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The Perk Station: Systems design for percutaneous intervention training suite

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Abstract - **Image-guided percutaneous needle-based surgery has become part of routine clinical practice in performing procedures such as biopsies, injections and therapeutic implants. A novice physician typically performs needle interventions under the supervision of a senior physician; a slow and inherently subjective training process that lacks objective, quantitative assessment of the surgical skill and performance. Current evaluations of needle-based surgery are also rather simplistic: usually only needle tip accuracy and procedure time are recorded, the latter being used as an indicator of economical feasibility. Shortening the learning curve and increasing procedural consistency are critically important factors in assuring high-quality medical care for all segments of society. This paper describes the design and development of a laboratory validation system for measuring operator performance under different assistance techniques for needle-based surgical guidance systems - The Perk Station. The initial focus of the Perk Station is to assess and compare three different techniques: the image overlay, bi-plane laser guide, and conventional freehand. The integrated system comprises of a flat display with semi-transparent mirror (image overlay), bi-plane laser guide, a magnetic tracking system, a tracked needle, a phantom, and a stand-alone laptop computer running the planning and guidance software. The prototype Perk Station has been successfully developed, the associated needle insertion phantoms have been built, and the graphic surgical interface has been implemented.**

Index Terms - Percutaneous Interventions, Augmented Reality, Training suite, Surgical guidance

I. INTRODUCTION

In recent years, numerous surgical guidance and navigation methods have been developed for needle-based surgery. Image-guided percutaneous needle-based surgery has become part of routine clinical practice in performing procedures such as biopsies, injections and therapeutic implants. Contrary to casual observation, needle-based surgery can be an exceedingly complex intervention. Translational and rotational motions, as well as bending and insertion forces can be combined for delicate needle control in needle-based surgery. Space and the means for desired maneuvering of the surgical device, however are extremely limited. Last but not least, detecting and recovering from errors such as internal bleeding increase the risk of these otherwise appealing outpatient procedures. Trainees usually perform needle interventions under the supervision of a senior physician. This is a slow and inherently subjective training process that lacks objective, quantitative assessment of the surgical skill and performance. Current evaluations of needle-based surgery are also rather simplistic: usually only needle tip accuracy and procedure time are recorded, the latter being used as an indicator of economical feasibility. Our early attempts at validation were based on bi-plane fluoroscopy, but were inconvenient and inherently inaccurate due to movement between insertion and imaging [1]. Many important nuances that pertain to collateral morbidity, side-effects, pain and patient discomfort are not captured in current surgical performance evaluation methods. To address these issues, we have developed a laboratory validation system for measuring operator performance of different assistance techniques and furthermore we are developing the *Perk Station*, an inexpensive, simple and easily reproducible surgical navigation workstation for laboratory practice with non-bio-hazardous specimens. This system will also provide a means to study the trajectory and gestures throughout the insertion procedure in addition to the endpoint accuracy. The study of hand gestures for each of these methods will provide useful information that can be used to help minimize the number of re-insertion attempts needed, as each re-insertion causes significant discomfort to the patient. This system promises a less resource exhaustive and more accurate means by which to validate needle insertion procedures.

A. CT/MR Image Overlay

We have developed the Image Overlay technique to assist with CT [2] and MRI [3] guided percutaneous interventions. Both iterations of the system consist of a flat display and a semitransparent mirror mounted on the gantry. The images for planning are taken immediately prior to the intervention and transferred to a laptop PC through DICOM protocol. When the physician looks at the patient through the mirror, the CT/MR image appears to be floating inside the body with correct size and position as if the physician had 2D 'X-ray vision' as shown in Fig. 1. The clinician marks the target and entry points on the CT/MR images shown on a stand-alone laptop computer. A virtual needle guide along the specified trajectory is superimposed on the overlaid anatomical image. The clinician then inserts the needle using the overlaid guide while simultaneously being able to see the anatomy and the patient; therefore, his/her focus need never be taken off the patient during the procedure.

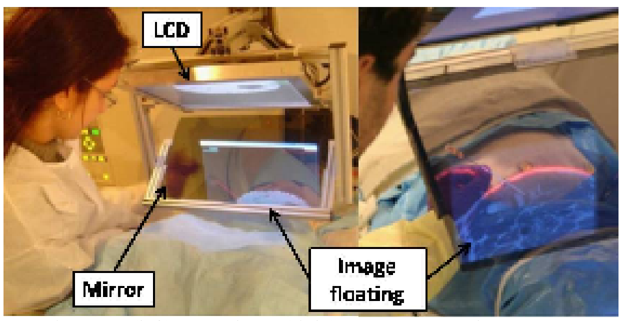

Fig. 1 CT (left) [2] and MR (right) [3] Image Overlay systems.

