Ultrasound in Med. & Biol., Vol. 42, No. 12, pp. 3043–3049, 2016

0301-5629/$ - see front matter

http://dx.doi.org/10.1016/j.ultrasmedbio.2016.07.008

● *Technical Note*

ULTRASOUND-GUIDED SPINE ANESTHESIA: FEASIBILITY STUDY OF A GUIDANCE SYSTEM

Alexander Seitel,* Samira Sojoudi,* Jill Osborn,† Abtin Rasoulian,* Saman Nouranian,* Victoria A. Lessoway,‡ Robert N. Rohling,*§ and Purang Abolmaesumi*

*Department of Electrical and Computer Engineering, University of British Columbia, Vancouver, British Columbia, Canada; †Department of Anesthesia, St. Paul's Hospital, Vancouver, British Columbia, Canada; ‡Ultrasound Department, BC Women's Hospital, Vancouver, British Columbia, Canada; and §Department of Mechanical Engineering, University of British Columbia, Vancouver, British Columbia, Canada

(*Received* 1 *February* 2016; *revised* 19 *May* 2016; *in final form* 9 *July* 2016)

Abstract—Spinal needle injections are guided by fluoroscopy or palpation, resulting in radiation exposure and/or multiple needle re-insertions. Consequently, guiding these procedures with live ultrasound has become more popular, but images are still challenging to interpret. We introduce a guidance system based on augmentation of ultrasound images with a patient-specific 3-D surface model of the lumbar spine. We assessed the feasibility of the system in a study on 12 patients. The system could accurately provide augmentations of the epidural space and the facet joint for all subjects. Following conventional, fluoroscopy-guided needle placement, augmentation accuracy was determined according to the electromagnetically tracked final position of the needle. In 9 of 12 cases, the accuracy was considered sufficient for successfully delivering anesthesia. The unsuccessful cases can be attributed to errors in the electromagnetic tracking reference, which can be avoided by a setup reducing the influence of the metal C-arm. (E-mail: purang@ece.ubc.ca) © **2016 World Federation for Ultrasound in Medicine & Biology.**

Key Words: **Model-based registration, Epidural needle insertions, Facet joint injections, Ultrasound, Guidance.**

INTRODUCTION

Needle insertions in the lumbar spine play an important role in pain management and regional anesthesia. Facet joint injections are commonly used to relieve pain in the lower back (Boswell et al. 2007), which is experienced by up to 80% of adults at least once in their lifetime (Rubin 2007). Epidural needle insertions are often applied for pain relief during labor and delivery, for surgical anesthesia and analgesia and for chronic pain management (Parr et al. 2009). Both procedures require careful placement of the injection needle to ensure effective delivery of therapy and to avoid damage to the spinal cord and nerves, dura and epidural vasculature. Conventionally, these procedures are either performed by solely relying on the sense of touch or under repeated fluoroscopic imaging and, thus, result in frequent needle re-insertions and exposure of the patient to radiation. Ultrasound guidance of these procedures has gained in popularity, but is still limited by its difficult interpretability (Yoon et al. 2013). Proposed ultrasound-based guidance techniques aim to enhance ultrasound images with information obtained from pre-operative images such as computed tomography and magnetic resonance imaging (Chen et al. 2010; Moore et al. 2009; Ungi et al. 2012). However, such pre-operative images are, especially in obstetric anesthesia, not always available.

In this study, we clinically evaluate our previously presented ultrasound guidance system for epidural needle insertions and facet joint injections (Rasoulian et al. 2015) on 12 patients. The system allows patient-specific augmentation of live standard 2-D ultrasound images with anatomical information from a statistical 3-D surface model of the lumbar spine and relation of this information to the position of the tracked injection needle.

