical student. An analogy in the airline industry would have a novice pilot flying a 747 filled with passengers across the Atlantic Ocean without having had the opportunity to practice on a simulator or fly an empty plane first.

Of course, the public would never tolerate such excessive risk-taking in aviation, even as most consider the apprenticeship model to be the state of the art in surgical training. Simulation-based training systems have only recently been postulated as training alternatives for surgeons, and those few systems that have been developed are very primitive.

Because the cost of training surgical residents is extraordinarily high, not to mention the costs for military medical personnel to maintain proficiency, the economic basis for research and development of surgical simulation systems is compelling. One group has estimated that the incremental cost of training chief surgical residents associated with extra operating room time alone amounts to about $58 million annually (Gorman, 1999). Efforts to decrease the cost of health care and of training are embodied in recent congressional actions that threaten these existing models of surgical education. The Balanced Budget Act of 1997, Public Law 105-33, will result in the loss of hundreds of millions of dollars that would have otherwise been used to support graduate medical education through the Medicare program. These budgetary pressures continue to mount in the private sector as well, as health maintenance organizations face rising costs and declining revenues. Clearly, successful efforts to develop virtual surgical training environments, especially one that has a Haptic based system, will be rewarded by a strong return on investment only if they are demonstrated to train surgeons as well as or better than traditional methods and at lower costs (Pflesser, 2002).

There is also increasing pressure to reduce medical errors. The Institute of Medicine recently reported that tens of thousands of medical errors occur each year; surgical misadventure was highlighted in the first paragraph of the report's executive summary (Kohn, 1999). Recommendation 7.2 of the report calls on professional societies to "recognize patient safety considerations in practice guidelines and *in standards related to the introduction and diffusion of new technologies…*" [Emphasis added]. The cost in human and financial terms of surgical errors should not be underestimated.

Interest in the use of artificial environments for training and certification to improve patient care is substantial, and validated precedents in the airline industry and the military suggest that medical applications have great potential (see (Issenbert, 1999), (Office of Naval Research, 1973), (Dusterberry, 1975), (Kilby, 1998), (McDonald, 1998), (Torkington, 2000), and (Smith, 1999)). Development has been strongest in the area of laparoscopic surgery, where a number of simulators and training programs have been reported. However, most of these utilize standard laparoscopic instruments applied to inanimate objects. Participants are appraised by an observer or by capturing motion data (see (Derossis, 1998), (Rosser, 1998), and (Rosser, 1997)). The use of virtual reality for surgical simulation has only recently been attempted for laparoscopic interventions (see (Chaudhry, 1999), (Gallagher, 1999), (Ota, 1995), and (Wilson, 1997)). These systems generally do not include force feedback, which limits their ability to simulate the tactile feedback that has been documented during actual laporoscopic surgical procedures (Bholat, 1999), and virtual reality representations have been inconsistent and require hardware that does not perform well for extended periods of time. Very recently, systems incorporating force feedback haptic devices have begun to emerge, but for the most part, these are prototypes that have not been studied recently. Using a virtual laparoscopic trainer, one group has reported the ability to document degradation in simulated operative performance accompanying sleep deprivation in a prospectively designed study (Taffinder, 1998). These preliminary findings suggest that further development of surgical simulation technology may ultimately permit the use of these systems for certification and credentialing as well as training (O'Toole, 1999). However, the ability to simulate *open* surgery requires a more integrated approach to provide convincing force feedback responses to interactions with a realistic virtual image (Sela, 2004) (Seymour, 2002).

A good first step for creating a full surgical trainer would be the development of a fractured femur simulator. This would provide medical personnel with hands-on experience in managing various types of fractures without risk to a human patient. Fractured femur injuries frequently occur to military (and civilian) personnel, and therefore training in appropriate medical techniques is desired. Such fractures would include femoral neck (intracapsular); intertrochanteric; subtrochanteric; femoral shaft; and supracondylar. Such fractures can be spiral or transverse, comminuted (broken into pieces), open, or uncomplicated. This paper will illuminate the features of an interactive surgical training environment by addressing the needs of a femoral surgical trainer.

