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Validation System of MR Image Overlay and Other Needle Insertion Techniques

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Abstract.

In order to develop accurate and effective augmented reality (AR) systems used in MR and CT guided needle placement procedures, a comparative validation environment is necessary. Clinical equipment is prohibitively expensive and often inadequate for precise measurement. Therefore, we have developed a laboratory validation system for measuring operator performance using different assistance techniques. Electromagnetically tracked needles are registered with the preoperative plan to measure placement accuracy and the insertion path. The validation system provides an independent measure of accuracy that can be applied to varying methods of assistance ranging from augmented reality guidance methods to tracked navigation systems and autonomous robots. In preliminary studies, this validation system is used to evaluate the performance of the image overlay, bi-plane laser guide, and traditional freehand techniques.

Keywords. validation system, augmented reality, image overlay, mri, needle placement, percutaneous procedures, image guided surgery,

Introduction

A comparative validation environment is necessary for an efficacious analysis of CT/MRI guided assistance techniques to be used in needle placement procedures. Clinical equipment is prohibitively expensive and often inadequate for precise validation. Precise measurement of placement accuracy by MRI is greatly limited by paramagnetic needle artifact and lack of distinct small targets. Scanner time cost can exceed $500/hour making statistically significant trials impractical. Therefore, we have developed a laboratory validation system for measuring operator performance of different assistance techniques. The validation system can be applied to varying methods of assistance ranging from augmented reality guidance methods to tracked navigation systems and autonomous robots.

Preliminary accuracy assessment of our MR image overlay system has been performed, but the excessive cost of scanner time has thwarted a large-scale study of the accuracy of this system. Therefore, an off-line validation system has been created in order to study needle placement accuracy; in particular we look at the accuracy of the image overlay and compare it to that of other insertion guidance methods. 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 ensures a less resource exhaustive and more accurate means by which to validate needle insertion procedures.

In this paper, we describe the validation system shown in Fig. 2, and its use for comparative analysis of the virtual image overlay, the bi-plane laser guide and unassisted freehand techniques. The image overlay displays CT/MR images and a virtual needle guide over the patient [1] and is calibrated such that the overlay a MR or CT image and virtual needle guide appears to be floating inside the patient in the correct size and position as shown in Fig. 2(a,c). The bi-plane laser guide uses intersecting transverse and adjustable parasaggital laser planes to mark the trajectory of insertion [2], as shown in Fig. 2(b,d).

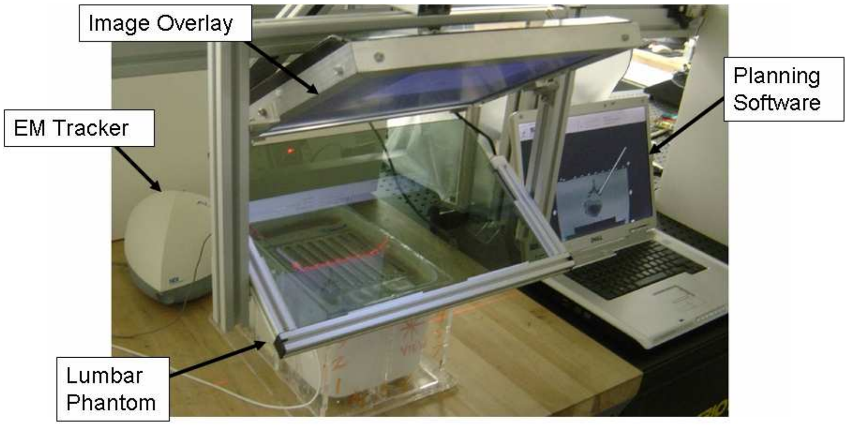

Figure 1. The validation environment shown with the image overlay system.

1. Validation System

Electromagnetic (EM) tracking (Aurora, Northern Digital, Waterloo, Ontario) is utilized to provide the position of the tip and orientation of the shaft of an instrumented needle as described in [3]. All necessary components must be registered with one another in order to track the needle with respect to the preoperative plan generated on the MR/CT images. The components of the system include: the Aurora EM Tracker, a tracked needle, the tracked phantom, the MR/CT images used for pre-operative planning and the AR guidance system. The system is shown in Fig. 1.

1.0.1. Phantom Design

A human cadaver lumbar spine phantom was designed to mimic the anatomy of a patient and aid in the process of registration. Lumbar vertebrae and simulated intravertebral discs are placed in proper alignment are embedded into a layered tissue mimicking gel (SimTest, Corbin, White City, OR) of two different densities emulating fat and muscle tissue. The gel phantom with lumbar spine is placed into an acrylic enclosure which was accurately laser-cut with 24 different pivot points spread over four sides for rigid-body registration. Stereotactic fiducial markers (MR-Spots, Beekley, Bristoll, CT) were placed on the phantom in precisely positioned laser-cut slots. The markers were placed in a ’Z’ shape pattern on three sides allowing for automatic registration between anatomical images and the phantom. The acrylic enclosure was designed such that different phantoms can be placed inside it for studying other procedures.