METHODS

The study was approved by the institutional Medical Research Ethics Board under No. H13-01968 before patient enrollment started. Twelve patients (9 female, 3

Address correspondence to: Purang Abolmaesumi, Department of Electrical and Computer Engineering, University of British Columbia, 2332 Main Mall, Vancouver, BC V6T1Z4, Canada. E-mail: purang@ece.ubc.ca

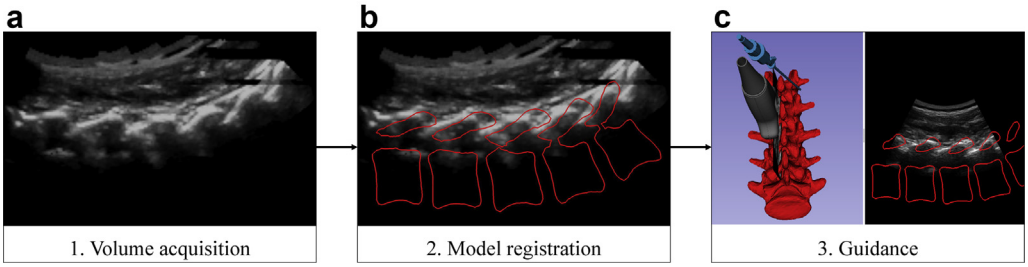


Fig. 1. Workflow of ultrasound-guided spine anesthesia. (a) An ultrasound volume is acquired from tracked 2-D ultrasound slices. (b) The statistical 3-D surface model of the lumbar spine (*red*) is optimized and registered to the reconstructed volume. (c) The registered statistical model of the spine is used to highlight anatomical features (in this case, the surface of the vertebrae on the right side) in the live 2-D ultrasound image and is visualized along with the tracked injection needle in the 3-D guidance interface (left side).

male) with an average age of 65 years undergoing a fluoroscopy-guided epidural needle insertion or facet joint injection participated in this study. Written informed consent was obtained from each subject in the study prior to the performed intervention. Although not excluded, no patients presented with scoliosis.

Ultrasound guidance system overview

The main idea behind the evaluated guidance system is to simplify interpretation of spinal ultrasound scans by augmentation with anatomical information of the target structure obtained by registering a statistical 3-D surface model of the lumbar spine covering the statistical variations in shape and pose of the vertebrae to the ultrasound space (Fig. 1). The model is built from 32 computed tomography segmentations of the lumbar spine from which shape and pose statistics are calculated separately by applying a principal component analysis on the ensemble of the lumbar vertebrae both on the point cloud (shape) and in the Lie space for the similarity transformations (pose) (Rasoulian et al. 2013). The lth vertebra of the model can be instantiated by applying different weights (shape coefficients w_k^s, pose coefficients w_k^p) to the kth principal component,

$$s_l = \Phi(\vec{w}^s, \vec{w}^p) = \Phi_l^p\left(\Phi_l^s(\vec{w}^s); \vec{w}^p\right) \quad (1)$$

where $\Phi_l^p(\vec{w}^p)$ denotes the similarity transformation, and $\Phi_l^s(\vec{w}^s)$ is a shape representation of the lth vertebra.

For registration with an unseen 3-D US volume, (i) the bone surfaces in US are extracted as the point cloud Y using the bone enhancement approach presented by Foroughi et al. (2007); (ii) the model is initialized in the US volume by a single landmark-based registration, assuming that the patient is oriented in prone position

