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Towards an Advanced Virtual Ultrasound-guided Renal Biopsy Trainer

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Abstract

Ultrasound (US)-guided renal biopsy is a critically important tool in the evaluation and management of non-malignant renal pathologies with diagnostic and prognostic significance. It requires a good biopsy technique and skill to safely and consistently obtain high yield biopsy samples for tissue analysis. This project aims to develop a virtual trainer to help clinicians to improve procedural skill competence in real-time ultrasound-guided renal biopsy. This paper presents a cost-effective, high-fidelity trainer built using low-cost hardware components and open source visualization and interactive simulation libraries: interactive medical simulation toolkit (iMSTK) and 3D Slicer. We used a physical mannequin to simulate the tactile feedback that trainees experience while scanning a real patient and to provide trainees with spatial awareness of the US scanning plane with respect to the patient's anatomy. The ultrasound probe and biopsy needle were modeled using commonly used clinical tools and were instrumented to communicate with the simulator. 3D Slicer was used to visualize an image sliced from a pre-acquired 3-D ultrasound volume based on the location of the probe, with a realistic needle rendering. The simulation engine in iMSTK modeled the interaction between the needle and the virtual tissue to generate visual deformations on the tissue and tactile forces on the needle which are transmitted to the needle that the user holds. Initial testing has shown promising results with respect to quality of simulated images and system responsiveness. Further evaluation by clinicians is planned for the next stage.

Keywords

Ultrasound; virtual training; kidney biopsy; needle to tissue interaction

1. INTRODUCTION

Ultrasound-guided kidney biopsy is a critically important tool in the evaluation and management of focal renal lesions such as malignancy and infection as well as diffuse primary parenchymal processes such as nephropathy or transplant rejection[1]. The overall

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prevalence of chronic kidney disease (CKD) in the general population is approximately 14 percent with more than 661,000 Americans suffer from kidney failure[2]. Ultrasound-guidance (USG) is becoming the standard of care for needle insertion procedures (Figure 1) due to increased safety, improved outcomes, and reduced patient discomfort and complications[3]. Ultrasound guided procedures offer economic advantages including reduced costs from a decrease in the needs for management of adverse effects. Furthermore, USG has replaced more expensive and cumbersome x-ray-based guidance systems such as CT and fluoroscopy that also expose patients and physicians to ionizing radiation.

USG needle biopsy skill training using the traditional apprenticeship model is inefficient and lacks objective metrics for post-training performance assessment[5]. Hence, there is an increasing need to develop alternative training methods such as virtual simulators that could provide objective measures of performance. Simulation-based medical education removes the patient from the early stages of the learning curve. It has been shown to be superior to traditional clinical medical education and is recommended for achieving clinical skills[6]. Simulation will play an increasingly important part in the training and assessment of procedural skills because it allows for deliberate practice with opportunities for immediate feedback without risk to patient[7].

There are several alternatives to virtual simulation-based procedure and anatomy trainers. Animal models are an alternative training option that are widely available, have anatomic structures including blood vessels, bones and nerves, and the ability to imbed differentiable physical targets in the model. These allow a realistic feel of tissue handling and ultrasound image acquisition for the learner. However, animal models have several disadvantages including high cost, the need for infection control, a limited shelf life of a few days, the need for refrigeration, and the time needed to prepare the model with the targets.

Physical phantoms are another training option. One popular product in the market is the Blue Phantom[8]. The advantages of Blue Phantom include portability, a large scanning surface, long shelf life and reusability. The disadvantages include high cost, fixed targets with no ability to embed additional targets, visibility of prior needle tracks and unrealistic tissue force feedback. After wear from repeated usage, phantoms develop needle injection patterns which students can copy diminishing learning outcomes. Furthermore, in these types of simulators, users obtain valuable psychomotor skills but no rigorous education in the relevant ultrasound anatomy, due to the lack of realism in the ultrasound images generated by the artificial tissue.

Broadly speaking, a virtual ultrasound-guided renal biopsy trainer will accelerate the training of ultrasound-guided renal biopsy in a risk-free environment, and ultimately improve the safety of kidney biopsy and ensuring that the biopsy procedure yields high quality specimen. Specifically, the system will benefit radiologists, nephrologists, and interventional radiologists in (a) improving 3D spatial awareness, (b) in better interpretation of ultrasound images during needle biopsy, (c) improving bi-manual dexterity while coordinating the needle and the probe movements and (d) better interpretation of the tactile feedback felt at the needle. Currently, commercially available ultrasound-guided procedure simulators employ physical based phantoms that are not widely used due to their cost, unrealistic response and limited scope of objective feedback and guided training[9]. In such simulators, users obtain valuable psychomotor skills but no rigorous education in the relevant ultrasound anatomy and, no realistic tactile feedback; and they also lack objective metrics including post-training performance assessment. Hence, there is a need for a cost-effective virtual simulator that will help clinicians train on their ultrasound imaging interpretation skills specific for performing a needle biopsy and their manual dexterity in needle handling with the aid of tactile feedback.

2. METHODS

We developed a real-time US guided, multimodal (visual and haptic feedback) simulator for kidney biopsy training tasks. The simulator consists of easily acquired low-cost hardware components and powerful open source computing libraries.

