Spinal Needle Navigation by Tracked Ultrasound Snapshots

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***Abstract*—*Purpose*: Ultrasound (US) guidance in facet joint injections has been reported previously as an alternative to imaging modalities with ionizing radiation. However, this technique has not been adopted in the clinical routine, due to difficulties in the visualization of the target joint in US and simultaneous manipulation of the needle. *Methods*: We propose a technique to increase targeting accuracy and efficiency in facet joint injections. This is achieved by electromagnetically tracking the positions of the US transducer and the needle, and recording tracked US snapshots (TUSS). The needle is navigated using the acquired US snapshots. *Results*: In cadaveric lamb model, the success rate of facet joint injections by five orthopedic surgery residents significantly increased from 44.4% ($p < 0.05$) with freehand US guidance to 93.3% with TUSS guidance. Needle insertion time significantly decreased from 47.9 ± 34.2 s to 36.1 ± 28.7 s (mean ± SD). In a synthetic human spine model, a success rate of 96.7% was achieved with TUSS. The targeting accuracy of the presented system in a gel phantom was 1.03 ± 0.48 mm (mean ± SD). *Conclusion*: Needle guidance with TUSS improves the success rate and time efficiency in spinal facet joint injections. This technique readily translates also to other spinal needle placement applications.**

***Index Terms*—Image-guided intervention, minimally invasive intervention, needle navigation, percutaneous, ultrasound (US).**

I. INTRODUCTION

SPINAL needle insertion procedures can greatly benefit from image guidance, since in deep anatomical structures, targets cannot be localized at a sufficient accuracy by palpation alone. Among various imaging modalities, ultrasound (US) is considered to be a promising method, owing to its low cost, safety, wide availability, and convenience of use. A safe and economical US-based needle guidance technique would make a significant impact on the management of patients with chronic back pain as well. A common source of back pain is the facet joints of the spine [1], which can be treated by injections. US guidance has been used routinely in a number of other spinal needle placements with larger or more superficial targets, such as the piriformis muscle and the sacroiliac joint [2]. There have been also attempts of using US guidance techniques for facet joint injections [3], [4]. However, despite promising initial results, US has failed to substitute fluoroscopy and CT guidance in the routine clinical practice for facet joint injections. This may be attributed to the challenges associated with the interpretation of sonographic images in this relatively deep and small target area. Unfortunately, the visualization of the spine in US suffers from major limitations. Low imaging frequency is required for sufficient penetration, resulting in poor spatial resolution. Furthermore, bone surfaces tend to cast acoustic shadows that hide important anatomical details from the observer.

Image-guided intervention systems can be integrated with tool position tracking technologies to enhance difficult clinical procedures. Mechanical [5] and optical tracking [6] have been previously used in a limited range of procedures. Electromagnetic (EM) tracking is a relatively recent method to be integrated with image guidance [7]. The ability to directly track the needle tip is one of the most advantageous features of EM tracking. The small size of the EM sensors allows seamless integration with existing needles and delicate surgical tools. Since the introduction of EM tracking in surgical navigation, the number of clinical applications of this technology has been steadily rising. EM tracking has been used to guide aortic stent-graft deployment [8], the placement of biopsy needles in liver and prostate tumors [9], [10], and in tandem with CT guidance for spinal needle placement [11]. Moore *et al.* used an electromagnetically tracked US probe and developed an augmented reality guidance system for facet joint injections [12]. They found that a prior 3-D model of the spine, typically obtained from CT, was necessary to achieve clinically satisfactory accuracy in needle placement, in phantom models and one cadaver.