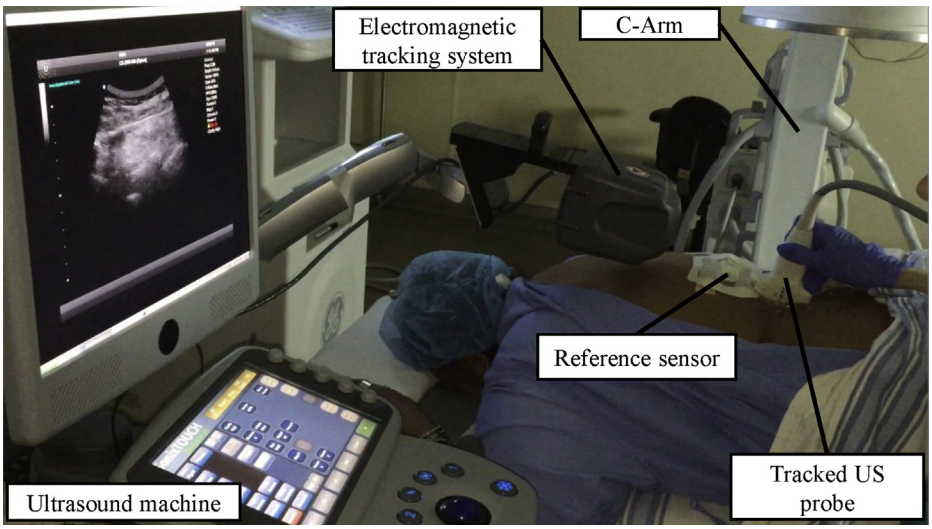


Fig. 2. Setup of the guidance system within the conventional setting in the intervention room. The fluoroscopic C-Arm was used for the conventional needle positioning procedure. The field generator of the electromagnetic tracking system was positioned near the T12 vertebra of the spine. The sonographer grabbed the ultrasound volume using a tracked 2-D ultrasound probe connected to the ultrasound machine. The reference sensor was used to achieve a consistent orientation of the reconstructed volume.

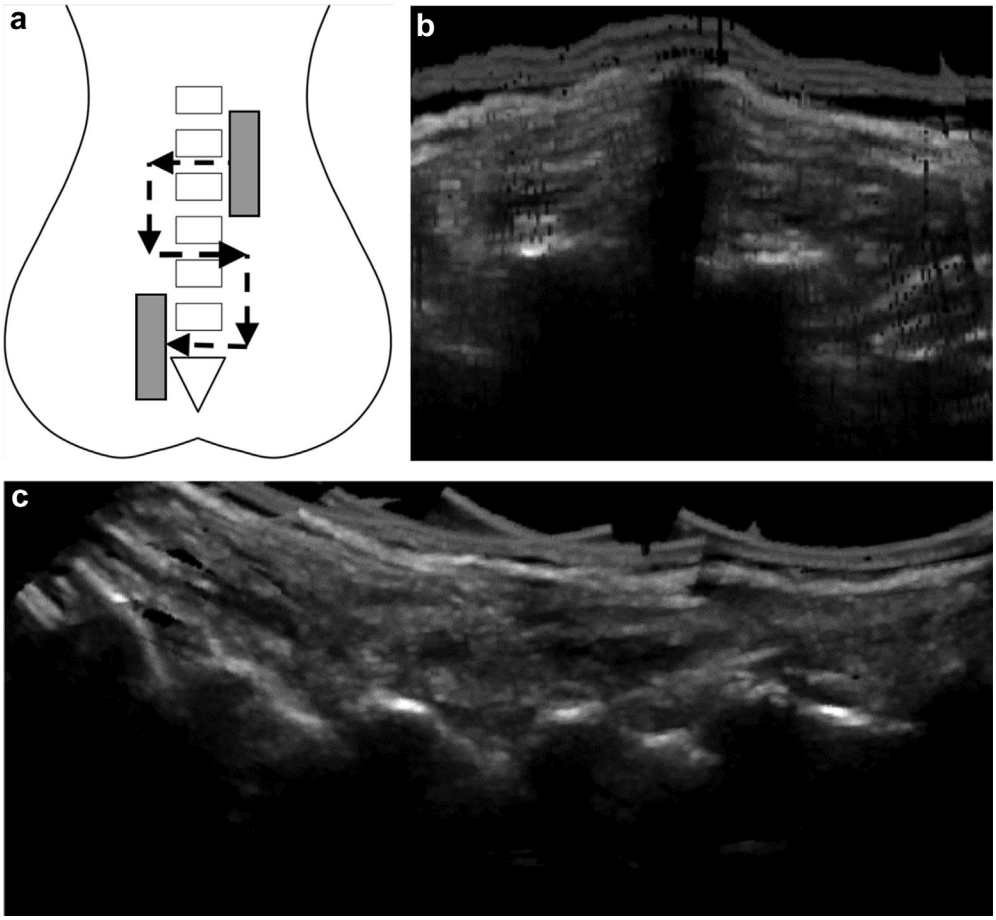


Fig. 3. Ultrasound volume acquisition. (a) The electromagnetically tracked transducer was moved laterally and from superior to inferior in a zigzag pattern, acquiring ultrasound slices in sagittal orientation. The zigzag scan was used as it was found to be easier to perform and provided high-quality images of the spine, covering the full extent of the vertebrae, the full extent of the lumbar spine and a small consistent overlap between sweeps. Slices of the reconstructed volume are shown for a transverse re-slice orientation in (b) and a sagittal re-slice orientation in (c).