2.1 Hardware

The Kidney Biopsy Virtual Trainer (KBVTrainer) simulator consists of a) a realistic torso mannequin, b) dummy ultrasound probe, c) dummy biopsy needle, d) electromagnetic tracker (Ascension 3D Guidance trakSTAR) to track the position and orientation of the ultrasound probe, e) haptic device (3D Systems Geomagic Touch) for force feedback at the needle, and f) an open source software interface using 3D Slicer, PLUS Toolkit, and iMSTK. The overall cost of the system hardware is low: ~$3000 for the haptic device, ~$5000 for the magnetic tracker, and ~$2000 for the computer system. The other components were sourced from discount retailers for <$150. The individual hardware components are shown in Figure 2.

2.2 Software Implementation

Visualization and hardware interfacing for the trainer were provided by 3D Slicer and PLUS Toolkit respectively. 3D Slicer is an open source platform for medical image analysis and visualization[10]. It provides powerful out-of-the-box capabilities for image re-slicing, fiducial registration and many other functions for image-guided therapy. PLUS Toolkit is an open source package that specializes in hardware interfacing and data acquisition for medical imaging[11]. PLUS manages the hardware interface for the Ascension 3DG magnetic tracker. PLUS has a well-supported interface with 3D Slicer through OpenIGTLink[12]. OpenIGTLink is an open source network communication protocol for transmitting data for image-guided therapies. A server/client connection is created between PLUS and 3D Slicer to provide the real-time tracking data. The OpenIGTLink functionality for 3D Slicer is encapsulated in the SlicerOpenIGTLink extension. In our implementation, this connection was made locally on a single system, but this information can be sent between computers using this network model. To model needle to tissue interaction, we used iMSTK, an open-source, interactive medical simulation toolkit designed for rapid prototyping of interactive simulation applications. iMSTK provides an easy to use framework that can be extended and interfaced with other third party libraries for the development of medical simulators without restrictive licenses[13]. iMSTK is also used to interface with the 3D Systems Geomagic Touch haptic device. Direct interfacing of the simulation library and the haptic device was done in this case to minimize any lag when interacting with the tissue models. Use of these libraries as a platform allowed for rapid prototyping of the simulator. All of these open source libraries have commercialization friendly licenses.

The workflow of the system is detailed in Figure 3. The Slicer application receives tracking data of the US probe dummy from a magnetically tracked sensor from a PLUS Server over a local network connection. Using the probe's tracking information, the pre-acquired US volume is resliced along the plane of the probe in order to generate an image that reflects the current location and orientation of the probe w.r.t the mannequin. A synthetic image of the needle that resembles the appropriate ultrasound appearance is generated using the needle's pose obtained from the iMSTK simulation as input. This image is fused with the ultrasound image to emulate the real needle inside the tissue (Figure 2). Deformation data from the needle-tissue interaction will then be used to deform the displayed ultrasound volume, showing real-time "interaction" with the image. The computed force data from the needle-tissue interaction model is transmitted back to the haptic device through PLUS interface allowing the user to experience the tactile feedback.

2.3 Needle-Tissue Interaction Model

Using the pre-acquired 3-D ultrasound volume, we generated geometric models of the organs and tissues that the needle passes through to reach the target area inside the kidney. For the tip of the needle to reach the target area inside the kidney, it needs to travel through various layers of heterogeneous tissue (skin, subcutaneous fat, muscle, retroperitoneal fat etc.). Each tissue layer poses different levels of resistance to the movement of the needle. To develop a high-fidelity needle-tissue interaction, it is paramount to (a) model and simulate the deformations of various tissue layers that are coupled with the needle motion (b) estimate the frictional forces between the walls of the needle with the tissue surrounding it and (c) estimate puncture forces given the shape of the needle tip.

The kidney models were generated from a manual segmentation of the kidney by an expert in the pre-acquired 3D ultrasound volume. 3D Slicer's segmentation tools (flying edges algorithm) were used to create a surface mesh from the segmentation. This mesh is further processed by smoothing and decimation in order to obtain a surface mesh. TetGen[14] was used to perform Delaunay tetrahedralization starting with the surface mesh from previous step. The kidney volume is modeled using co-rotational finite elements[15] discretized in time using backward Euler time stepping scheme. We use linear shape functions on the tetrahedral elements for the finite element formulation. The needle is modeled as an idealized rigid straight line controlled by an external user through manipulation of the haptic device. Such an idealization is justified since the bending in the needle observed during renal biopsy is limited. When the needle pierces the tissue volume, nearest node, measured by the least perpendicular distance to the needle axis, is projected to the needle and is constrained stay along the needle axis until it is released during retraction of the needle. Any new node that is added to the set of constrained nodes will be projected to the needle such that its distance to the needle tip is the least (compared to the ones already in the set). Further, nodes that are released (during needle retraction) should travel past the needle tip. This process emulates the needle insertion.

