

# Perk Tutor: An Open-Source Training Platform for Ultrasound-Guided Needle Insertions

Tamas Ungi\*, Derek Sargent, Eric Moulton, *Student Member, IEEE*, Andras Lasso, *Member, IEEE*, Csaba Pinter, Robert C. McGraw, and Gabor Fichtinger, *Senior Member, IEEE*

**Abstract**—Image-guided needle placement, including ultrasound (US)-guided techniques, have become commonplace in modern medical diagnosis and therapy. To ensure that the next generations of physicians are competent using this technology, efficient and effective educational programs need to be developed. This paper presents the Perk Tutor: a configurable, open-source training platform for US-guided needle insertions. The Perk Tutor was successfully tested in three different configurations to demonstrate its adaptability to different procedures and learning objectives. 1) The Targeting Tutor, designed to develop US-guided needle targeting skills, 2) the Lumbar Tutor, designed for practicing US-guided lumbar spinal procedures, and (3) the Prostate Biopsy Tutor, configured for US-guided prostate biopsies. The Perk Tutor provides the trainee with quantitative feedback on progress toward the specific learning objectives of each configuration. Configurations were implemented through simple rearrangement of hardware and software components, attesting to the modularity and ease of configuration. The Perk Tutor is provided as a free resource to enable research and development of educational programs for US-guided intervention.

**Index Terms**—Medical education, needle placement, simulation, ultrasound (US) guidance.

## I. INTRODUCTION

**I**MAGE-GUIDED needle placement has become ubiquitous in modern diagnosis and therapy. Image-guided needle-based interventions offer significant advantages over conventional surgery, as they typically reduce pain, complications, procedure time, recovery time, and overall costs. Placing a needle

in a target position visible on an image is a complex and delicate process that demands exquisite tool control and hand-eye coordination by the practitioner. The procedure requires training and experience, which trainees traditionally acquire on patients under the supervision of a senior physician. In addition to exposing the patient to risk of potential errors, the learning process is hindered when you subject novice learners to the stress of a real clinical situation and by the lack of objective, quantitative feedback. In contrast, the goal for the modern learner is to arrive at the bedside of a real patient with proficiency already demonstrated in the requisite skills. This approach is not only safer for patients, but has also been shown to enhance learning [1].

Computer-assisted training enables focused and deliberate practice that incorporates continuous quantitative feedback on performance, which are crucial aspects for skill acquisition [2], [3]. Simulation models exist along a wide spectrum of physical fidelity, ranging from cadaver models to pure virtual reality. There has been a movement away from traditional cadaver and animal models due to expense, ethical considerations, and simple logistical reasons [4]. Virtual simulation models have been tried in procedures, such as pericardiocentesis, diagnostic peritoneal lavage, thoracocentesis [5], prostate brachytherapy [6], spinal biopsy [7], central venous catheter insertion [8], and transhepatic cholangiography [9]. Generally, pure virtual simulators are helpful in teaching advanced trainees to acquire mastery of the technique, but they detach trainees from the real physical environment and tools, which may be a problem for novice trainees. The physical context with objects, tools, dimensions and, in many cases, ambient noise, and illumination of the environment are important aspects in the early phase of learning.

Synthetic phantom models combine the advantages of physical dimensionality and computer controlled working environment. Phantom models have been found to be effective in teaching procedures, such as ultrasound-guided epidural and spinal needle insertions [10] and transrectal prostate biopsy [11].

As an image guidance modality, ultrasound (US) enjoys steadily increasing popularity, due to its low cost, portability in the clinical environment, availability, and safety. US-guided needle placement, however, is extremely difficult to perform and it demands mastery of many elements of the essential skillset in image-guided needle placement. According to a survey of US-guided spinal needle interventions [12], “perhaps the only disadvantage of the US-guided injection technique is the long learning curve that is required for the physiatrists to be well acquainted with the simultaneous manipulation of US transducers, placement of needles, and the correct interpretation of musculoskeletal sonographic images.”

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\*T. Ungi is with the School of Computing, Queen’s University, Kingston, ON K7L 3N6, Canada (e-mail: ungi@cs.queensu.ca).