One of the major difficulties in freehand US-guided needle insertions is that the needle is only visualized in the US image after it penetrates the skin and some soft tissue under the transducer. Aiming at a target point in the US image before the needle appears in the image requires significant experience and good

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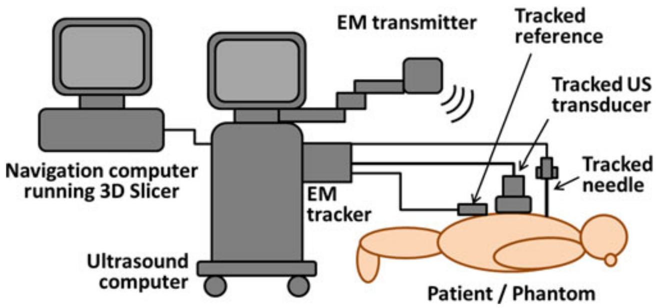

Fig. 1. Schematic layout of the tracked US navigation system.

hand-eye coordination skills. The correct needle orientation has to be maintained precisely during the delivery of the needle in the target to avoid major adjustments. In many situations, the target is only visible to the US from certain angles and the needle manipulation space may be limited by the US transducer itself. We propose a solution to the aforementioned two problems by taking snapshots of the tracked US image and show them in a virtual navigation scene to guide the tracked needle along them, without the use of the US transducer during insertion. This allows both the transducer and the needle to be placed at the ideal insertion point, i.e., the skin point with the shortest path to the target, and the operator to fully focus on needle steering during the insertion. The existing workflow of US-guided facet joint injection [4] is augmented in only the needle insertion step. Instead of using just the US machine display for navigation, an additional virtual navigation scene is also used for real-time feedback on the needle position.

The objective of this paper is to present a spinal needle insertion navigation system using tracked US snapshots (TUSS) to allow US-guided needle insertions without holding the US probe at the insertion site. The TUSS navigation software is developed as an open-source platform that enables the rapid development of image-guided needle placement applications using tracked US for various anatomical targets and clinical indications. TUSS navigation was tested by five orthopedic surgeon residents in this study, guiding facet joint injections in cadaveric lamb and synthetic human spine models. We also report the targeting accuracy of our navigation system and a comparison with freehand US-guided needle placement.

II. MATERIALS AND METHODS

A. Navigation System

The navigation system consists of a data acquisition and a visualization component. These components use network communication, and run on two separate computers: the US machine collects image and tracking data, and the navigation computer is responsible for visualization. The schematic layout of the system is shown in Fig. 1.

Images are acquired using a SonixTouch (Ultrasonix, Richmond, BC, Canada) US machine with a GPS extension. US imaging frequency is set to 6.6 MHz and all imaging parameters that would affect image geometry are fixed after system calibration. The GPS extension uses the DriveBay EM position tracker (Ascension, Burlington, VT) with an adjustable arm to conveniently hold the EM transmitter close to the target area. An L14-5GPS linear US transducer (Ultrasonix) and a 19-gauge calibrated nerve block needle (Ultrasonix) are tracked using built-in pose sensors. An additional Model 800 EM tracking sensor (Ascension) attached to the target phantom or specimen serves as the coordinate reference. Sterile cover for the needle sensor is provided by a sleeve integrated on the needle product. The reference sensor is attached to the skin outside the sterile field. This is feasible in the spine region while remaining within the accurate operating range (0.78 m) of the reference sensor. A gigabit Ethernet network connects the US machine to the navigation computer. The navigation computer has an Intel Core2Quad processor, 3 GB RAM, NVIDIA GeForce 8800 GT graphics card, and it runs under Windows XP operating system.

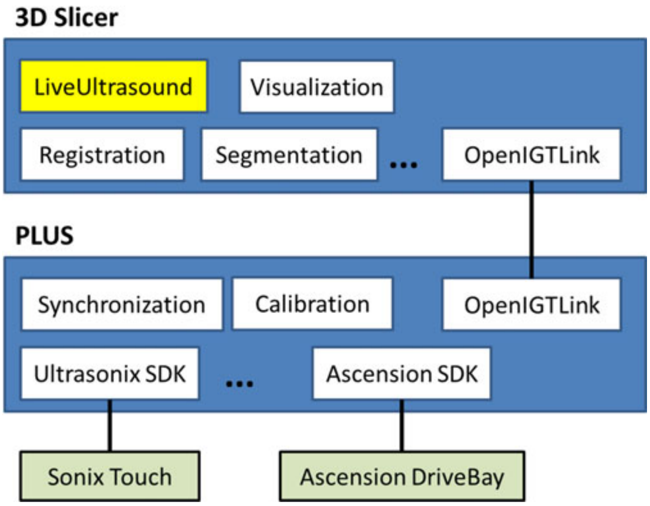

Fig. 2. Software components of the navigation software. The LiveUltrasound Slicer module is specifically developed for tracked US snapshot navigation of needles. Note that all system components are parts of the PLUS or the 3D Slicer open-source software platforms.