The nodes are constrained along the needle axis using orthogonal projection constraints given as aa^T, where a is the unit vector representing the axis of the needle (Figure 4). At any given time step, the set of constrained nodes (if any) need to be updated such that they remain along the axis of the needle at the end of solver update. In order to enforce this, we use *Modified Conjugate Gradient (MCG)* algorithm[16,17]. At any given time step we solve a linear system of equations $Kv = f$ emanating from the finite element model of the kidney tissue along with the constraints as $SKv = Sf$ where S is the global (encompassing all nodes) orthogonal projector which is obtained by block-diagonal assembly of the node-level orthogonal projectors $S_i = a_i a_i^T$ where v is the quantity that is being solved for. At the beginning of MCG iteration, the constrained node is projected back to the updated needle pose by finding the corresponding point on needle it was occupying in the previous time step. We also simulated the forces on the needle which will be experienced by the user through the haptic device. First, the forces perpendicular to the needle are computed as a post-processing step based on the current deformation of the kidney. The external force that the needle exerts on the tissue is balanced by the internal forces due to local strains on the nodes that are in contact with the needle. Second, the forces along the needle that provide the resistance to the advancement of the needle are simulated depending on the direction of motion of the constrained nodes along the needle axis. Further, this force is scaled depending on the sampled grayscale value from the original US. The needle-tissue interaction model described above was implemented in iMSTK.

3. RESULTS

The Kidney Biopsy Virtual Trainer (KBVTrainer) is the results of our efforts towards the goal of creating an effective open source trainer. We used a mannequin to simulate the tactile feedback that trainees experience while scanning a real patient and to provide trainees with spatial awareness of the US scanning plane with respect to the patient’s anatomy. The assembled system is shown in Figure 2, with hardware elements enumerated in the methods section labeled. Modules from the Slicer IGT extension[18] were used to manage the registration and calibration of the coordinate systems of the hardware device, and to drive the re-slicing of the US volume to obtain the displayed image. In our current system we used a kidney mesh composed of 2591 tetrahedral elements (Figure 5). With this mesh, the needle-tissue interaction simulation ran at 55–60 fps in iMSTK. The number of constrained points did not make a marked difference in convergence of the MCG and hence the simulation frame rate. Figure 5 also demonstrates the alignment between the original ultrasound data and the model used for finite element modeling. This alignment is critical so that tissue deformations produced by the force modeling can be accurately represented to the user.

Figure 6 shows the 3D Slicer based user interface of the KBVTrainer. The top of the side panel contains a number of view controls, including toggling between 3d (as seen in Figure 5) and 2d or slice (as seen in Figure 6) views of the kidney data and showing or hiding the kidney model overlays. The lower section of the panel contains scenario controls. This version of KBVTrainer implements a simplified biopsy scenario, where the user must locate the desired insertion plane of the needle into the lower pole of the kidney, insert the needle, verify its location, and then advance the needle into the target area of the kidney (outlined in red by the simulator). Once the task is completed the user can review their performance and see the path of the needle taken through the kidney model in the 3d view. Figure 7 shows a user performing the task, and the resulting path in the simulator. The user holds the probe in one hand and manipulates the needle in the other while monitoring the procedure on the simulator screen.

4. DISCUSSION AND FUTURE WORK

Using widely available hardware components and powerful open source libraries, we were able to rapidly build a low-cost virtual renal biopsy trainer. This trainer will be a powerful tool in helping train radiologists and nephrologists in spatial awareness, interpretation of US images during needle biopsy and improving bi-manual dexterity while using the US probe and the needle. Next, we will evaluate the prototype by conducting face and content validation studies. The system will be tested by experienced interventional radiologists. Face and content validation will collect subject rating of the graphics realism and responsiveness of the interface and force feedback. The real-time performance of the interactive model will be evaluated to determine whether it can provide visual and force feedback over 30Hz and 1kHz refresh rates, respectively, for high fidelity psychomotor skill training. The subjects will be asked to complete a questionnaire that rates the trainer in various aspects on a 5-point Likert scale. The questions will also investigate (1) ease of operating the system; (2) realistic appearance of the visualization module; (3) adequacy of force feedback; (4) mental and physical demand required when using the interface; and (5) potential areas of improvement for the interface and the whole system. This feedback will guide the on-going improvements to the system.

5. REFERENCES

[1]. Uppot RN, Harisinghani MG and Gervais DA, "Imaging-Guided Percutaneous Renal Biopsy: Rationale and Approach," Am. J. Roentgenol 194(6), 1443–1449 (2010). [PubMed: 20489082]

[2]. "Kidney Disease Statistics for the United States | NIDDK.", <https://www.niddk.nih.gov/health-information/health-statistics/kidney-disease.> (22 1 2019).

[3]. Slawsky K, McInnis M, Goss TF and Lee DW, "The clinical economics of ultrasound-guided procedures," Waukesha GE Healthc. (2011).

[4]. Yesudas SS, Georgy NK, Manickam S, Raheena a, Monai RC, Noble B. a and Pillai a., "Percutaneous real-time ultrasound-guided renal biopsy performed solely by nephrologists: A case series," Indian J. Nephrol 20(3), 137–141 (2010). [PubMed: 21072153]

[5]. Bridges M and Diamond DL, "The financial impact of teaching surgical residents in the operating room," Am. J. Surg 177(1), 28–32 (1999). [PubMed: 10037304]

[6]. McGaghie WC, Issenberg SB, Cohen ER, Barsuk JH and Wayne DB, "Does simulation-based medical education with deliberate practice yield better results than traditional clinical education? A meta-analytic comparative review of the evidence.," Acad. Med 86(6), 706–711 (2011). [PubMed: 21512370]

[7]. Farjad Sultan S, Shorten G and Iohom G, "Simulators for training in ultrasound guided procedures," Med. Ultrason 15(2), 125–131 (2013). [PubMed: 23702502]

[8]. "Blue Phantom Ultrasound Training Medical Models and Ultrasound Simulators.", <https://www.bluephantom.com/> (22 1 2019).