D. Sargent and R. C. McGraw are with the School of Medicine, Queen’s University, Kingston, ON K7L 3N6, Canada (e-mail: dsargent@qmed.ca; 3rcm4@queensu.ca).

A. Lasso, C. Pinter, and G. Fichtinger are with the School of Computing, Queen’s University, Kingston, ON K7L 3N6, Canada (e-mail: lasso@cs.queensu.ca; pinter@cs.queensu.ca; gabor@cs.queensu.ca).

E. Moulton is with the Department of Electrical and Computer Engineering, Queen’s University, Kingston, ON K7L 3N6, Canada (e-mail: 8em3@queensu.ca).

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Position tracking and motion analysis of the surgical tools can predict the quality and functional outcome of surgical tasks [13] and can predict skill level [14], [15]. At the same time, there is no consensus as to what metrics should be used to analyze recorded procedure data. Currently, the most common metrics are procedure time, number of hand movements, economy of motion, and score penalty for basic adverse events such as needle–bone collisions [16]–[18].

We expect that in the near future extensive research will take place in image guided and especially US-guided percutaneous needle placement teaching and training. In order to support these activities, we develop the Perk—“percutaneous”—Tutor as a free open-source software toolkit for clinical education researchers. The Perk Tutor provides a host of guidance techniques commonly available in clinical-grade image-guided needle placement navigation systems. The Perk Tutor can be rapidly configured between different clinical procedures and training scenarios without software development. The Perk Tutor aspires to provide a platform for education researchers to experiment with various training and performance evaluation schemes. Importantly, owing to the use of common platform, their methods and results will be reproducible and comparable.

In this paper, we explain the concept, design, architecture, and functions of Perk Tutor. We present examples for how it can be configured between clinical applications and training scenarios. We review directions of ongoing work. Finally, we explain how researchers can obtain and use the Perk Tutor for their own studies.

## II. MATERIALS AND METHODS

We envision laboratory technicians at teaching institutions to configure the Perk Tutor for a specific clinical procedure, tune training scenarios, and replicate or purchase the requisite phantom. After such configuration, the Perk Tutor would allow deliberate practice for students without supervision, and provide continuous, quantitative feedback on their performance. The main requirement for the Perk Tutor was to make it accessible and configurable for end users at a technician level of expertise. Although the concept to a large extent is invariant to image guidance modalities, clinical procedures, and anatomical sites, the first uses of the Perk Tutor are US-guided percutaneous spinal needle placement and transrectal prostate biopsy.

Following previous works on surgical skill assessment, the Perk Tutor employs electromagnetic (EM) tracking for localizing the US-imaging probe and the surgical needle in space and time, from which performance metrics are computed.

### A. Overview of Perk Tutor

The Perk Tutor’s hardware components—illustrated in Fig. 1—are the US computer, the Perk Tutor computer, tracked US probe, tracked needle, phantom with attached reference position sensor, and the EM tracker device. The US computer handles image and tracking data acquisition, while the Perk Tutor computer runs the Perk Tutor software. The US computer and the Perk Tutor computer are connected through a standard network connection. The tracker interacts with the position

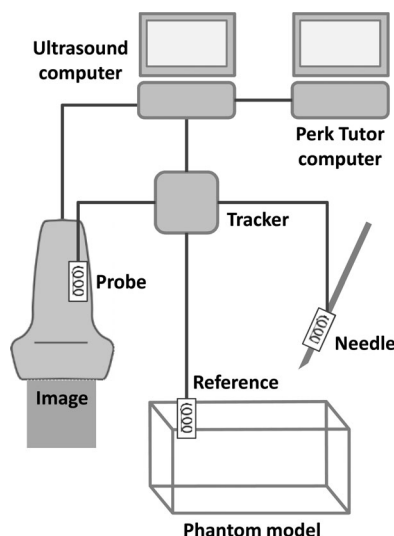


Fig. 1. Main hardware components of the Perk Tutor. Here, the boxed coils in the needle, probe, and phantom model represent the position sensors monitored by the tracker.