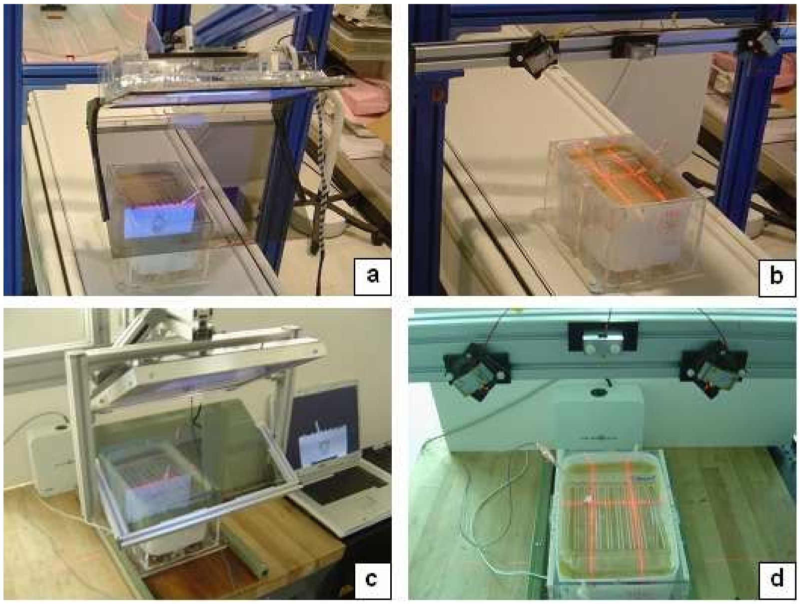

Figure 2. Image overlay (a,c) and bi-plane laser guide (b,d) AR needle placement systems with spine phantom. MR scanner feasibility trials (a,b) and laboratory validation system with tracked needle (c,d).

1.0.2. MR Image Registration

In order to register preoperatively obtained MR or CT images (and their respective preoperative plans) to their corresponding physical space, techniques similar to those described in [4] are used. The Z-frame registration uses three stereotactic fiducial markers in the shape of a 'Z' on each of the left, right, and bottom faces of the phantom (Fig. 4). Axial images are taken near the center of the phantom; the locations of other images of the phantom are known with respect to this reference. The central image is used for registration, where the nine fiducial markers are segmented by applying an adaptive threshold and morphological operations to the image. The centroid of each marker was then found and the position of each marker with respect to the Dicom image was recorded into a set of nine points. After the nine distinct points were identified, the transformation from the scanner's image space to the phantom's coordinate system was computed. The RMS error incurred in the image to phantom space registration for a typical MR image was 1.26mm.

1.0.3. Electromagnetic Tracker Registration

The NDI Aurora EM tracking system is used to localize an instrumented needle with respect to the phantom. A 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. Data was obtained by pivoting about the 24 pre-defined divot points with the pointer. These points were used for registration between phantom coordinate system and that of the EM tracker by finding the transformation which aligns the known point locations obtained from the mechanical design specifications with the collected data points. The RMS error incurred in the rigid-body registration was 0.93mm. Fig. 3 illustrates the placement of the fiducial markers in the image and phantom space.

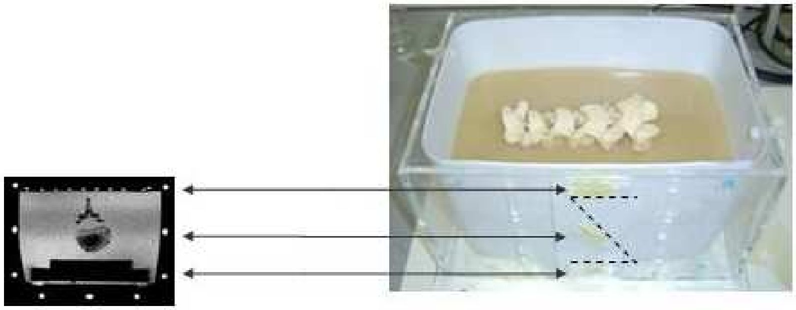

Figure 3. Phantom design showing spine partially embedded in gel and fiducial markers both on the phantom and their corresponding MR image.

This registration process requires only 5-10 minutes and is necessary only when the 6-DOF reference body tool is repositioned on the phantom. The rest of the registration process is automatic. Once both steps in registration are complete, an instrumented needle may be tracked as it maneuvers along a planned path within the phantom. To maximize the system's accuracy, future efforts will include distortion mapping and error compensation as described in [5].

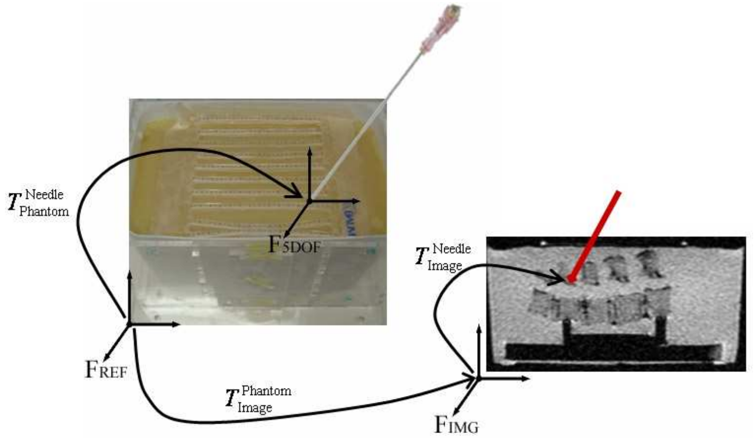

Figure 4. Frame transformations for the registration process shown on the spine phantom and its corresponding MR images. The tracked needle is represented in the original image space where the preoperative plan was made.