[9]. Blum T, Rieger A, Navab N, Friess H and Martignoni M, "A Review of Computer-Based Simulators for Ultrasound Training," Simul. Healthc. J. Soc. Simul. Healthc 8(2), 98–108 (2013).

[10]. Fedorov A, Beichel R, Kalpathy-Cramer J, Finet J, Fillion-Robin J-C, Pujol S, Bauer C, Jennings D, Fennessy F, Sonka M, Buatti J, Aylward S, Miller JV, Pieper S and Kikinis R, “3D Slicer as an image computing platform for the Quantitative Imaging Network,” Magn. Reson. Imaging 30(9), 1323–1341 (2012). [PubMed: 22770690]

[11]. Lasso A, Heffter T, Rankin A, Pinter C, Ungi T and Fichtinger G, “PLUS: Open-Source Toolkit for Ultrasound-Guided Intervention Systems,” IEEE Trans. Biomed. Eng 61(10), 2527–2537 (2014). [PubMed: 24833412]

[12]. Tokuda J, Fischer GS, Papademetris X, Yaniv Z, Ibanez L, Cheng P, Liu H, Blevins J, Arata J, Golby AJ, Kapur T, Pieper S, Burdette EC, Fichtinger G, Tempany CM and Hata N, “OpenIGTLink: an open network protocol for image-guided therapy environment.,” Int. J. Med. Robot 5(4), 423–434 (2009). [PubMed: 19621334]

[13]. Ortiz R, Arikatla S, Halic T, Radigan S, Girault A, De S and Enquobahrie A, “iMSTK: an open source interactive medical simulation toolkit,” CARS 2016—Computer Assist. Radiol. Surg. Proc. 30th Int. Congr. Exhib, Heidelberg, Germany (2016).

[14]. Si H, “TetGen, a Delaunay-Based Quality Tetrahedral Mesh Generator,” ACM Trans. Math. Softw (2015).

[15]. Felippa CA and Haugen B, “A unified formulation of small-strain corotational finite elements: I. Theory,” Comput. Methods Appl. Mech. Eng 194(21–24), 2285–2335 (2005).

[16]. Baraff D and Witkin A, “Large steps in cloth simulation,” Proc. 25th Annu. Conf. Comput. Graph. Interact. Tech. - SIGGRAPH ‘98, 43–54, ACM Press, New York, New York, USA (1998).

[17]. Ascher UM and Boxerman E, “On the modified conjugate gradient method in cloth simulation,” Vis. Comput 19(7–8), 526–531 (2003).

[18]. Ungi T, Lasso A and Fichtinger G, “Open-source platforms for navigated image-guided interventions,” Med. Image Anal. 33, 181–186 (2016). [PubMed: 27344106]