FEMORAL SURGICAL OVERVIEW

Commonly, when a significant injury has occurred to the upper leg, the femur will be broken. Often, a surgeon repairs the femur by reducing the femur (aligning the broken pieces together, removing any unusable, damaged material) and then inserting a rod through the core of the femur. Most of the surgery is routine, but the final portion – inserting the interlock pin through the rod – is difficult to perform and requires numerous visuospatial skills to perform correctly. The specific, high-level steps performed during such a surgery are (See Figure 1):

Figure 1: Femoral Surgical Techniques

1. ***Tap a hole into the proximal end of the femur, at the hip***. This requires using an awl to push through the hip skin and muscle to find the trochanter, which is the part of the bone that starts the femur. The initial incision is extremely important for this step, as it makes the process of finding the correct starting location on the trochanter much easier. Once the initial location is found, a tap hole is created to allow for the next step.

2. ***Bore out the center of the femur down to just above the knee***. While it may seem like the most extreme step, the center core of the femur is made of a different material than the rest of the femur, and is therefore actually fairly straightforward for a surgeon to bore out. Care must be taken not to drill out of the core, and to stop at the proper location in the distal femur.

3. ***Insert the femoral rod through the hip***. Once the hole is drilled, the rod must be inserted at the hip, through the drilled-out core, down almost to the knee.

4. ***Drill and lock the proximal femoral nails to fix the rod into place at the hip***. This is often done using a mechanical apparatus to ensure proper insertion of the nails through the holes in the proximal end of the rod. While complicated, there are fewer issues concerning flex and rotation and so the mechanism provided by the manufacturer works well.

5. ***The final, and most complicated step is to drill and insert the distal interlock nail***, which must be done using only a fluoroscope for visualization, as there is typically no significant incision at the knee. This procedure consists of the following sub-tasks:

a. Command the fluoroscope operator such that the fluoroscope is looking straight through the hole in the femoral rod. On the fluoro images, the scope is correctly aligned when only a single, perfect circle is seen.
b. Insert the guide pin into the leg in an approximate position near the femoral rod holes, all the way to the femur.
c. Carefully move the tip of the pin over the femur until the tip is at the center of the hole as verified by fluoroscope images.
d. Without changing the tip position, orient the pin such that it is pointed directly through the femoral rod hole.
e. Attach the guide pin to the drilling mechanism, without changing the orientation or position of the pin.
f. Drill through the bone, through the rod, and through the other side of the bone, but without drilling out of the femur.
g. Remove drill, and place interlock pin according to manufacturer directions.

INSTRUCTIONAL PLAN

One of the biggest challenges in instruction is facilitating the conceptual understanding of the interdependence and relationships between the component parts of an integrated system (Holland, Holyoak, Nisbett, & Thagard, 1986) (Merrill, 2002) (Pollock, Chandler, & Sweller, 2002) (Reigeluth, 1999) (Sweller, 1988) (Sweller & Chandler, 1994) (Sweller, van Merriënboer, & Paas, 1998). For example, learning to perform an orthopedic surgical procedure, such as the repair of a femoral trauma, necessitates that the learner be able to perform many component skills, such as selecting the best start point, navigating to the target point, inserting equipment correctly, and using Fluoroscopic imaging to facilitate the entire process. While each component skill has its function, it is the holistic system of the skills set that provides the framework for successful completion of the procedure.