in the US volume; and (iii) the shape and pose coefficients of the model are optimized using the expectation maximization algorithm minimizing the objective function

$$Q = \sum_{l=1}^{L} \sum_{m,n=1}^{M,N} P\left(\vec{x}_n^{\,l} \middle| \vec{y}_m\right) \left\| \vec{y}_m - \left(R\Phi\left(\vec{x}_n^{\,l}; \vec{w}^s, \vec{w}^p\right) + \vec{t}\right) \right\| + \gamma^s I^s \vec{w}^s + \gamma^p I^p \vec{w}^p \quad (2)$$

where L is the number of objects in the model (here 5), M and N are the number of points in the bone point cloud and the number in the model respectively, $\vec{x}_n^{\,l}$ is the nth point in the lth model vertebra, $\vec{y}_m$ is the mth point in the target point cloud and the two latter terms of the equation are used for regularization of the shape and pose coefficients. As determined in Rasoulian et al. (2013), 95% of the shape and pose variations is captured by the first 25 and 7 modes, respectively. The model is capable of reconstructing an unseen observation with distance error below 2 mm using the first 20 modes of variation.

The system (Fig. 2) is implemented on a SonixTouch ultrasound machine (Ultrasonix Medical, Richmond, BC, Canada) that incorporates an electromagnetic tracking system (Ascension Technology, Shelburne, VT, USA), which is used to track the patient, the ultrasound transducer and the injection needle. The volume acquisition and guidance software is implemented as a module within 3DSlicer (Fedorov et al. 2012). For a detailed explanation of the guidance system, the reader may refer to Rasoulian et al. (2015).

Study procedure

Prior to each intervention, an experienced sonographer scanned the lumbar spine of each subject, using