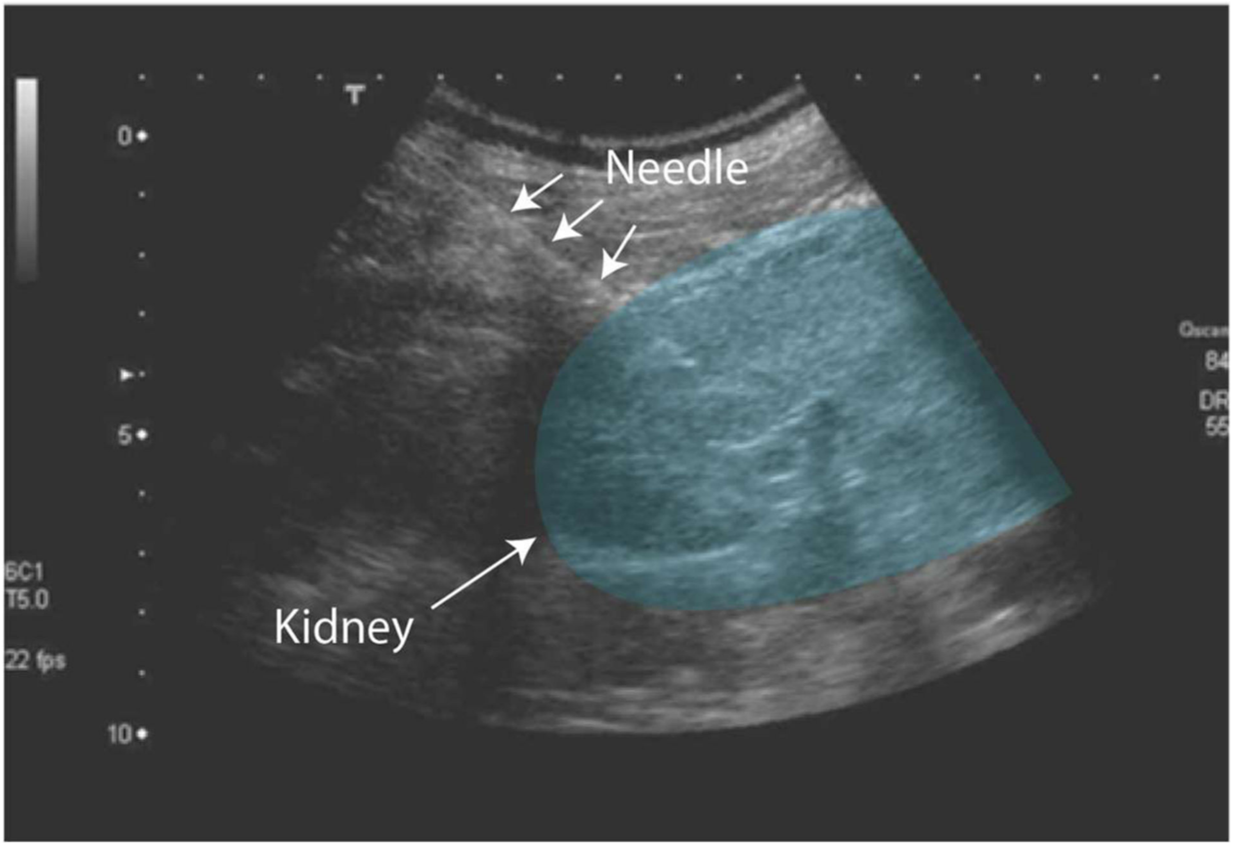


Figure 1.

Ultrasound of kidney during needle biopsy. The needle inserted into the lower pole of the kidney is indicated with arrows.

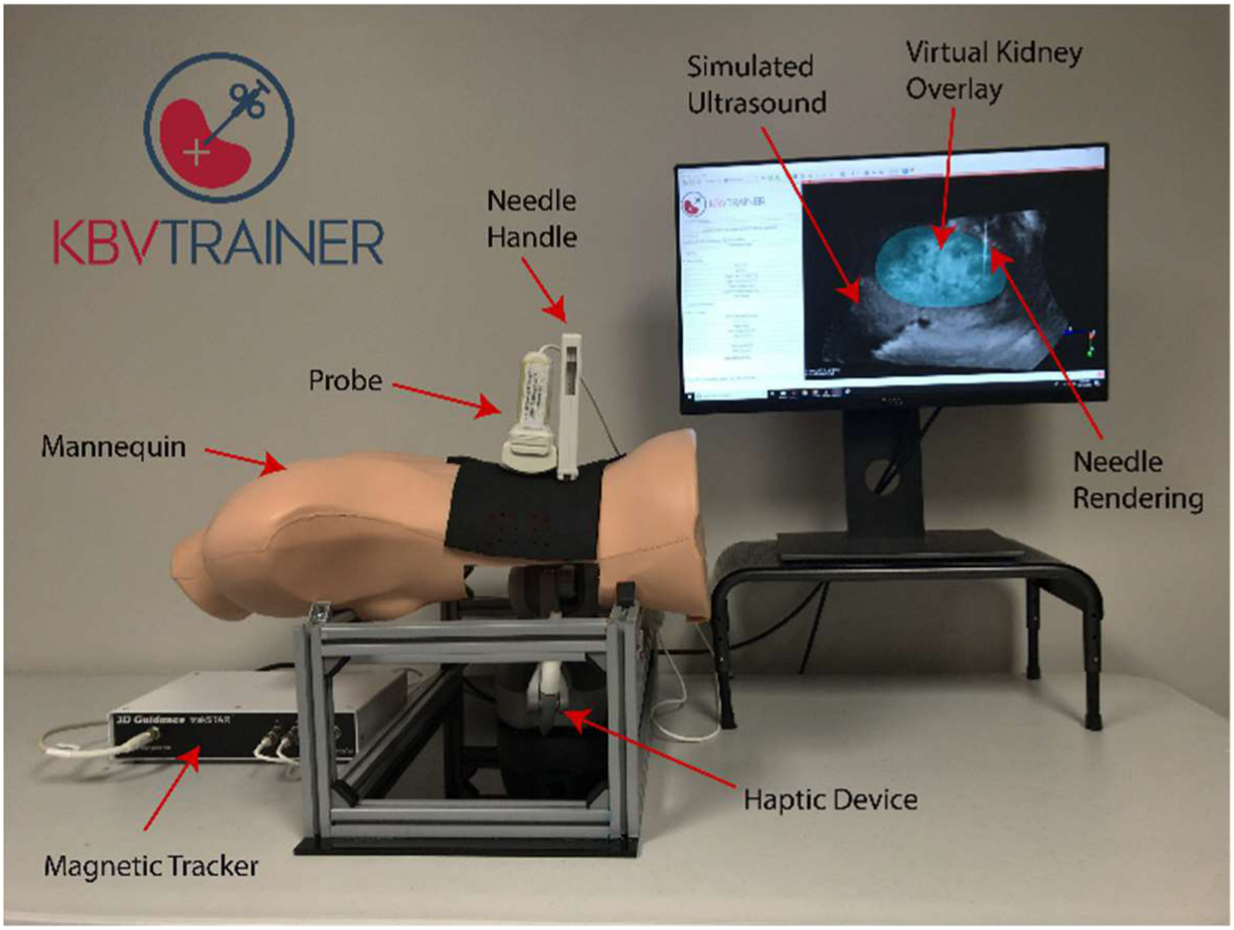


Figure 2.