Our system is based on a commercially available product, which has been approved by major health authorities for routine usage in operating rooms. The setup time is low (approximately 10 min), and as such, integration to a clinical environment will not require major changes to the existing layout.

B. Navigation Software

The software components of the navigation system are shown in Fig. 2. The software is composed of two, freely available open-source software toolkits. The US machine and the electromagnetic tracker are operated by the Public Library for Ultrasound (PLUS) open-source software package[1] [13]. PLUS provides an abstraction layer for specific hardware programming interfaces. Most importantly, it synchronizes the image and tracker data streams based on optimal correlation, and provides a calibration method for the tracked US transducer using a pose recovery scheme based on multiple N-wires. The OpenIGTLink broadcaster application of the PLUS package is

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[1] www.assembla.com/spaces/plus

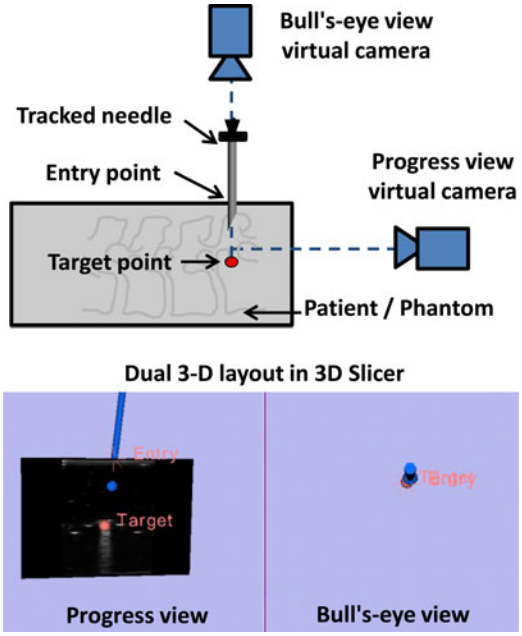

Fig. 3. Dual 3-D navigation layout of the graphical user interface in the needle insertion work phase.

used to send the tracked US image frames to the navigation computer through the OpenIGTLink communication protocol at a frame rate of 10 Hz [14]. More details of the tracker system and the navigation software are available from the websites of products and of these open-source software toolkits.

The navigation computer receives the tracked US images, and provides the graphical user interface for needle guidance. The navigation software is implemented as an interactive module for the 3D Slicer application framework [15]. This module is named LiveUltrasound and is shared under the open-source license of 3D Slicer.[2] It provides real-time visualization of the tracked US images and the tracked needle in the 3-D graphical views of 3D Slicer, as well as the ability to take tracked US snapshots for TUSS guidance.

The navigation software provides needle guidance along an insertion plan. The plan is defined in 3D Slicer by the entry point and target point, i.e., the planned location of the needle piercing the skin and the planned final needle tip position, relative to the tracked US image. The dual 3-D view layout with an insertion plan is shown in Fig. 3. One of the 3-D views is set to "bull's-eye view," in which the virtual camera superimposes the target and entry points. The coincidence of the target and entry points indicates correct virtual camera orientation. The other 3-D view is set to "progress view," showing the US image plane parallel to the virtual camera image plane and is used to monitor the current penetration depth of the needle.

The orientations of the bull's-eye and progress views are aligned with the position of the operator, with respect to the patient (see Fig. 4). The direction of needle motion toward the operator is shown in the bull's-eye view as a downward motion relative to the navigation monitor, while the progress view shows this motion as toward the camera. This arrangement provides intuitive hand–eye coordination during needle insertion.