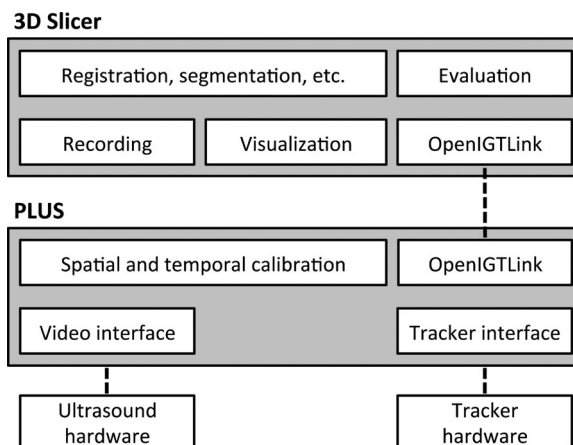


Fig. 2. Software architecture of the Perk Tutor.

sensors embedded in the US probe, the needle, and the phantom model.

The software components of the Perk Tutor are shown in Fig. 2. Software components for US image acquisition and position tracking data collection are implemented using the PLUS (Public Library for US) open-source software package<sup>1</sup>. *PlusServer*—an application in the PLUS package—connects the US video source and tracker systems and transmits the synchronized tracked US image data to the Perk Tutor computer using the OpenIGTLink network protocol [19].

The Perk Tutor’s graphical user interface (GUI) is implemented as interactive 3D Slicer<sup>2</sup> modules. The OpenIGTLink IF module of 3D Slicer is used to receive the tracked US image data stream from the *PlusServer* application. Specific functionalities required by Perk Tutor—not available in the 3D Slicer application—are bundled in an extension (PerkNav)

<sup>1</sup><https://www.assembla.com/spaces/plus>  
<https://www.assembla.com/spaces/slicerigt>  
<sup>2</sup>[www.slicer.org](http://www.slicer.org)

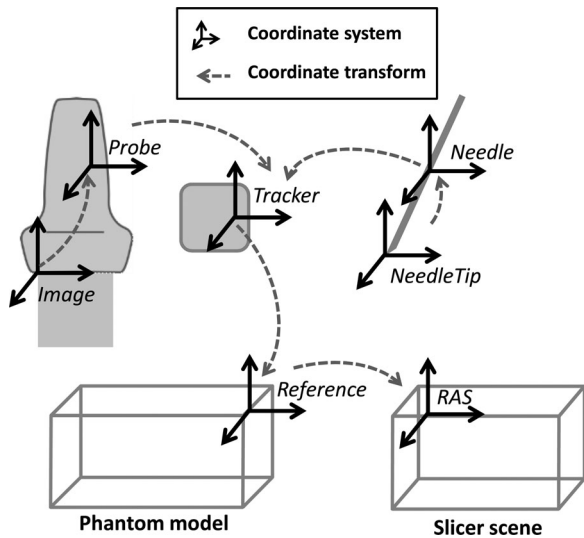


Fig. 3. Important Perk Tutor coordinate systems and transformations.

downloadable from the 3D Slicer Extension Manager. In particular, custom modules are written to allow for real-time US visualization (Live US), trajectory recording of probe and needle motion (Transform Recorder) and offline analysis of recorded trajectories (Perk Procedure Evaluator). All of Perk Tutor’s 3D Slicer modules are freely available from an open-source repository<sup>3</sup>.

### B. Calibration of Perk Tutor

Calibration of the Perk Tutor is necessary to allow the tracked tools—US probe, needle, and phantom model—to be displayed in a common coordinate system. The pertinent Perk Tutor coordinate systems and the transforms between them are shown in Fig. 3.

The Perk Tutor’s GUI makes use of the standard 3D Slicer viewports, which adopt a patient-based coordinate system. In particular, the main axes of the Perk Tutor’s display coordinate system are along the right, anterior, and superior (RAS) anatomical directions. A series of linear rigid transformations is used to convert the 3D Slicer models of the tracked objects into the RAS coordinate system. To avoid confusion, coordinate transforms are labeled using an unambiguous naming convention, which is applied to the source code, configuration files, documentation, and GUI. This convention specifies that  $T_{A \text{ To } B}$  denotes the transformation that maps an object expressed in coordinate frame  $A$  to coordinate frame  $B$ . Using this convention, the position of the reference EM sensor affixed to the phantom model is computed in the RAS coordinate frame using the following equation:

$$P_{\text{RAS}} = T_{\text{ReferenceToRAS}} \cdot P_{\text{Reference}} \quad (1)$$

where the transformation matrix  $T_{\text{ReferenceToRAS}}$  is computed through a registration process that correlates physical landmarks on the phantom model to corresponding positions on the graphical model of the phantom in the RAS coordinate frame [20].