Hardware components of the trainer

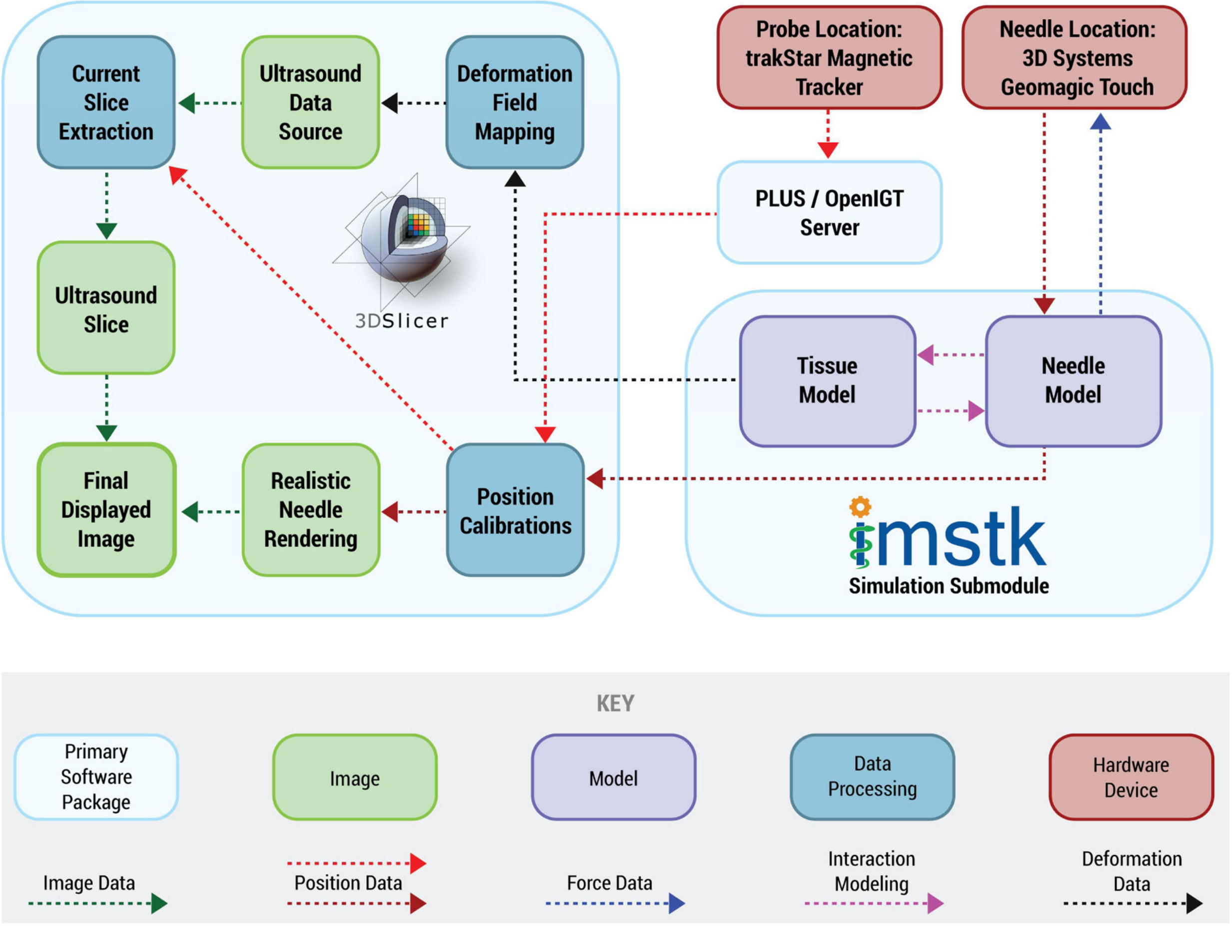


Figure 3.
KBVTrainer simulator software workflow

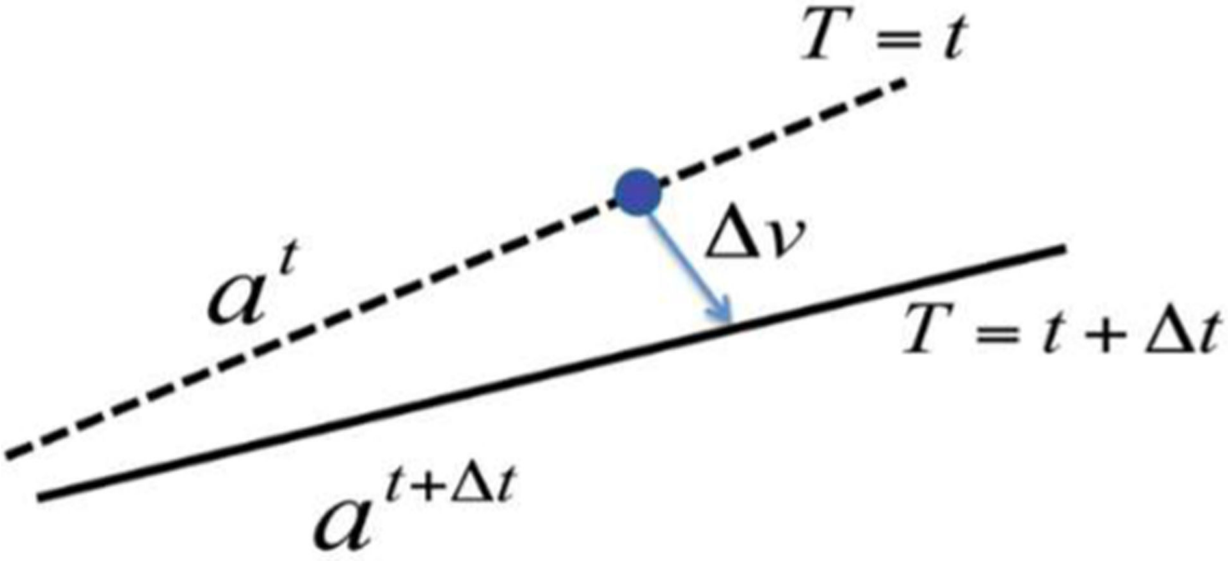


Figure 4.