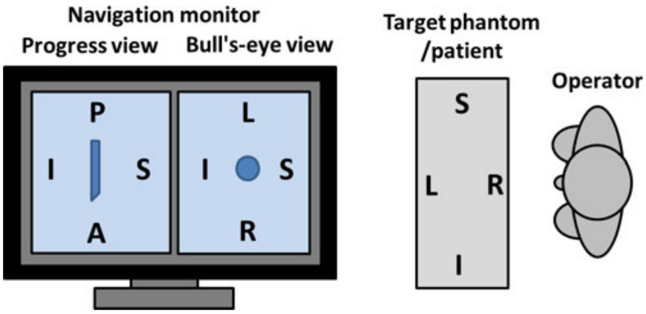

Fig. 4. Bull's-eye view orientation for intuitive navigation. Letters denote directions in the "patient" coordinate system: *S* for superior, *I* for inferior, *P* for posterior, *A* for anterior, *R* for right, and *L* for left.

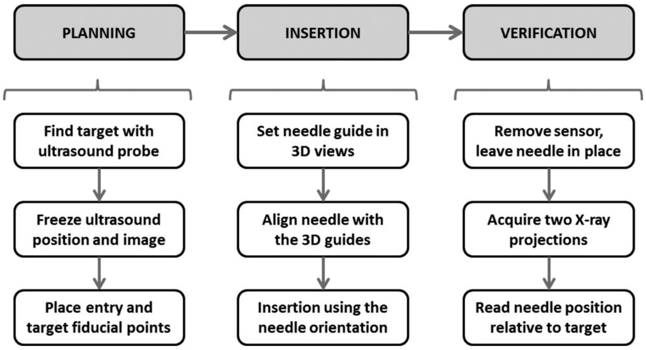

Fig. 5. Workflow steps for the needle insertion experiments.

C. Operator Population

A total of five orthopedic surgery residents participated in this study as operators to test the TUSS-guided needle navigation. None of the operators had used any form of tracked US needle guidance before performing the experiments. This study was approved by the Queen's University Health Sciences and Affiliated Teaching Hospitals Research Ethics Board.

D. Needle Insertion Protocol

Each needle insertion procedure consists of three main phases (see Fig. 5). In the planning phase, the operator locates the target by US, and one or more tracked snapshot US images are taken by the navigation software. Target and entry points are marked on the US snapshots. In the insertion phase, the navigation 3-D views are adjusted to the planned needle direction before they appear to the operator on the navigation monitor in the dual 3-D view. Using the navigation scene, the operator aligns the tracked needle tip on the entry point, and then aligns the needle angle with the entry-target line of the insertion plan using the bull's-eye view. Finally, the operator inserts the needle along the planned trajectory, while observing the bull's-eye and progress views for real-time feedback on the position of the needle relative to the insertion plan. The needle insertion is considered complete when the tip of the needle in both the

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[2] www.assembla.com/spaces/slicerigt

TABLE I
SUMMARY OF EXPERIMENT FEATURES

Objective	Procedure	Endpoint
System accuracy	Target copper spheres in clear plastic gel	Distance between target and needle tip
Human anatomy	Target facet joints in synthetic human spine models	Fluoroscopic verification
Biological tissue	Target facet joints in fresh cut lamb lumbar spine regions.	Fluoroscopic verification, procedure time

bull's eye and progress views overlaps with the target point of the needle plan.

In the verification phase, two orthogonal X-ray images are acquired using a GE OEC 9800 fluoroscopy system (GE Healthcare, Chalfont St. Giles, U.K.) to assess the true needle tip position relative to the planned target. This phase will be eliminated eventually from the workflow, once sufficient evidence proves the reliability of TUSS guidance.

E. Experiment Design

Tracked US snapshot navigation of needle insertion was studied in three experimental setups. Each experiment focused on different aspects of the navigation method. Table I summarizes major features of the experiment.

First, targeting accuracy was studied using small artificial targets without anatomical landmarks. Copper spheres of 1.6-mm diameter were placed in acoustically clear, but visually not transparent Plastisol gel (M-F Manufacturing Company, Inc., Fort Worth, TX) at a 50 mm depth from the surface. The needle tip was navigated to these targets using TUSS, and its distance from the surface of the copper spheres was measured using orthogonal X-ray projection images, and treated as targeting error (see Fig. 6).