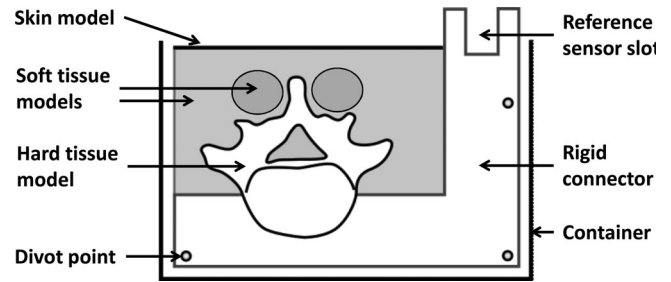


Fig. 4. Main components of a Perk Tutor phantom model.

To transform the needle tip and US image positions to the RAS coordinate frame, the first step is to map these positions to the Reference coordinate frame. This can be done using the following two equations:

$$P_{\text{Reference}} = T_{\text{TrackerToReference}} \cdot T_{\text{NeedleToTracker}} \cdot T_{\text{NeedleTipToNeedle}} \cdot P_{\text{NeedleTip}} \quad (2)$$

$$P_{\text{Reference}} = T_{\text{TrackerToReference}} \cdot T_{\text{ProbeToTracker}} \cdot T_{\text{ImageToProbe}} \cdot P_{\text{Image}} \quad (3)$$

where  $T_{\text{NeedleTipToNeedle}}$ —often called the needle calibration transformation—accounts for difference in the position of the needle’s sensor and the position of the needle tip. This transformation is computed by fixing the needle tip and subsequently pivoting the needle base in a spherical motion [21]. The transformation  $T_{\text{ImageToProbe}}$ —often called the US probe calibration transformation—is computed using a pose recovery scheme based on a multiple N-wire calibration phantom [22]. The transformations  $T_{\text{NeedleToTracker}}$  and  $T_{\text{ProbeToTracker}}$  are directly acquired by the tracker system using the embedded EM position sensors in the needle and the US transducer, respectively. Finally,  $T_{\text{TrackerToReference}}$  is formed by inverting the  $T_{\text{ReferenceToTracker}}$  transformation given by the tracker using the reference sensor embedded in the phantom. Once the needle tip and image positions have been expressed in the reference coordinate frame using (2)-(3), they can be subsequently mapped into RAS coordinate frame via (1).

### C. Perk Tutor Phantom Models

Phantom models can be built in-house if the desired model is not available commercially, or to reduce costs. Components of a typical Perk Tutor phantom model are shown in Fig. 4. Although a spine-based phantom is shown in this illustration, the basic components can be combined in different configurations to adapt to any anatomical region of interest or an abstract geometrical target.

Using this simple design for the Perk Tutor phantoms, custom models can be quickly and easily created. The first step to designing a custom Perk Tutor phantom is to create a mechanical design of the rigid model portions: the hard tissue (bone) model, the reference sensor holder slot, and the rigid connector part. This step can be accomplished using mechanical modeling software (Solid Edge ST5, Siemens PLM, Plano, TX). When creating the rigid phantom portions, it is important to include a

<sup>3</sup>[www.assembla.com/spaces/slicerigt](http://www.assembla.com/spaces/slicerigt)

minimum of three pivot points for landmark-based calibration. The pivot points are optimally placed on all sides of the working volume to minimize the registration error between the reference and RAS coordinate systems. After the individual rigid components have been created, they should be fused together to form a single rigid body. At this point, the rigid portions of the model are ready to be fabricated. The soft tissue portions of in the Perk Tutor are modeled with a gel having tissue-like acoustic and mechanical properties. Gels of varying consistencies may be layered to simulate different tissue regions, such as muscle and fat. See [23] for a review on tissue substitutes for US imaging. Finally, the soft-tissue gel is covered with a rubber sheet, simulating patient's skin. The size and shape of the whole phantom ideally corresponds to the simulated body part to enhance face validity.