The constrained node is projected to the updated needle axis at the beginning of every frame.

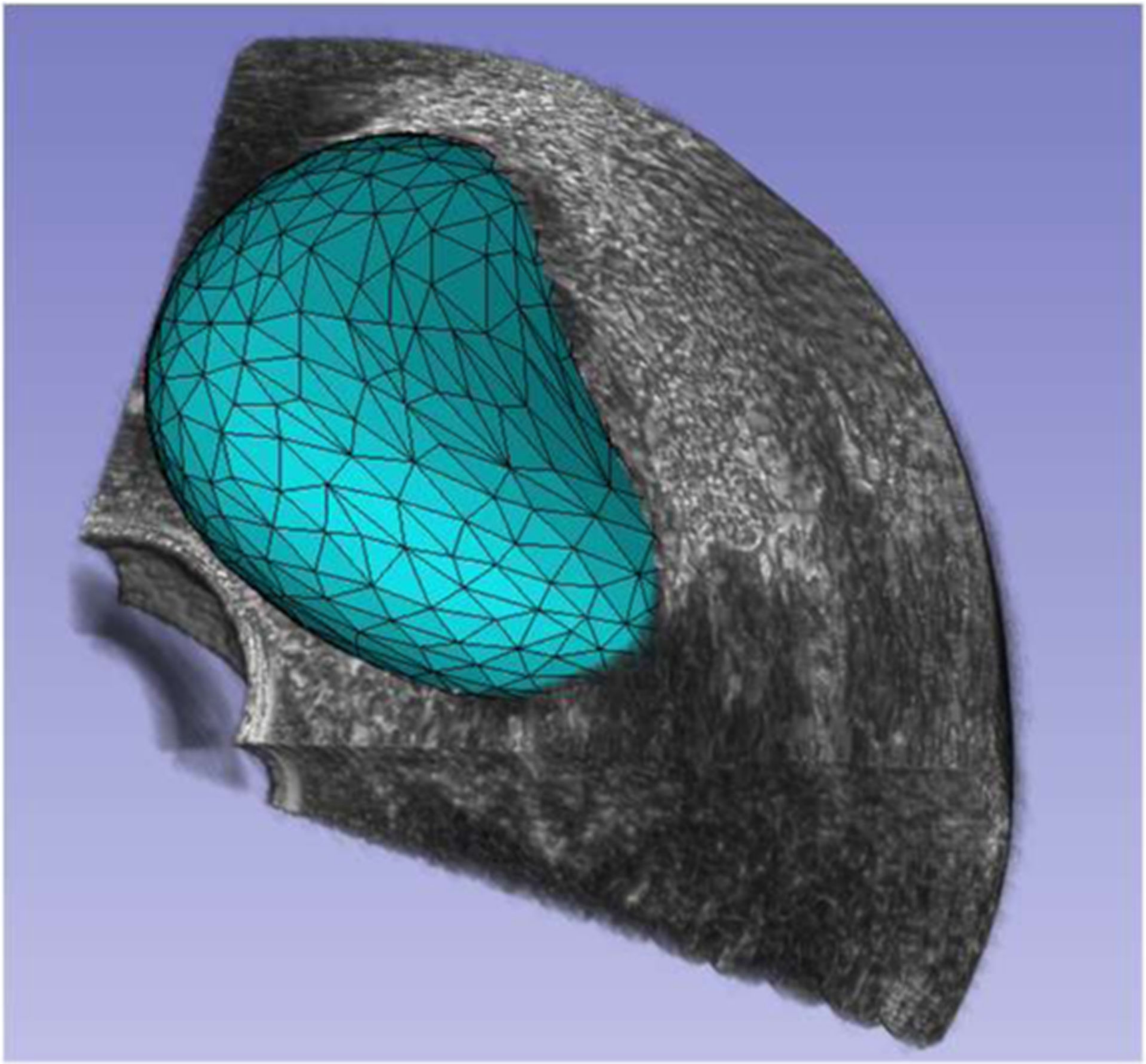
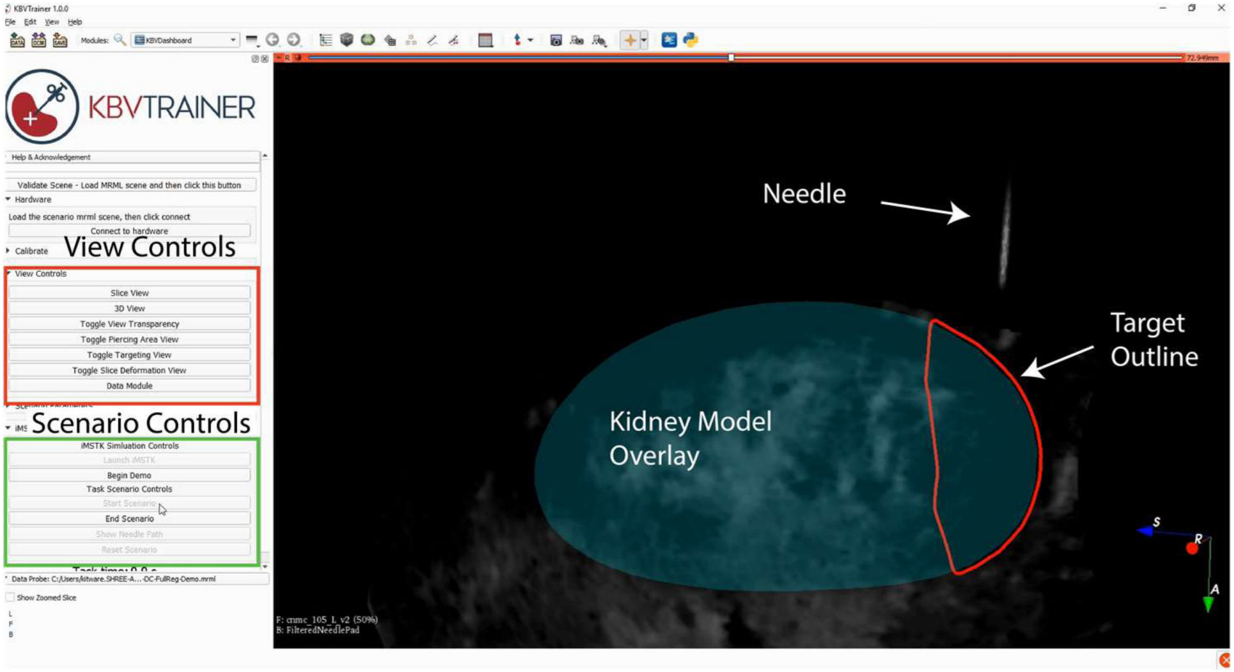