B. Bi-plane Laser Guide

The bi-plane laser guide [4] is a technique for needle insertion where the intersection of two laser planes is used to denote the insertion axis. It consists of a fixed transverse laser plane and para-sagittal laser plane that is adjusted to the appropriate angle and position. By keeping a crosshair at the tip and on the head of the needle, the trajectory is defined as shown in Fig. 2. Bilateral (left and right) needle insertions are often required; therefore, two such para-sagittal lasers with angle guides are attached to the horizontal rail.

C. Conventional Freehand

The conventional method for percutaneous needle insertion is the traditional freehand technique. Typically, there is not in-situ guidance information available. The physician inserts the needle by estimating the angle and depth of insertion from CT/MR images and mentally registering this to the patient. The success of this technique depends heavily on the experience and skill of the physician.

II. DESIGN OF THE SYSTEM

The Perk Station system comprises of: Image Overlay [2,3], Bi-plane Laser Guide [4] and a single transverse laser for freehand needle insertion, capabilities for tracked freehand navigation, a phantom and a stand-alone laptop computer. Additionally, for trajectory/gestures study, an electromagnetic tracking system (Aurora System, Northern Digital, Waterloo, Ontario) is incorporated. The conceptual design of the full system is shown in Fig. 3.

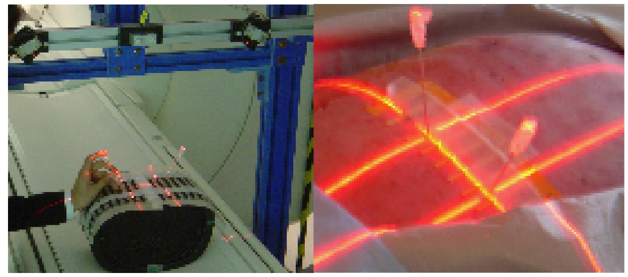
Fig. 2 Bi-plane Laser Guide system comprise of transverse and sagittal plane lasers. [4]

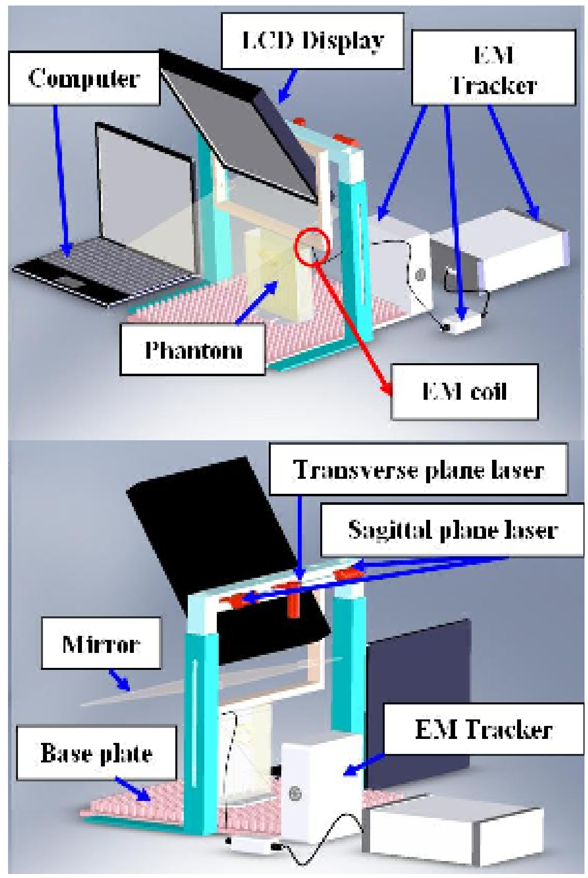

Fig. 3 CAD designs of the Perk Station, with Image Overlay (top) and Laser Guide & tracked navigation configuration (bottom).

A. The main structure of the Perk Station

The image overlay is mounted on one side of the system and the Laser Guide and tracked navigation system on the opposite side. The user can swap between the techniques simply by turning the system around as seen in Fig. 3.