Second, feasibility in human anatomy was tested using a synthetic, rapid prototyped spine model, placed in Plastisol gel. Cellulose (15 g/L) was mixed to the gel to simulate acoustic speckle of real soft tissue [see Fig. 7(b)]. The spine model was painted with X-ray contrast material (barium-sulphate) to show contrast on fluoroscopic images. The needle was navigated to the facet joints of this spine model using TUSS. Success or failure of needle placement was assessed using two X-ray projection images by a radiologist, blinded to the identity of operators. Registered bone surface model with tracked needle positions were also available during the verification of insertion outcomes (see Fig. 8). This helped with the interpretation of needle positions relative to the bone anatomy.

Third, feasibility in biological tissue was tested using two fresh cut lamb lumbar spine regions. Tracked needles were navigated to the facet joints of the spine using TUSS. In order to assess the difference between TUSS-based navigation and freehand US-guided needle placement without position tracking, the cadaveric lamb model facet joint needle insertions were repeated in the same model without TUSS by all operators, thereby creating corresponding pairs of trials. Success of each insertion was assessed in the same way as in the synthetic human spine model.

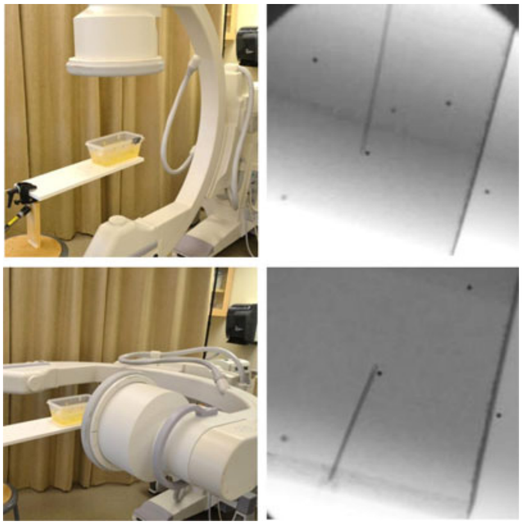

Fig. 6. Two orthogonal fluoroscopic (upper row and lower row) images were taken to verify the needle position relative to the target in the system accuracy study (middle column) and the anatomical target study (right column).

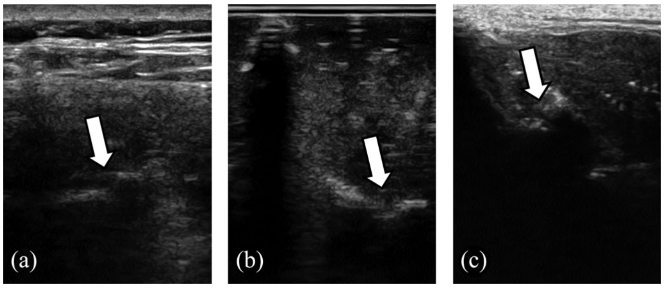

Fig. 7. US image of a lumbar facet joint in (a) human tissue, (b) anatomical phantom, and (c) lamb. Arrows point to the facet joints.

Needle insertions in the synthetic human spine phantom and the lamb model were carried out in groups to reduce experiment time. TUSS images were taken from the tracked live US stream for facet joints of five consecutive anatomical segments. Single mouse pointer clicks on these snapshots in the 3-D views were used to define target and entry points for the needle insertion plans (see Fig. 9).

F. Evaluation

Targeting error in the accuracy tests was defined as distance of the needle tip from the surface of targeted copper spheres. Insertion time was defined as time from the definition of the insertion plan in the navigation software until the final placement of the needle. In freehand US guidance, the measurement of the insertion time started when the operator identified the target on the US image. Success in facet joint needle placement was defined as the radiographic image of the needle tip being between the articular processes in the posteroanterior fluoroscopic view, and overlapping the articular processes in the lateral view. Targeting error and insertion time were expressed as mean ±