In addition to the Perk Tutor phantom components discussed earlier, other supplementary objects can be embedded in the soft-tissue gel. For example, a liquid filled rubber tube can be placed within a soft tissue model to simulate the spinal canal or blood vessels. Various options and ready CAD models are available from the Perk Tutor website.

#### D. Recording and Analysis of Needle Trajectories

The Perk Tutor uses an infrastructure for recording and analyzing needle trajectories previously described in [24]. The transform recorder module of the Perk Tutor is used to record needle motion by observing the tracked needle transformation object through the MRML software architecture of 3D Slicer [25]. Each change in the tracked needle transformation is time stamped, logged, and saved to an XML file, creating a needle trajectory. The XML files can then be loaded into the Perk Procedure evaluator module for offline trajectory analysis. Currently, the Perk Procedure evaluator is capable of computing the procedure time, accuracy metrics, path length for the needle and the probe, and potential tissue damage. Since needle motion inside the soft tissue is of greater importance than needle motion outside the tissue, virtual surgical shapes are modeled in Perk Procedure evaluator (*vtkMRMLSurgicalShape*) allowing needle motion to be separated into in-tissue and out-of-tissue components. For this purpose, a combination of virtual prism shapes (*vtkMRMLPrismShape*) is used to represent the soft-tissue gel portion of the Perk Tutor phantom models. Additional metrics for both recorded and real-time motion analysis can be developed and easily added using Perk Tutor's modular and open-source architecture. For performance metrics that require simple distance between a target point and tracked objects, the standard measurement module of 3D Slicer is used.

#### E. Experimental Configurations of Perk Tutor

To evaluate Perk Tutor's configurability, we opted to test the configurations, each corresponding to a different training or clinical procedure: the Targeting Tutor configuration, the Lumbar Tutor configuration and the Prostate Biopsy Tutor configuration. An overview of learning objectives of these three training configurations is summarized in Table I.

TABLE I  
LEARNING OBJECTIVES FOR PERK TUTOR CONFIGURATIONS

Configuration	Learning Objectives
Targeting Tutor	Hand-eye coordination in US-guided needle insertion; minimize needle-target distance.
Lumbar Tutor	Familiarize with US anatomy of the spine; guide needle into anatomical targets.
Prostate Biopsy Tutor	Spatial distribution of biopsy cores; insert needle into all prostate segments.

The learning objective corresponding to the first Perk Tutor training configuration—the Targeting Tutor—is improving accuracy of US-guided needle placement. This configuration is intended to introduce the trainee to the basic skills of US-guided needle placement and makes no effort to mimic anatomy.

The learning objectives corresponding to the second Perk Tutor training configuration—the Lumbar Tutor—are: 1) recognition of lumbar spine landmarks in US images and 2) developing proficiency at US-guided needle placement in the lumbar spine region. This configuration was chosen due to the importance of US-guided needle insertion in the lumbar spine region. Related procedures range from epidural anesthesia to lumbar punctures and facet joint injections.

The learning objective corresponding to the third Perk Tutor configuration—the Prostate Biopsy Tutor—is improving transrectal US-guided prostate biopsy skills. In prostate biopsy procedures, diagnostic success relies on distributing biopsy cores so that they cover all prostate segments [11]. Accordingly, the spatial distribution of prostate cores needs to be used as a feedback metric in the Prostate Biopsy Tutor designed.

#### F. Perk Tutor Configuration Process

The configuration of the Perk Tutor to achieve specific learning objectives consists of three main steps: 1) build the target phantom model, 2) configure the PLUS software by editing its XML configuration file, 3) create the 3D Slicer configuration scene.

The rigid component of the Targeting Phantom was designed using Solid Edge ST3 software (Siemens PLM Software, Plano, TX), and fabricated using a rapid prototype printer. The rigid connector part of the Lumbar Phantom was also designed using Solid Edge ST3 software, while the anatomical shape was manually created using the Editor module of 3D Slicer to extract bone contours from a patient CT dataset. It was also built using a rapid prototype printer. For the Prostate Biopsy Phantom, we used a commercially available plastic prostate model, the Model 053 US Prostate Training Phantom (CIRS, Norfolk, VA).