The main structure of the Perk Station is an extruded aluminium frame, which is light weight but sufficiently strong to hold the weight of all devices. The current design of the Perk Station is shown in Fig. 4. The base plate is designed to allow the phantom to be translated from one side to the other side during the training as seen in Fig. 4

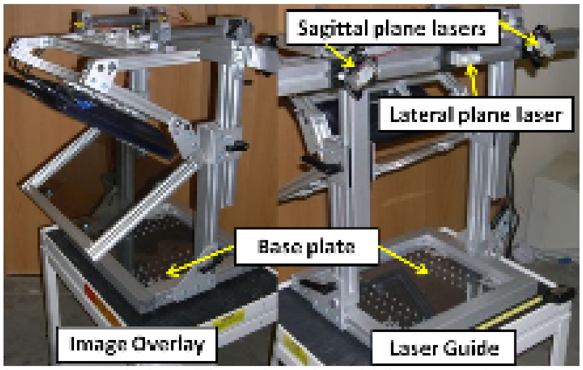

Fig. 4 Current design of the Perk Station with image overlay and laser guide units.

The structure is designed to portable, and is therefore sufficiently lightweight and able to be folded to be placed in a suitcase as seen in Fig. 5. The weight of the whole system including with main structure, image overlay system is 16.5 kg. The overall dimensions of the folded system are 57x55x29 cm.

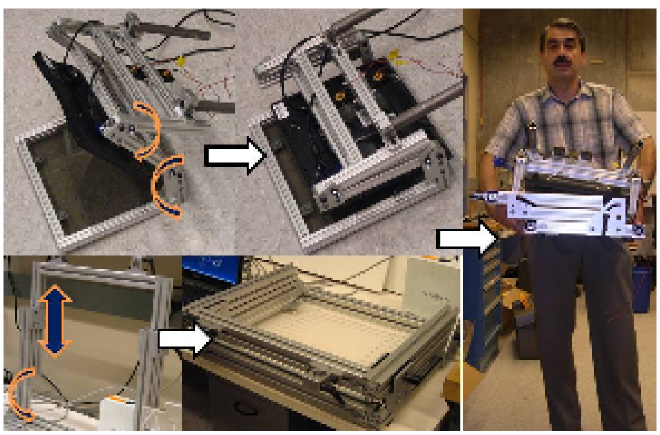
Fig. 5 Perk Station is folded and ready to pack in a suitcase

B. Phantom design

The phantom is designed to simulate the physical and anatomical reality of human tissue. It is manufactured with different types of mixtures with different stiffness to mimic muscle and fat layers.

Two phantoms are used for the Perk Station, one phantom with a vertebra and one with Stereotactic Fiducials. Plastisol, the material used in the phantom with the vertebra, is designed to simulate the density of muscle tissue (M-F, Manufacturing Company, Inc). The phantom's two tissue layers were mixed with different ratios of the Plastic liquid PVC and the plasticizer adipate ("Liquid Plastic" and "Liquid Super Soft Plastic"). The ratios of liquid PVC to adipate for the layers were 4:1 and 5:1 respectively from the bottom to the top. The material used in the phantom with Stereotactic Fiducials was Gelatin porcine skin for electrophoresis Type A (Sigma-Aldrich Inc). The ratios of the Gelatin to water were 1:9 and 1:3 respectively from the bottom to the top.

We follow modular design methodology, by having a reusable external housing (outside box) in which, various kinds of geometrical or anatomical phantoms (inside box) can be 'plugged' in. The reusable external housing (outside box) is equipped with external markers (stereotactic fiducials and EM tracking coils), and can be easily realigned under the overlay. A "Z" shaped fiducial pattern and 28 divot points are laser cut into the container to facilitate registration between the CT/MR and navigation space. Both CT and MRI compatible version of the outside box have been manufactured with appropriate fiducial marks used for registration between MR images and the physical phantom. The phantom is registered to navigation space with a calibrated electromagnetic (EM) tracked pointer used to localize the divot points. As described in [8], the NDI Aurora EM tracking system is used to localize an instrumented needle with respect to the phantom. An EM tracked 6 degree-of-freedom (DOF) reference tool is fixed to the phantom and a calibrated pointer tool is used for rigid-body registration of the phantom to the tracker. The needle tip is instrumented with a 5 DOF EM tracking coil, so that we can analyse the user's motions and validate the accuracy of needle placement relative to the phantom [7].