2. Experimental Methods

Prior to beginning trials, numerous needle paths were created in the EasySlice planning software that the author's have developed and is described in [1]. The software stores the insertion and target points for each planned path as well as the angle of insertion needed to accurately reach the desired target. For each of the three needle insertion methods (image overlay, bi-plane laser guide and freehand interventions) presented, subjects were randomly assigned three different paths in three different axial MR slices. The entire insertion attempt was recorded with the tracking software. The software then provides insertion and target point error, both in and out of the image plane. Needle axis orientation error is also computed. Simple forms of gesture tracking are now provided, including distances from the trajectory during insertion and the number of re-insertion attempts.

2.1. Results

To demonstrate workflow, four needle insertions were performed with each technique in a clinical MRI environment. As expected, accuracy could not be assessed due to large artifacts as shown in Fig. 5(a). In the validation testbed, the measured needle trajectories were graphically overlaid on the plan and targeting MR image as shown in Fig. 5(b). Twenty insertions were performed with each technique. Position and orientation errors were measured. Initial analysis showed that the results correlate with direct validation performed using fluoroscopy described in [2]. The image overlay's mean error in the image plane was 1.4mm and 2.5^o with standard deviations of 0.5mm and 1.9^o respectively. The laser guide's average error was 1.8mm and 2.0^o (1.2mm and 1.8^o standard deviation), and freehand produced average errors of 2.0mm and 5.2^o (1.4mm and 2.3^o standard deviation).

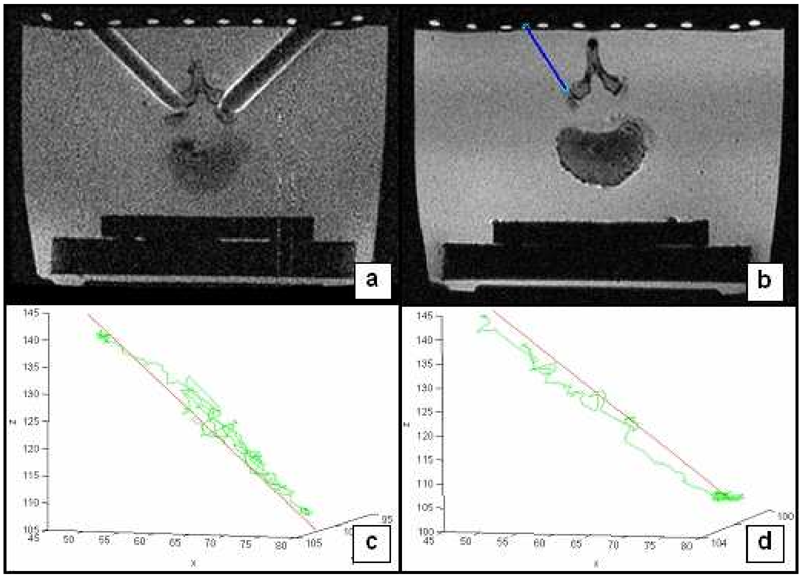

Figure 5. Typical results from an MR image (a) and a tracked path (b). Logged trajectory showing multiple corrections (c) and direct path (d).

3. Discussion

Initial assessments of the image overlay, laser guide, and freehand needle insertions were performed with the validation system. Experiments with experienced radiologists are currently underway. Future experiments will provide independent, large scale accuracy assessment of needle insertion procedures using commercial surgical navigation systems, image overlay, laser guidance, and traditional techniques. The goal is to quantitatively compare placement accuracy, consistency, and other important characteristics such as the needle trajectories throughout the entire placement procedure.

In typical needle placement procedures, the interventionalist will often probe the patient's anatomy until the desired target is reached. This probing action can result in a great deal of discomfort to the patient as well as significant bruising to the area. Analysis of the needle trajectory can provide information about the number of insertion and repositioning attempts that were made during an intervention. Fig. 5(c) illustrates a trajectory that resulted from repeated reinsertions and Fig. 5(d) shows an insertion with minimal repositioning attempts. This information enables researchers to study the systems' ability to minimize discomfort to the patient during the procedure. We intend to use gesture tracking techniques similar to those described in [6].

We also hope to implement the tracking system in clinical trials within a CT scanner, while utilizing the gesture tracking information given by the system for planning interventions. Future applications of this system may also include: providing realtime accuracy and position feedback to a user in vivo and evaluating the accuracy of needle placement procedures in clinical training settings. Applications of this system may also be extended further into autonomous robotic systems and many other augmented reality systems.

Acknowledgements

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