US images were acquired using a Sonix Tablet (Ultrasonix, Richmond, BC, Canada) US machine for all Perk Tutor configurations. Integrated GPS extension of the Sonix Tablet machine was used for EM tracking. This tracking extension is comprised of a DriveBay EM tracker (Ascension, Burlington, VT), and an adjustable arm that holds the electromagnetic transmitter. For the Targeting Tutor and the Lumbar Tutor, US imaging was

TABLE II  
DESIGN AND PROCEDURE-SPECIFIC FEEDBACK METRICS

Configuration	Design	Specific feedback
Targeting Tutor	Point target(s) in clear soft tissue model	Distance between needle tip and target point
Lumbar Tutor	Lumbar spine model in soft tissue model	US image and needle tip position relative to target
Prostate Biopsy Tutor	Soft tissue rectum and prostate models	Number of prostate segments reached

performed using an L14/5GPS linear array transducer (Ultrasonix). The L14/5GPS features an integrated electromagnetic position sensor, which allowed the  $T_{\text{ProbeToTracker}}$  transformation to be tracked in real time. For the Prostate Biopsy Tutor, an EC9/5 endocavity transducer (Ultrasonix) was used. Unlike the L14/5GPS, the EC9/5 does not have an integrated position sensor; therefore, a Model 800 electromagnetic sensor (ascension) was attached to the probe to obtain the  $T_{\text{ProbeToTracker}}$  transformations.

3D Slicer scenes are created for different Perk Tutor configurations by loading the 3-D graphic models of the system components (target phantom, needle, and US probe) and determining the transforms for the appropriate spatial relationships between the models (system calibration). 3-D models for the Targeting Phantom and the Lumbar Phantom were created during their design process, and are available freely in the public domain from the Perk Tutor website. A 3-D model for the Prostate Biopsy Phantom was created using the Editor module of 3D Slicer by manual contouring of a 3-D US volume reconstructed from 2-D tracked US images using the PLUS software package.  $T_{\text{ReferenceToRAS}}$  was computed using the Fiducial Registration module of 3D Slicer for the Targeting and Lumbar Tutors. In the Prostate Biopsy Tutor  $T_{\text{ReferenceToRAS}}$  was the identity transform, since the 3-D prostate model was directly derived from tracked US data. Calibration transforms for the US probe ( $T_{\text{ImageToProbe}}$ ) and the needle ( $T_{\text{StylusTipToStylus}}$ ) were obtained using the fCal application from the PLUS software package.

### III. RESULTS

To test Perk Tutor's reconfigurable design, we implemented the three aforementioned US-guided training scenarios: the Targeting Tutor, the Lumbar Tutor, and the Prostate Biopsy Tutor. The Perk Tutor was found to easily accommodate the three training configurations. Trainees of all configurations benefit from common needle trajectory feedback metrics, such as procedure time, needle path length, and potential tissue damage. The design and specific performance metrics for configurations are summarized in Table II. A brief discussion of each implemented configuration is given as follows.

The Targeting Tutor (see Fig. 5) makes use of the Targeting Phantom, which is a synthetic model comprised of a set of simple geometrical targets at varying depths; a target is specified as the circular planar area at the tips of the four vertical posts

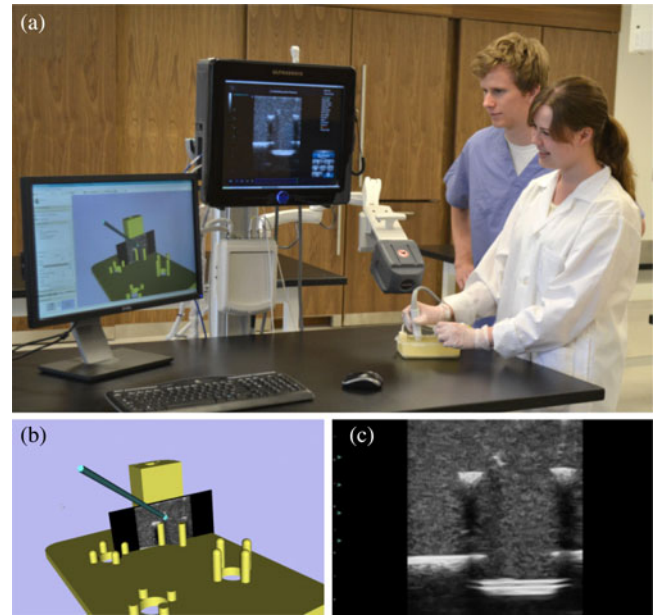


Fig. 5. Targeting Tutor in use (A) US image of the vertical posts and (C) US image overlay on virtual Targeting Tutor model. (B) Cyan rod is the virtual needle.