Figure 5.

Ultrasound volume rendering (gray) with registered tetrahedral kidney model (blue).



Load the scenario mrml scene, then click connect

Data Probe: C:/Users/kitware.SHREE-A…-DC-FullReg-Demo.mrml

Figure 6.

KBVTrainer UI, showing the simulator during a task. The view and simulator controls are highlighted on the left. I the slice view, the kidney model, target area, and needle overlay of highlighted.

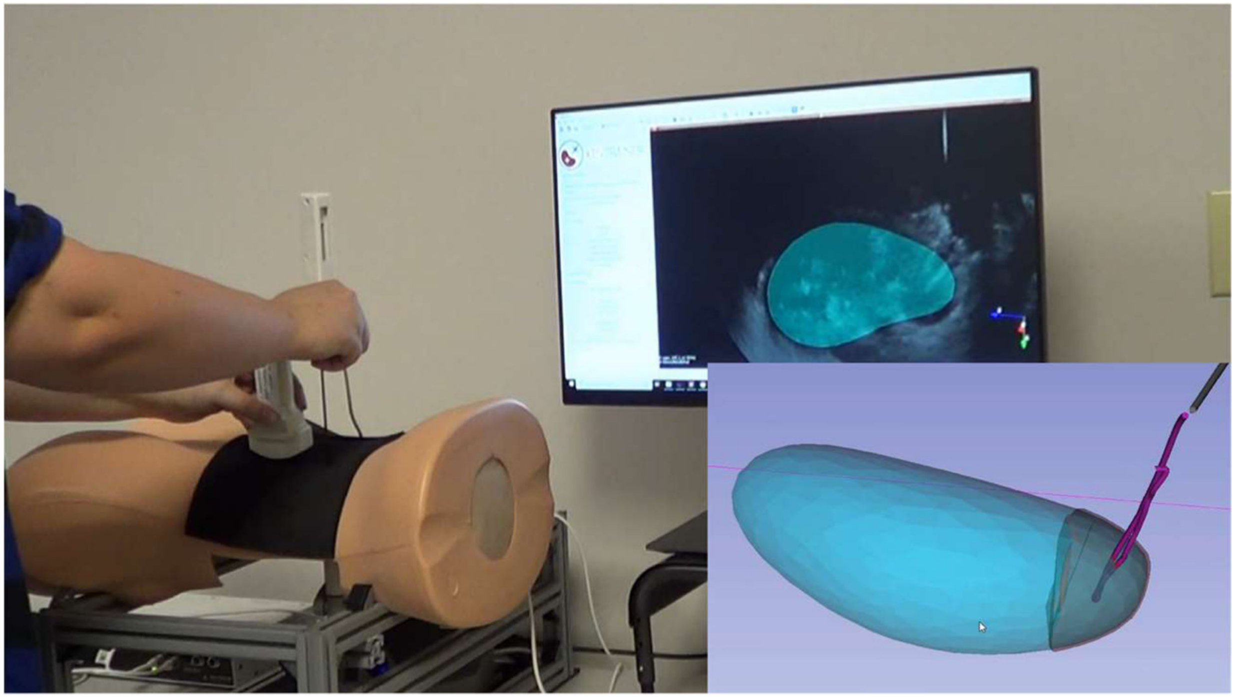


Figure 7.

The KBVTrainer in use. The user has located the needle in the virtual tissue space and is preparing to advance into the kidney. Inset: The post task view, showing the path of the needle (dark purple) within the kidney model and the target area.