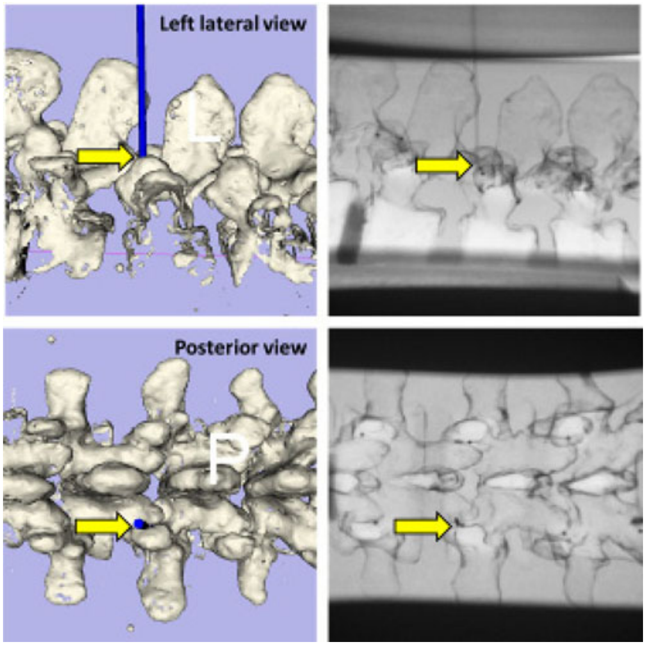

Fig. 8. Interpretation of needle position in the synthetic human spine model is assisted using bone surface model from the registered CT volume of the model (left side). Orthogonal fluoroscopic images (right side) were used as an independent verification method for needle tip position. Arrows points at the needle tips.

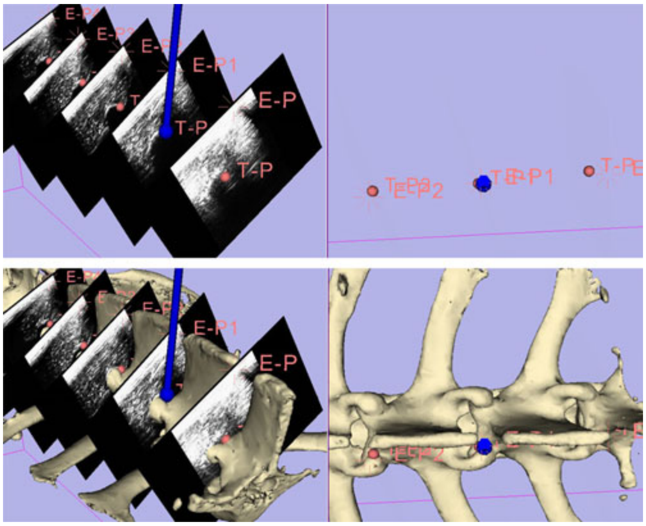

Fig. 9. Needle navigation scene in 3-D Slicer with dual 3-D view shows multiple facet joint targets in the cadaveric lamb model. The tracked needle (visualized as a blue stick) is placed in target “P1” (upper panel). Registration of the CT volume to the EM tracker results in a scene augmented with the bone surface model. Bone surface model was only used for training and validation (bottom panel).

standard deviation. The success rate of needle insertions was expressed as percentages. Linear regression was used to analyze trends in targeting error and procedure time with repeated needle insertions. Success rate between TUSS navigation and the freehand US-guided method was compared using a McNemar test. Significance was defined as $p < 0.05$ in all statistical tests.