The associated needle insertion phantom is transparent and is designed to house various types of subjects. For the spinal pain management embodiment of the system, the phantom comprises a human vertebra embedded in different layers of gel mimicking muscle and fat, under a neoprene skin as shown in Fig. 6 (upper). The other phantom comprises stereotactic fiducials as targets embedded in gels with different height as shown in Fig. 6 (lower).

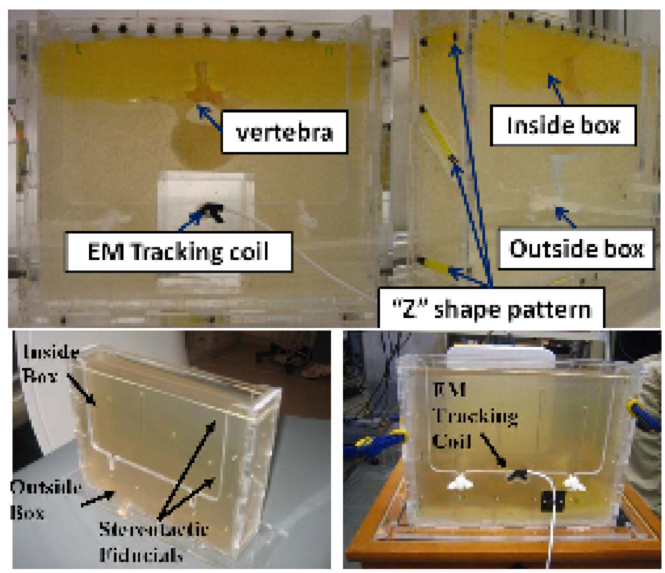

Fig. 6 The phantom with a vertebra (upper) and a phantom with Stereotactic Fiducials (lower)

C. Software

The Perk Station software provides user-friendly intuitive interface that combines functions and elements of image overlay, laser guide and tracked navigation, as well as motion analysis and statistical performance metric tools.

The current iteration of the software is in a standalone package called EasySlice. The software is currently under development and further refinement. In progress is the implementation of a dynamically loadable module for the open source 3D Slicer medical imaging and intervention software (www.slicer.org) from National Alliance of Medical Image Computing (NAMIC). The usage of software is described in next section. Screen captures of the EasySlice software are shown in Fig. 7.

III. Calibration And Operation

A. Image overlay

The phantom image(s) is loaded into the software as would be done with the image overlay, only now the images come from a local repository instead of through the DICOM interface. The software starts the workflow with 'Calibration' step, wherein, the user registers the image overlay system to the phantom by visually aligning fiducials seen on image and as seen in the physical object through the mirror. After the system has been calibrated, the software enters the 'Planning' phase wherein, the user can specify entry point and target points. The software then calculates the insertion angle, insertion depth and needle trajectory. The needle trajectory is overlaid on the image, displayed on the mirror, and hence on the phantom through the mirror. The next step that follows is 'Insertion'. In this step, the software connects to the tracking system and starts tracking the needle tip position. Once the needle insertion is complete, in the 'Validation' step, the 'actual' entry and end points, along-with the actual trajectory of the needle are used to generate the performance metrics which are presented to user in final 'Evaluation' step.

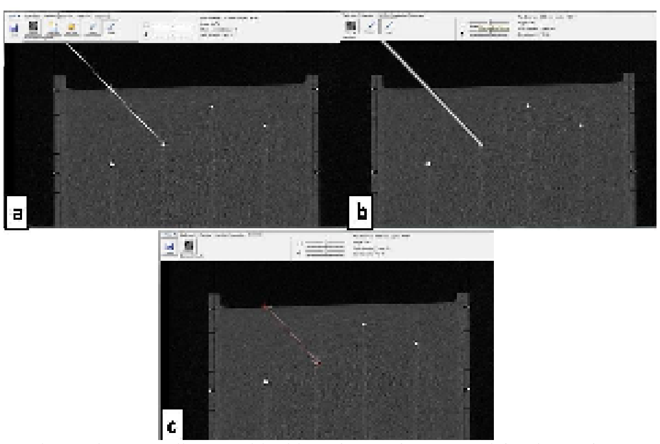

Fig. 7 The EasySlice graphical interface software used for the CT/MR image overlay and the Perk Station. The workflow is split into phases: a) planning b) guidance c) insertion and target point error measurement.