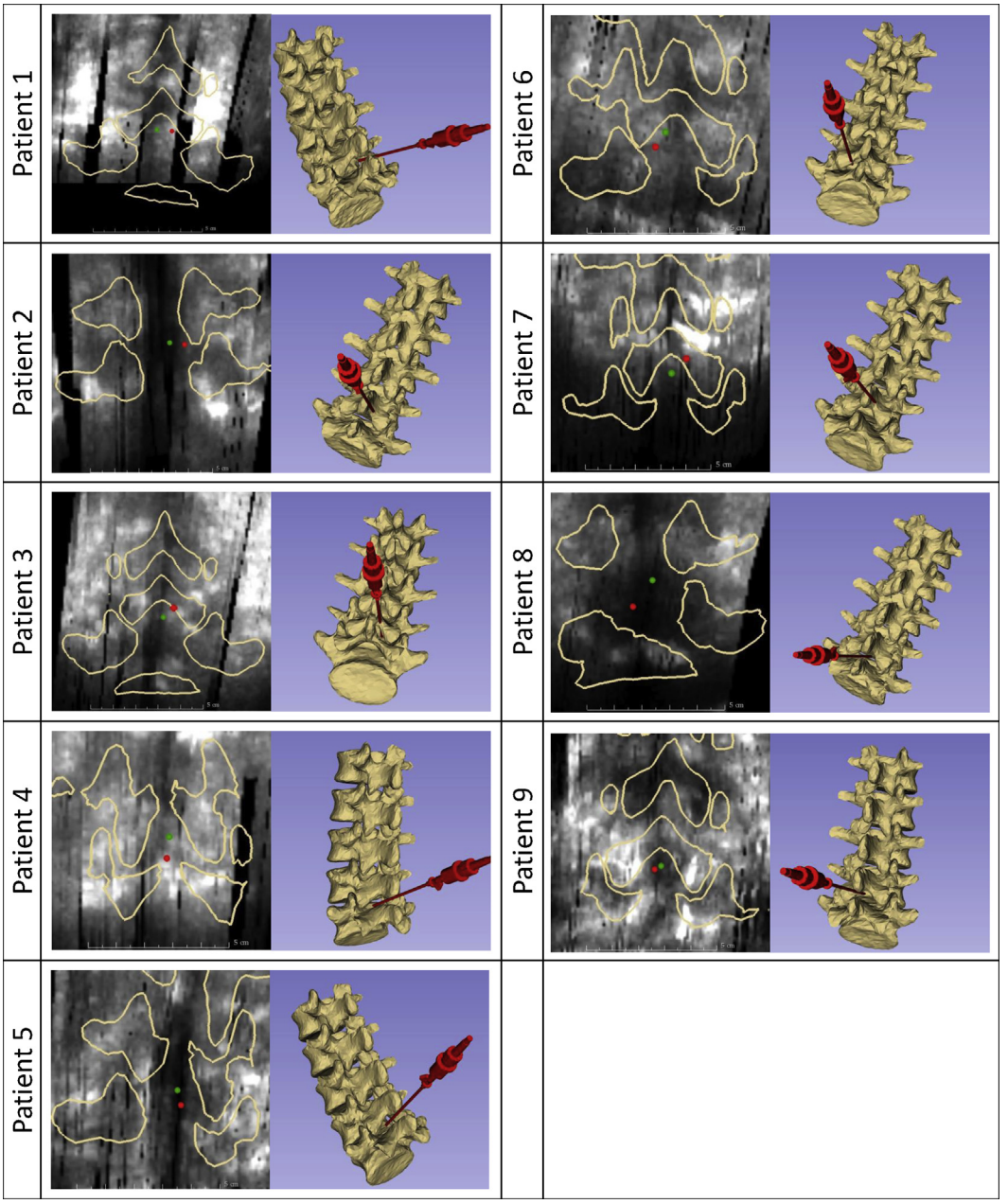


Fig. 4. Results for epidural needle injections. For each patient, 2-D and 3-D views are visualized. In the 2-D view, the *green point* indicates the position of the epidural space as annotated by the sonographer. The ultrasound slice shown is re-formatted from the volume such that it is perpendicular to the needle vector as tracked by the electromagnetic tracking system. The *red point* indicates the intersection of the needle vector with that slice; the cut through the registered model is overlaid in beige. The 3-D view is used to visualize if the tracked needle intersects somewhere with the registered model surface (the defined measure of success).

the tracked C5-2 transducer, following a zigzag pattern by moving it laterally and from superior to inferior, acquiring ultrasound slices in sagittal orientation. The recorded ultrasound slices were then used to reconstruct a 3-D ultrasound volume using the volume reconstruction algorithm available in the Public Library for Ultrasound imaging research (PLUS, https://www.assembla.com/spaces/plus/wiki) (Fig. 3).

The procedure was performed in the conventional way using fluoroscopic images to identify the target region and control advancement of the injection needle (18G PERIFIX Tuohy Epidural Needle, 18G Spinocan Spinal Needle/Quincke Bevel for facet joint injections, B. Braun Medical, Bethlehem, PA, USA). Once the correct placement was confirmed by the anesthesiologist, the pose of the injected needle was recorded by