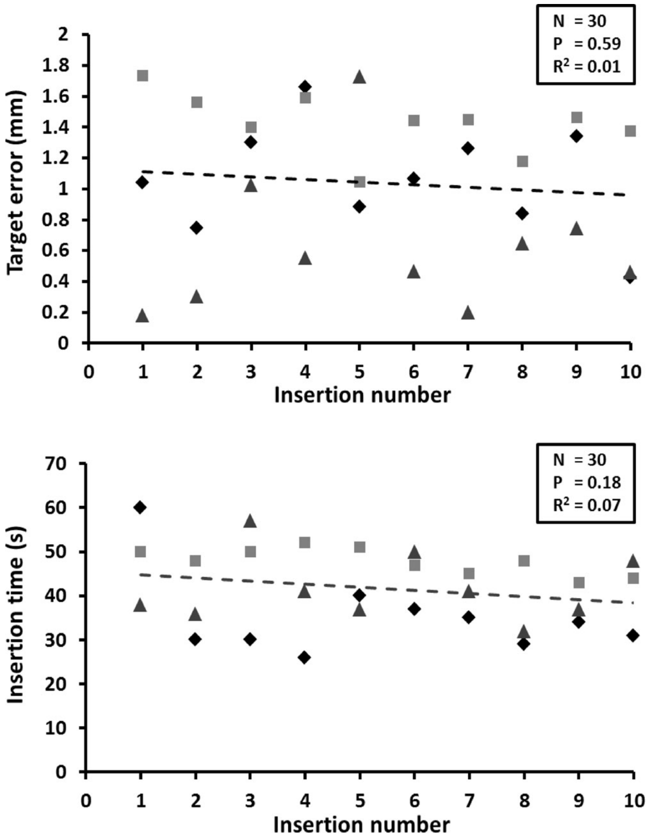

Fig. 10. Targeting error and insertion time of all needle insertions in the system accuracy study. *Upper panel*: Scatter plot of needle tip targeting error versus insertion number. *Lower panel*: Scatter plot of insertion time versus insertion number. Different marks represent each operator.

III. RESULTS

The TUSS system was successfully implemented and calibrated. System accuracy and the human anatomy feasibility tests were executed by three operators. Thirty needles were successfully positioned for accuracy testing. Targeting error was 1.03 ± 0.48 mm (average ± SD). Maximum targeting error was 1.93 mm. Time from needle plan definition until final needle placement was 42.0 ± 9.17 s (average ± SD). Maximum insertion time was 60 s. Targeting error did not change significantly as the number of needle insertions increased within operators (see Fig. 10). Insertion time somewhat decreased with repeated insertions, but this trend was not statistically significant either.

Facet joint needle placements in the synthetic human spine phantom were successful at first attempt in 29 insertions out of the total 30 (96.7%) insertions by three operators (ten facet joints each). In case of the single missed facet joint, postprocedure analysis confirmed that the needle was placed at the planned position; however, the operator confused the facet joint with the gap between the vertebral lamina and the transverse process.

Cadaveric lamb facet joint needle placements were completed by all the five operators. TUSS guidance resulted in a success rate of 47 out of 50 cases (94%) as confirmed by postinsertion orthogonal fluoroscopic images. With freehand US-guided needle placement, success rate was 44% (22 of 50), which is

TABLE II
SUMMARY OF NEEDLE INSERTION RESULTS IN THE LAMB MODEL

	TUSS guidance	**Freehand US guidance**
Number of insertions	50	50
Success rate	* 94 %	44 %
Insertion time (s ± SD)	* 36.1 ± 28.7	47.9 ± 34.2

*p<0.05 vs. Freehand US guidance.

significantly lower ($p < 0.001$) compared to TUSS-guided insertions. Furthermore, the insertion time was significantly less (36.1 ± 28.7 s) with TUSS guidance compared to freehand US guidance (47.9 ± 34.2 s), as shown in Table II.

IV. DISCUSSION

Our results show that TUSS navigation has sufficiently high accuracy for facet joint needle insertions in a patient-based synthetic human spine phantom and in a cadaveric lamb model. In contrast to earlier findings [12], [16], these results suggest that EM-tracked facet joint injections may be routinely performed without ionizing radiation imaging.

Postinsertion fluoroscopic analysis, and registration with CT-based bone surface models reveal that all of the few missed needle placements were due to inaccurate US localization of the facet joint by the operators. This indicates the importance of training before this new procedure is introduced in clinical practice. The identification of the facet joint by US is not a straightforward task even with a profound knowledge of the spinal anatomy.

Operators in this study had no prior experience in US-guided facet joint injections and did not practice other forms of US-guided needle insertions on a daily basis. This operator population was chosen because our preliminary investigations had shown that experts in US-guided spinal injections achieved a similarly good accuracy with freehand US guidance as with TUSS guidance. Whether experts can benefit from TUSS after adapting it into their routine, or it only helps less experienced operators in achieving better accuracy at an early phase of their learning curve, remains a question for future studies.