Initial learning is best facilitated through the exploration of underlying concepts that allow the learner to generate connections to other knowledge they already have (Holland, Holyoak, Nisbett, & Thagard, 1986) (Reigeluth, 1999) (Vygotsky, 1934/1987). Because learners construct new understanding based on their existing knowledge, didactic and other methods of direct instruction can be ineffective if the students do not have a previous knowledge structure to support the ability to construct knowledge from a lecture (Jonassen, 1999) (Merrill, 2002) (van Merriënboer, Clark, & de Croock, 2002). Without prerequisite knowledge, students often construct understanding based on erroneous assumptions or misinterpretations of information (Jonassen, 1999). Active engagement in a contextualized environment, such as a simulation or problem-based scenario, helps students to re-conceptualize any faulty preconceptions and build more comprehensive knowledge structures, as well as aid in the transfer of that knowledge to other contexts (Bransford, Brown, & Cooking, 1999).

In order for transfer to occur for a new context, initial learning must take place at a deep level. That is, superficial memorization of facts or procedural knowledge will not aid in the transfer of knowledge to other context. What is required is that people learn with understanding (Bransford, Brown, & Cooking, 1999) (van Merriënboer, Kirschner & Kester, 2003).

Merriënboer (van Merriënboer, Clark and de Croock, 2002) provided a framework for the design of complex learning systems that addressed the need for a holistic approach to instruction and included a supportive structure and integrated, task-specific constituent skills to foster deep understanding. Deep understanding results from the identification of meaningful patterns of information and deducing the implications of those patterns for future outcomes (Bransford, Brown & Cooking, 1999).

Learning is most effective in a dynamic environment that requires students to actively choose and select strategies, consider resources, and engage in deliberate practice that includes feedback to monitor progress in the knowledge domain (Ericsson, Krampe & Tesch-Romer, 1993). Instructional strategies that engage learners as active participants in their learning by focusing their attention on critical elements, encouraging abstraction of common themes or principles, and evaluating their own progress toward understanding serve to promote both deep knowledge structures and flexible transfer. This instructional model will make use of such active learning strategies on the initial learning of the component skills associated with the orthopedic surgical repair of a femur and the transfer of this skill based knowledge to performance on a fully simulated intracranial femoral repair procedure.

The instructional modules are comprised of two forms: mastery of component skills and procedural application. All modules will make use of the virtual fluoroscopy module to facilitate a deep understanding of the use of fluoroscopic imaging in the localization and navigation to the target point of the procedure. Initially we envision six component skill modules wherein the student will use the simulator to move through a series of exercises that develop the cognitive and psychomotor skills required to perform the outcome procedure. These modules include: 1) using fluoroscopy to identify rotation and position of the bone, 2) identifying the start point placement, 3) using fluoroscopy and retract/advance techniques for optimal placement of distal interlock, 4) orienting the distal interlock placement of screw, 5) identifying 3-D orientation for placement of screw, and 6) practice drilling.

Metrics will be provided to the trainees for each module so they may gauge their progress through each technique. Metrics will include, but not be limited to, the number of tries to correct response, soft tissue damage, systematic processes used, path variance and depth. Upon completion of the six component skill modules, the trainees will proceed to the full procedural simulation module.

The procedural simulation module will provide an environment that closely replicates the actual procedure required for repairing a femoral trauma. Learners will be expected to initiate the processes and techniques required to complete the procedure in sequence and with acuity. Metrics will be provided for the students throughout the procedure so they may monitor their progress throughout. Metrics will include, but not be limited to, the amount of resistance for each step, the number of fluoroscopy images used, soft tissue damage, path variance and depth, logical path to point of distal interlock, drilling force, and overall successful placement of screw in femur. The chart below (Figure 2) indicates the proposed curriculum that includes the six component skill modules and the procedural module.