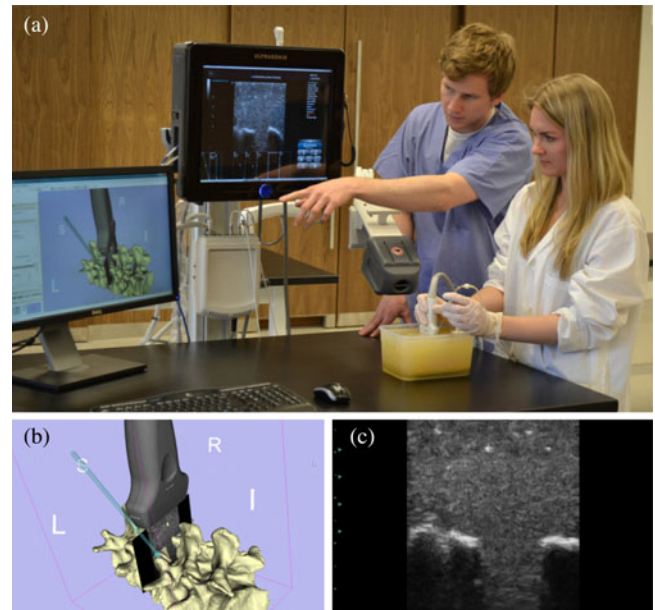


Fig. 6. Lumbar Tutor in use (A) US image of the Lumbar Phantom's spinous process and (C) US image overlay on virtual lumbar spine model. (B) Cyan rod is the virtual needle.

[see Fig. 5(b)]. The US transducer can be positioned above the targets, so that the reflection of two of the posts appears in the US image. Trainees are tasked with inserting the needle between the posts, into the target region. Fig. 5(a) shows a photograph of the Targeting Tutor in use. Specific performance feedback is given to the trainees using the distance between the tracked needle tip and the ideal target position of the phantom.

The Lumbar Tutor utilizes the Lumbar Phantom (see Fig. 6). The first learning objective in this configuration, recognition of

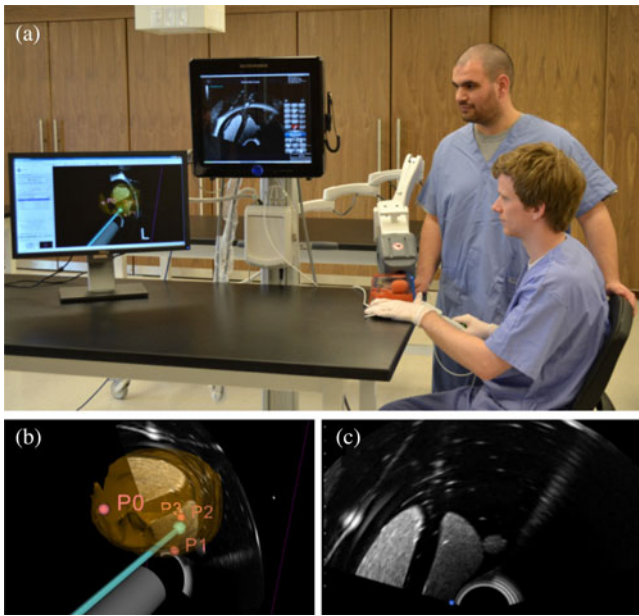


Fig. 7. Prostate Biopsy Tutor in use (A) US image of Prostate Phantom and (C) US image overlay on virtual prostate model. (B) Cyan rod is the virtual needle.

the spinal anatomical landmarks in US images is achieved by direct visual feedback in the 3-D display, whether the tracked US image plane intersects the target anatomical structure or not. The second learning objective of the Lumbar Tutor, needle navigation to anatomical targets is supported by the tracked needle model. Feedback on success or failure of needle placement is determined using recorded needle tip positions relative to the anatomical target areas.