US guidance methods use landmarks on the images that can be identified with high confidence, since US provides only a limited view of the underlying structures; the needle path is planned relative to these landmarks [17]. Selection of these landmarks with the proposed software is not limited to one US slice. Landmark points (fiducials) in the 3D Slicer software can be placed, named, and highlighted in US slices of different orientations. These landmarks can be observed for needle navigation in different 3-D views of the virtual scene, as in the proposed method for facet joint injections. Further investigation on procedures other than facet joint injections using anatomical landmarks is needed to assess the full potential benefit of the presented system. Specifically, for spinal nerve blocks, US guidance has another advantage over fluoroscopy by directly visualizing the target nerve [18].

It has been found in a single-center comparative study that US-guided facet joint injections produce skin infections more often than the fluoroscopy-guided alternative [19]. Tracked US snapshot guidance has an advantage that skin disinfection can be applied around the needle entry point between the time of US snapshot and the needle insertion. However, positioning of the reference sensor far enough to allow manipulation around the needle insertion point, and at the same time close enough to avoid loss of registration with patient motion or skin sliding must be elaborated for every clinical scenario.

For a new technology, a significant hurdle of dissemination can be the initial difficulties at the early phase of the learning curve. Our study shows that needle placement accuracy with TUSS is high even at the first trial by a new user. We have not detected any significant improvement in accuracy with the number of TUSS-guided needle insertions using point targets. This suggests that TUSS is a very intuitive navigation method for various medical specialists, even when they use it for the first time. A trend of decreasing insertion time can be observed using anatomical targets as opposed to point targets; however, this may be attributed to the acquaintance with US anatomy through practice.

Similar tracked US guidance for facet joint injections was presented earlier [12]. A large, 4.87-mm average targeting error was reported with tracked US needle guidance. Since there were a number of differences between that system and the one presented in this report, e.g., different electromagnetic tracker systems, single versus dual 3-D view, different target and needle representations etc., the source of this error is not certain. Moore *et al.* reported that a significant improvement in accuracy (targeting error dropped to 0.57 mm) was reached by adding a 3-D surface model of the bone to the needle guidance scene. This suggests that depth perception in the guidance scene plays an important role for the operators in the software user interface. Depth perception from the 3-D surface model may have been substituted by the dual 3-D in our virtual navigation scene.

There have been attempts to augment US-guided spinal needle navigation with 3-D surface model of the bone around target regions. When preinsertion CT image exists, it can be registered with the tracked US coordinate system to add CT slices, or the bone contour to the scene of tracked needle and US [12]. The US image can be further augmented with an extracted 2-D slice of the registered CT volume, corresponding to the spatial position and orientation of the actual US image [16]. However, one of the goals of US needle guidance is to eliminate the need for ionizing radiation, at least in some clinical cases of spinal needle placements. To avoid CT imaging, when the surface of vertebrae is partially visible in the tracked US slices, a deformable statistical shape model can be registered to the US to complement the needle navigation scene with a 3-D bone model [20], [21]. Our presented method is inherently capable of registration of 3-D spine models, either from CT imaging or statistical shape models, due to the built-in registration features of 3D Slicer.

Deformation of the anatomy between the snapshot acquisition and the needle insertion may limit the use of TUSS in soft tissue targets. Application of this method in procedures like kidney biopsy has to be preceded by the assessment of the effect of tissue deformation. However, other skeletal targets, which can be modeled as rigid targets, may immediately benefit from TUSS guidance.

All software used in our experiments is open source, and can be used in whole or as components in public or private software products without restrictions. This ensures that the presented procedures and results can be easily reproduced and disseminated by others. The flexibility in rapid configuration of the 3D Slicer user interface allows creating a layout and orientation of the needle navigation view that is optimal for the usage of the operators. PLUS creates an abstraction layer over different imaging and tracking hardware; therefore, this application can be used with different hardware types without additional software coding, only by defining the devices in the PLUS configuration XML file.

In conclusion, TUSS navigation allows for significantly better success rate and lower insertion time in facet joint injections by medical residents than freehand US needle guidance. Operators achieved good needle placement accuracy immediately as they started to use this guidance technique, which can be attributed to the intuitive user interface. This method may enable US guidance to be routinely used in facet joint injections, improving the safety and accessibility of treatment of patients with spine diseases.

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