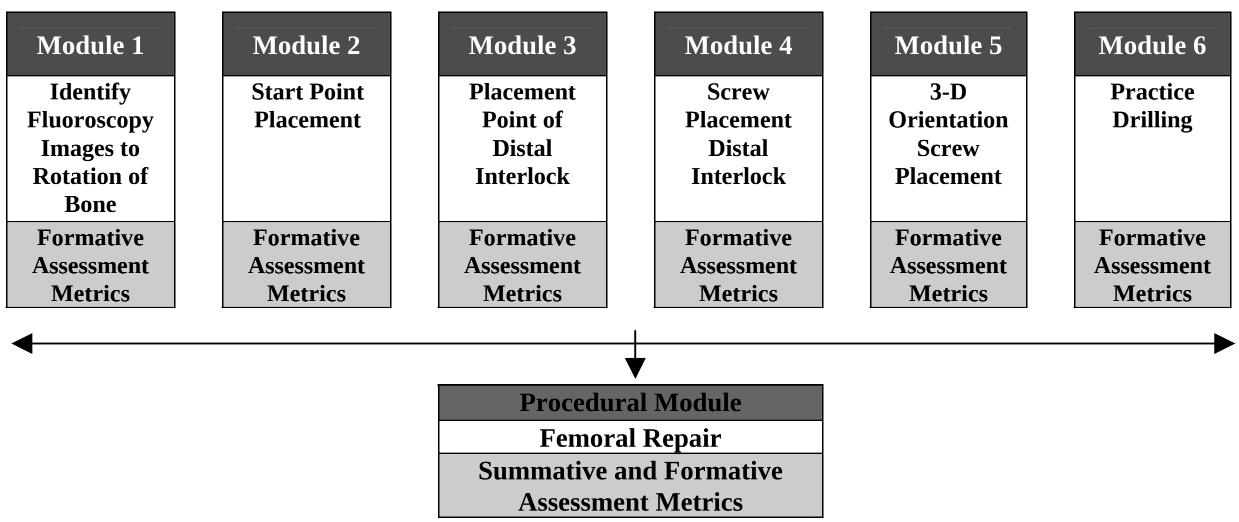

Figure 2: Instructional Curriculum Composed of Six Systems Modules

FORCE FEEDBACK SYSTEM

A force-feedback device[1] is used to simulate skin elasticity and bone contact. The surgical instrument (i.e. the nail) is moved around in 3-space using a 3 degree-of-freedom input and force-feedback. The virtual nail’s motion is slaved to the motion of this device’s end-effecter. There are two modes to this slaved motion: *orientation* and *translation*.

The trainee has successfully performed the procedure when the tip of the nail is contacting the bone, and the

[1] Cybernet’s Stylin’ 3D

orientation of the nail lines up with the slot in the femur rod (see Figure 3).

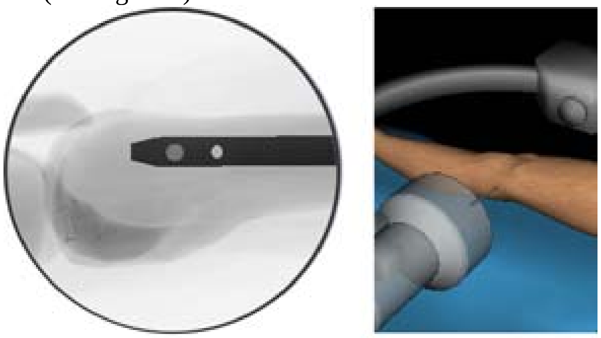

Figure 3: Successful Proximal Interlink Orientation

Orientation

In this mode, the tip of the nail does not move. The head of the nail is slaved to the motion of the force-feedback device, which does not convey forces in this mode. This mode allows the user to manipulate the orientation of the surgical nail.

Translation

In this mode, the whole nail moves in 3D with the motion of the force-feedback device. Forces from the skin elasticity and the bone contact and friction are fed to the user via the three motors on the device when in this mode. The force feedback is simulated using a number of virtual 3D force-feedback controls. These are:

1. *Skin contact point* – When the virtual nail first contacts the skin of the leg, this point is recorded. As the user penetrates further into the skin, the force-feedback device renders a force that is a spring to this contact point, which simulates the elasticity and resistance of the skin and soft tissue. This effect has a threshold distance, which, when exceeded, has the effect of moving the recorded point closer to the actual nail-head in order to simulate the skin penetration. Moving out of the skin effectively deactivates the force-feedback.
2. *Skin contact vector* – When the virtual nail first contacts the skin of the leg, a virtual line-segment is recorded. One endpoint of this segment is the skin-contact point. The other is the closest point on the line running down the center of the femur and support rod. This haptic control acts as a spring that pulls the nail point to the skin contact vector, which simulates the elasticity of the skin in any direction tangential to the skin.
3. *Bone surface* – This is a virtual 3D plane that is continually redefined as the tangent plane on the bone that is closest to the virtual nail point. The orientation of this plane is constantly adjusted until it is crossed (i.e. contacted) at which point it freezes. This is essentially a directional spring-damper control that simulates the hardness of the bone. It also has a term for a frictional force that simulates the nail scraping against the bone.

VIRTUAL REALITY SYSTEM

The surgical trainee is able to manipulate the view orientation of the leg and can also translate and orient the fluoroscope about the patient's leg. The X-Ray view is slaved to the fluoroscope's position and orientation and approximates the semi-transparent view typical of such an instrument.

Using a virtual reality engine[2], we have created the initial simulation of the femur and surrounding leg. We have obtained anatomical models of skin and muscle from a third party source[3] that sufficiently supports this training environment. The polygon supports excellent visualization without heavily burdening the processor. The models include skin, muscle, bone, and circulatory system. The skin is a simple poly mesh, and the muscles have a skin mesh for each major muscle plus a basic texture.

The resulting simulation is shown in Figure 4, and is composed of three views:

Upper-Left, Fluoroscope Control View

This view allows the user to control the position and orientation of the fluoroscope. Future work includes the adding of voice-recognition software for fluoroscope, enabling a more authentic and real surgical experience. During an actual operation, a technician who responds to commands from the surgeon controls the scope. Therefore, voice recognition would be used to simulate calling out instructions to the surgical assistant.

Upper-Right, Fluoroscope Monitor

This view represents the output from the fluoroscope, that is, the x-ray view. This version of an x-ray is not a perfect representation of an x-ray, but the simplified model used was accepted as more than adequate by

[2] Cybernet's OpenSkies engine.
[3] Cache Force Computing.

orthopedic surgeons. In the figure, the view is of the knee looking down on it, and shows the surgical nail already inserted.

Bottom, 3D Interactive "Surgery" View

This view represents the 3D view of the operation and can be adjusted rotationally and zoomed in and out. The surgical view will be augmented with an actual latex leg and surgical table to help surgeons immerse themselves in the environment (see Six Surgical Training Modules).

TRAINING EXPERIMENT

Cybernet and the University of Michigan created a demonstration system based on a 3 Degree of Freedom (DoF) haptic device. This demonstration system consists of three virtual reality views (Figure 4) and is connected to the haptic device. The user then manipulates the fluoroscope with the control view (to align the scope with the hole in the femoral nail. Next, the user manipulates the virtual pin using the haptic device to align the pin with the hole in the nail. While manipulating the pin, the user experiences forces relating to interaction with the skin, muscle, and bone.

The current implementation simulates the proximal interlocking procedure. This software renders the surgical environment graphically, rendering 3D versions of the patient's leg (including the skin and bone), the surgical area, the fluoroscope, and femur rod and the surgical nail. The objective is to train medical students how to line up the surgical nail with the slots in the femur support rod.