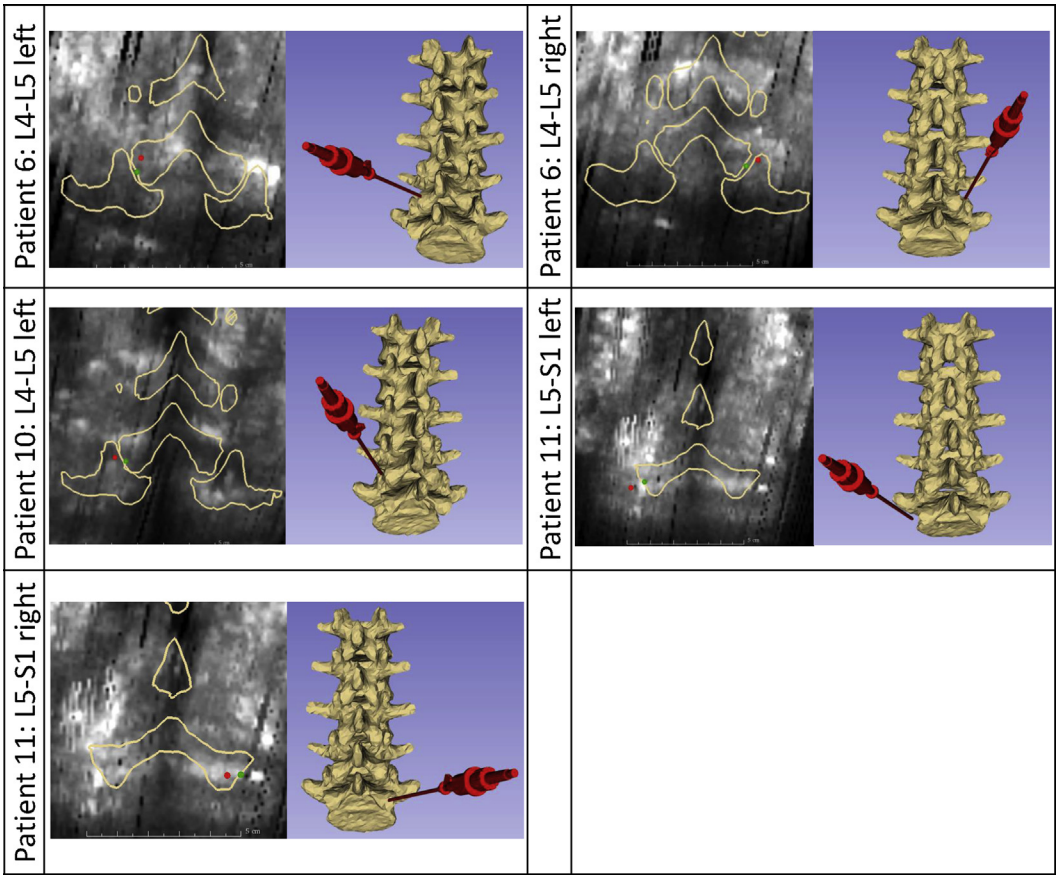
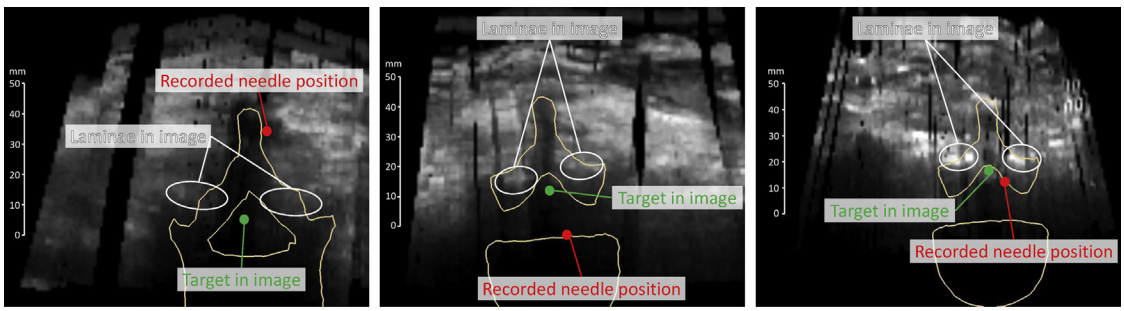


Fig. 5. Results of facet joint injections for five patients. The 2-D view on the left for each patient depicts a coronal reformation of the ultrasound volume at the center of the facet joint (*green point*), the intersection of the needle vector with this coronal plane in *red*,- and the registered model as *beige* overlay. On the right, the 3-D relation between the tracked needle and the registered model is visualized.

inserting an electromagnetically tracked sensor held by a sterile needle (SonixGPS 0.5-mm needle sensor, Ultrasonix) through the hollow injection needle. Finally, the electromagnetically tracked needle was removed, and the anesthetic agent was injected.

Evaluation

The recorded data were evaluated to determine the feasibility of the statistical 3-D surface model of the lumbar spine to highlight target structures in the ultrasound volume.