The Prostate Biopsy Tutor utilizes the Prostate Biopsy Phantom, which consists of two different soft tissue types: one for the prostate gland and one for the surrounding tissue (see Fig. 7). A photograph of the Prostate Biopsy Tutor in use is shown in Fig. 7(a). The Prostate Biopsy Tutor offers a quantitative check by the number of prostate segments reached and visualizes biopsy positions relative to the prostate contour.

#### IV. DISCUSSION

The Perk Tutor is a configurable open-source training platform for US-guided interventions. We tested the configurable design of the Perk Tutor in three training scenarios for targeting, lumbar needle placement, and prostate biopsy tutoring. These experiments show the ability of the Perk Tutor to accommodate different clinical applications and different learning objectives without software or hardware design work.

The Perk Tutor has the advantage of providing continuous quantitative feedback for the trainee during practice, which is not available in the traditional apprenticeship approach. As well, the Perk Tutor allows trainees to practice at their own pace to the point of mastery, without the stress of a real clinical situation. This makes transition to clinical procedures easier for the trainees, when they have the necessary procedures practiced to the point of automatic execution. A recent review by McGaghie

*et al.* concluded that simulation-based education is superior to traditional clinical education in a wide range of interventional procedures [3]. Feedback from supervisors is hampered by subjectivity, which strengthened the need for objective performance measures [26]. The Perk Tutor addresses this issue by providing computer-generated metrics and performance benchmarks. There has been significant interest in simulators for US-guided needle interventions [5]–[9]. There are currently three major and somewhat interrelated drawbacks to existing simulators: procedural specificity, lack of access for education researchers, and high cost. The Perk Tutor addresses all of these shortcomings. The configurable design of the Perk Tutor allows users to customize the system to serve their own particular training objectives. The Perk Tutor is distributed as an open-source toolkit for education researchers who can freely modify its functionality. Open-source fosters collaboration and standardization among educational researchers. We expect that upon gathering a critical mass of researchers, those users will enrich the Perk Tutor with custom modules. The Perk Tutor is a work in progress that we consider as a seedling to arouse the interest of education researchers who will either modify the open-source system or provide us with requests for modifications and new features. To assess the effect of the Perk Tutor on skill development and retention requires further investigations. We believe that multicenter studies will follow, owing to the openness and accessibility of the Perk Tutor.

We are currently implementing new features, such as incorporating in the quantitative evaluation how the trainee positions the US probe. Measurement data for this are readily available, as the Perk Tutor tracks both the needle and the US probe in both space and time. A related limitation is that the current Perk Tutor focuses on the execution of the US-guided needle placement, while the planning and confirmation of the procedure are also important parts of the intervention as a whole.

In deploying the Perk Tutor, setup calibration and learning how to operate the graphical user interface required a few days of technician training for a new user. To some extent, this is a reflection of the tradeoff between simplicity and flexibility. To maintain the configurable design of the Perk Tutor, new users need to invest considerable time in initial training. It is our opinion, however, that the overall benefits of a configurable system far outweigh the pains of the steep initial learning curve. As configuring Perk Tutor to new applications does not involve software development, it is accessible to a broad range of users. Learning how to use the Perk Tutor is significantly easier and less costly than implementing a system for each procedure. The open-source software significantly offsets the cost of a training system. The price of the Perk Tutor is further moderated by allowing users to fabricate their own phantoms. Alternatively, users may purchase commercial phantoms and equip those with EM tracking by following instructions for assembly and calibration provided on the Perk Tutor website. The incorporated EM tracker device and the laptop computer are additional cost items.

The Perk Tutor is distributed under a Berkeley Source Distribution (BSD)-style open-source license that contains no restrictions on use of the software, phantom design, or documentation.

The authors intend to encourage usage of the software in open-source and commercial applications alike. Collaborative development is supported by the Perk Tutor website, where source code, issue tracking, wiki documentation, events, and meetings are accessible freely at [www.assembla.com/spaces/slicerigt](http://www.assembla.com/spaces/slicerigt).

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Authors' photographs and biographies not available at the time of publication.