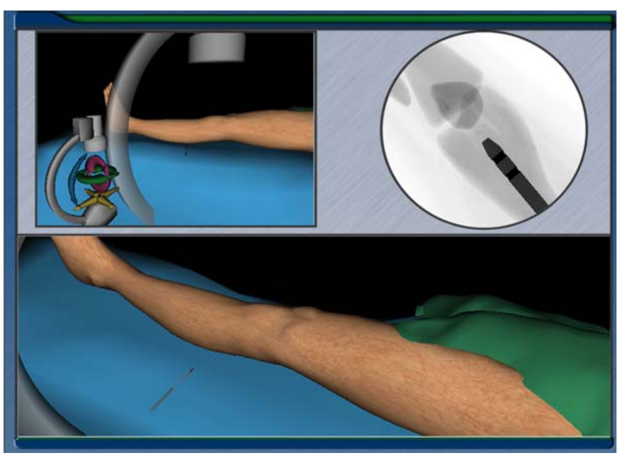

Figure 4: Startup view of the haptic femur surgical simulation. The upper left view is the fluoroscope control screen, the right view is the fluoroscope monitor (showing the knee from the top down), and the bottom view is the interactive "surgical" view. The interlock pin to be inserted can be seen lying on the surgical table in the bottom view.

The student has successfully performed the procedure when the tip of the nail is contacting the bone, and the orientation of the nail lines up with the slot in the femur rod. This process can be seen in the series of fluoroscope captures taken from the simulation shown in Figure 5. Starting in the upper left, we see the initial scope capture of the knee and femoral nail. Going from left to right, top to bottom, the fluoroscope is first maneuvered to align the nail hole with the scope (third image), then the pin tip is aligned with the center of the hole (fifth image), and then the pin is aligned rotationally to go straight through the hole (last image).

The results from the demonstration are very promising. The University of Michigan Medical School authors have found that even this preliminary system is useful for femur surgery training. Two examples of such experiments are Identifying Images and Start Point Displacement.

Identify Fluoroscopy Images to Rotation of Bone

One of the tasks a surgeon needs to perform is rotating and moving the bone or the fluoroscope, and determining exactly where certain locations on the bone are.

For this experiment, the student views an image of the femur with the fluoroscope with the goal of properly aligning the holes of the femoral rod in the image. The student can use the computer interface to take fluoroscopic images of the femur, move/rotate the fluoroscope, and move/rotate the femur.

In this experiment, the measurements are: time to align the holes properly and number of fluoroscopic images. Preliminary experiments showed that a novice student would take an average of three minutes and 35 fluoroscopic images to complete the task. With two hours of training, the averages were reduced to thirty seconds with 12 fluoroscopic images.

Module 2: Start Point Displacement

This location where the incision should be created in order to place the guide wire correctly is the start point displacement location.

For this experiment, the student will only be able to view the leg of the patient, the location of the probe, and the images from the fluoroscope. The force feedback system emulates the probe.

In this experiment, the measurements are: time to position the probe tip in the center of the holes (total task time), total number of discrete movements, total travel distance, and number of fluoroscopic images taken. Lower values for all of these metrics are preferred.

Preliminary experiments show the following changes in the average values:

	Initial	After Training
Total Time	10 min	3 minutes
# of movements	63	15
Total travel dist.	563 mm	160 mm
# of images	54	12

SIX COMPONENT TRAINING MODULES

Based on the system described in the paper, we envision six training modules that will form the basis of a haptic femoral surgical training simulator. Many of the

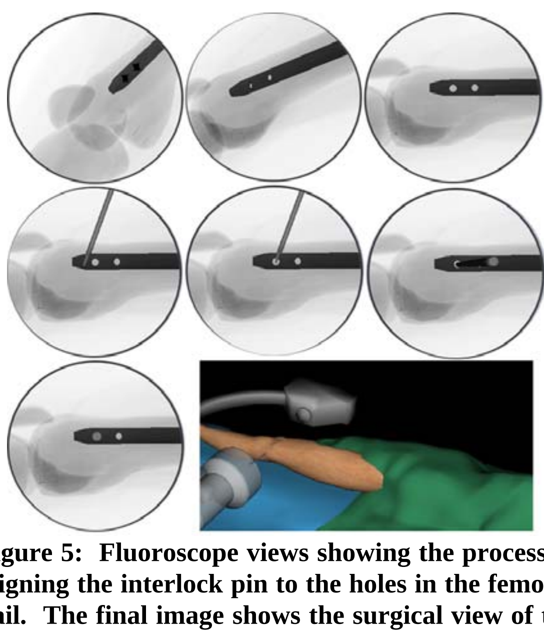

Figure 5: Fluoroscope views showing the process of aligning the interlock pin to the holes in the femoral nail. The final image shows the surgical view of the fluoroscope and pin alignment.

techniques for the specific modules have already been developed and illustrated in the Training Experiment detailed above. However, in addition to expanding those tasks, the surgical environment must also be created.