Patient 2 Patient 3 Patient 7

Fig. 6. Qualitative assessment of epidural cases for which anatomical information could not be provided accurately (P2, P3, P7; cf. Fig. 4). An expert sonographer delineated laminae (*white ellipses*) and the target area (*green circle*) in the target ultrasound plane of the volume, which is shown along with the recorded tip position of the needle (*red circle*) and the overlay of the statistical 3-D surface model of the lumbar spine.

An expert sonographer qualitatively assessed the augmentation of the US images with the registered statistical model with respect to their accordance with visible spine signatures in 3-D ultrasound data.

We quantitatively assessed the accuracy of augmentation for guidance with respect to the final pose of the needle inserted fluoroscopically: Epidural needle guidance was considered successful if the tracked needle did not intersect with the bony structure of the registered model. Facet joint needle guidance was considered successful if the trajectory of the tracked needle was within 5 mm of the center of gravity of the facet joint, the accuracy considered to be sufficient for the anesthetic block to be effective (Greher et al. 2004).

RESULTS

Follow-up examinations of patients yielded 90% reduction of pain for all cases between 1 and 3 months after the intervention, which indicates that the inserted needle used as a reference was placed at the correct anatomical location.

Qualitatively, 3-D ultrasound augmentation was found to be successful in all cases. The registered model is shown for all cases with respect to the ultrasound volume in Figures 4 and 5.

Quantitatively, epidural needle guidance was successful in 66% (6/9) of the cases in which the needle trajectory did not intersect any bony structures of the registered model. Figure 4 illustrates the registered model with respect to the position of the needle, the ultrasound volume and the anatomical epidural landmark as defined by our sonographer. All three of the quantitatively unsuccessful cases could be attributed to errors in the electromagnetic tracking used as a reference measure. For these cases, as illustrated in Figure 6, the tracked needle tip position (*red point*) exhibited large deviations compared with the anatomical structure aimed at in the ultrasound volume as identified by an expert sonographer (*green point*).

Facet joint needle guidance was successful in 80% (4/5) of the cases in which the needle trajectory was within a 5-mm radius around the center of gravity of the facet joint of the registered model (Fig. 5). On average, an error of 5.1 $\pm$ 0.7 mm could be determined.

DISCUSSION AND CONCLUSIONS

In this feasibility study, we have reported that registration of a statistical 3-D surface model of the lumbar spine to the US domain can be used to augment US images and highlight anatomical details surrounding the epidural space and the facet joint region. Our method eases the interpretability of the complex spine anatomy in ultrasound data, suggesting that it is likely to improve ultrasound guidance of such spinal procedures. In all cases in which correct augmentation could not be confirmed, the reference measurement was found to be wrong (Fig. 6). The errors of the electromagnetic needle tracking might be attributed to the fluoroscopic unit present in the room (Franz et al. 2014) used for the conventional insertion. We thus believe that in case of purely US-based guidance, these errors can be significantly reduced. Furthermore, novel tracking hardware such as the tabletop field generator (Northern Digital, Waterloo, ON, Canada) promises to further increase tracking accuracy, as found in a previous study (Maier-Hein et al. 2012). Coverage of the scanned volume by the tracked 2-D US slices was in parts incomplete, resulting in regions in the volume containing no anatomical information. Although most of these regions are rather small, some larger ones might have influenced the registration performance. Providing the sonographer with direct feedback of the reconstructed volume and the ability to correct these missing parts of the volume will improve volume acquisition. We also expect improvements in model registration by extending our training population used for model generation. Currently, our model training set consists of only 32 subjects and their statistical variations in shape and pose of the individual vertebrae. This suggests incorporation of more training samples covering a wider spectrum of spine anatomies. For example, we could acquire data from an additional 5 patients in whom needle insertion was performed between the L5 vertebra and the sacrum, which could not be considered for evaluation in this study because our model does currently not cover the sacrum. We plan to extend the model once training data for this part are available and apply it to these additional patient cases. Future work will include the introduction of a registration reliability measure that allows design of an ultrasound augmentation that is provided only when clinically acceptable error margins are satisfied.

Acknowledgments—We thank the Canadian Institutes of Health Research (CIHR) and the Natural Sciences and Engineering Research Council of Canada (NSERC) for funding this work.

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