B. Bi-plane Laser Guide

The software loads up the planning image as with the image overlay. The entry and target points are marked. The software then calculates the insertion angle and insertion depth and provides this to the user. The transverse plane of the laser guide defines the insertion plane. The adjustable angle guide for para-sagittal laser is set to the insertion angle using an integrated protractor as directed from software and translated along the rail until the crosshair generated at the intersection of the two lasers (transverse and para-sagittal) is coincident with the percutaneous entry point. The trainee places the needle tip at the entry point and aligns the shaft such that a crosshair generated by the intersection of the lasers is also present on the head of the needle. The needle is inserted to the specified depth while maintaining alignment under the laser crosshair as shown in Fig. 9.

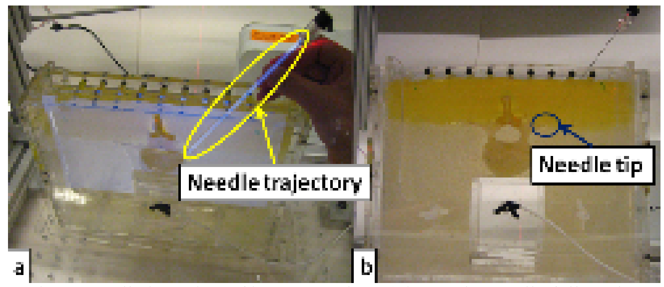

Fig. 8 Needle insertion of image overlay; a) insert the needle follow the path and d) compare the result by visualization through the transparent gel.

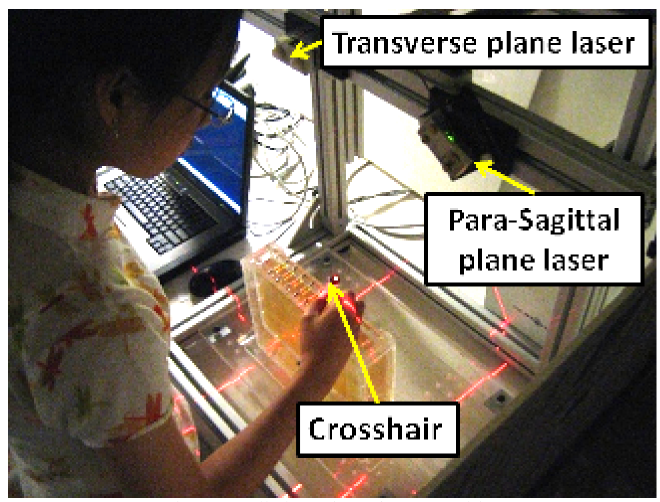

Fig. 9 Needle insertion of Laser Guide

C. Conventional Freehand

When used for traditional freehand needle insertion, the software loads up the planning image and the entry and target points are marked as with the previous two modalities. The software then calculates the insertion angle and insertion depth and presents it to the user as would be done on a standard CT/MR console. The trainee inserts the needle with that angle and depth without any concurrent visualization by mentally registering the plan to the physical phantom without any additional guidance.

IV. Conclusion And Discussion

The Perk Station is a replicable and adaptable tool for teaching computer-assisted surgery at all levels, from high-school science classes to clinical residency. It is small, portable, and light weight, and it fits in a suitcase when disassembled. The apparent simplicity of the Perk Station should not belie its potentials in teaching and training medical professionals, particularly medical students and residents. There is a general misperception and under-appreciation among the public of the skills required for needle based surgeries. In reality, trainees gravitate to learning centres where procedural skills are taught. There is also popular trend to minimize the steep learning curve by using simulations. Patients and patient advocates are less tolerant of training on clinical cases. Increased clinical workloads have also demanded increased provider productivity. The changing financial climate and commercial initiatives have catapulted to the forefront the need of training and performance evaluation without involvement of human subjects. Static or declining reimbursements have driven the need for economical solutions: training systems of with accuracy, efficiency, simplicity, and low cost. The Perk Station promises to fit in these trends eminently.

The Perk Station has been successfully designed and constructed. Preliminary evaluation tests and calibration procedures are underway. The system is debuting in undergraduate teaching in Fall 2008.

To promote transferability, the complete design of the Perk Station, including hardware blueprints, phantom designs, and software source code will be made publicly available as open source upon sufficient refinement and evaluation of the current iteration of the system. Simple design and low cost allows interested parties to replicate the hardware and install the software. The Perk Station is modular, so users can further downscale its functions and thus save on hardware. The distribution website will also supply medical image data and pre-made surgical plans so that users can operate the Perk Station without having access to medical imaging facilities. Documentation and tutorials will also be provided on the website.

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