Mock Surgical Environment

For effective surgical training, it is important to convey a sense of the actual environment to the trainee. A spatial context for the developing the student's procedural understanding must be provided. It is possible that a virtual mockup that differs drastically from the real surgical environment may even result in negative training, which is worse than no training whatsoever. In order to bring the virtual simulation as close as possible to real surgery, props are required. One of the most important props will be a simulated patient's leg.

It is common practice for the surgeon grasp the patient's leg while performing the distal interlock. Placing a mock leg into the physical environment brings up one major issue that must be addressed. If the haptic device must operate in the region very close to the mock-leg, then there will likely be problems with the device's links colliding with the mock leg, not to mention that the situation where the device's link collide with the user's arms/hands/body must be avoided. This can be handled by placing the device carefully by, for example, placing the device upside down might very well minimize intersection of the spaces potentially occupied by the links, the user, and the mock leg. Also, the leg is not real, so we can eliminate collisions by removing sections of the leg to accommodate the device links.

Module 1: Identify Fluoroscopy Images to Rotation of Bone

This is equivalent to the first experiment described in the previous section.

Module 2: Start Point Displacement

This is equivalent to the second experiment described in the previous section. An additional useful capability is to enhance the haptic software library to create the feeling of cutting skin, providing the student with a virtual scalpel.

Module 3: Placement Point of Distal Interlock

This module addresses the technique for using fluoroscopy and retract/advance techniques for optimal placement of the distal interlock. This task requires the student to place an awl on the correct part of the bone while interacting with the forces felt by interacting with the bone, muscle, and tissue. They must learn to slide it in an appropriate manner. In this module, the student will only be able to view the leg of the patient and the images from the fluoroscope.

A new device, an awl, must be simulated for its force feedback requirements. However, such a device is functionally equivalent to a probe, though the response to muscle, tissue, and bone is different

Module 4: Screw Placement Distal Interlock

This module addresses the technique for orienting the distal interlock placement of the screw. In this module, the student will only be able to view the leg of the patient, the location of the screw, and the images from the fluoroscope.

A new object, the screw, must be simulated for its force feedback requirements. However, such a device is functionally equivalent to the Awl, though the response to muscle, tissue, and bone is different. While the force will be felt at the point, the device that holds the screw to be held requires two hands, and that device needs to be integrated into the force feedback architecture.

Module 5: 3-Dimensional Orientation Screw Placement

This module addresses the technique for identifying the 3-dimensional orientation for the placement of the screw. In this module, the student will only be able to view the leg of the patient, the location of the screw, and the images from the fluoroscope.

Module 6: Practice Drilling

This module addresses the technique for drilling into the femur. This module is different from the others because of the drilling aspect, which can vary widely. In this module, the student will only be able to view the leg of the patient and the images from the fluoroscope.

The drilling system must be 6 DOF and include a wide range of forces, not only including straight drilling, but slippage and break through. Breakthrough is when the drill bit goes too far past the bone.

CONCLUSIONS

In this paper we detail the instructional environment, Haptic system, and virtual reality system for creating an interactive virtual surgical training environment. By using femoral surgery as an example, we detailed six example modules that form the basis of a full surgical simulation.

Through such techniques, learners can master basic surgical techniques in a realistic environment, reducing the risk of mistakes in the operative field. Specific metrics, such as damage to the soft tissue, path variance, number of fluoroscopy images used, and drilling force can all be used to evaluate the student's skill prior to performing actual surgery.

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