A System for Ultrasound-Guided Spinal Injections: A Feasibility Study

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Abstract. Facet joint injections of analgesic agents are widely used to treat patients with lower back pain, a growing problem in the adult population. The current standard-of-care for guiding the injection is fluoroscopy, but has significant drawbacks, including the significant dose of ionizing radiation. As an alternative, several ultrasound-guidance systems have been recently proposed, but have not become the standard-of-care mainly because of the difficulty in image interpretation by anesthesiologists unfamiliar with complex spinal sonography. A solution is to register a statistical spine model, learned from pre-operative images such as MRI or CT over a range of population, to the ultrasound images and display as an overlay. In particular, we introduce an ultrasound-based navigation system where the workflow is divided into two steps. Initially, prior to the injection, tracked freehand ultrasound images are acquired from the facet joint and its surrounding vertebrae. The statistical model is then instantiated and registered to those images. Next, the real-time ultrasound images are augmented with the registered model to guide the injection. Feasibility experiments are performed on ultrasound data obtained from nine patients who had prior CT images as the gold-standard for the statistical model. We present three ultrasound scanning protocols for ultrasound acquisition and quantify the error of our model.

Keywords: multi-vertebrae model, statistical pose+shape model, 3D ultrasound, spine, registration.

1 Introduction

Lower back pain is one of the most common medical problems in the adult population. It is estimated that up to 80% of adults experience during a lifetime at least one episode of back pain that is a major cause of disability [12]. Facet joint injections of analgesic agents have been used for the patients not responsive to conservative management. The current standard-of-care for guiding the injection is fluoroscopy, but has significant drawbacks, including the significant dose

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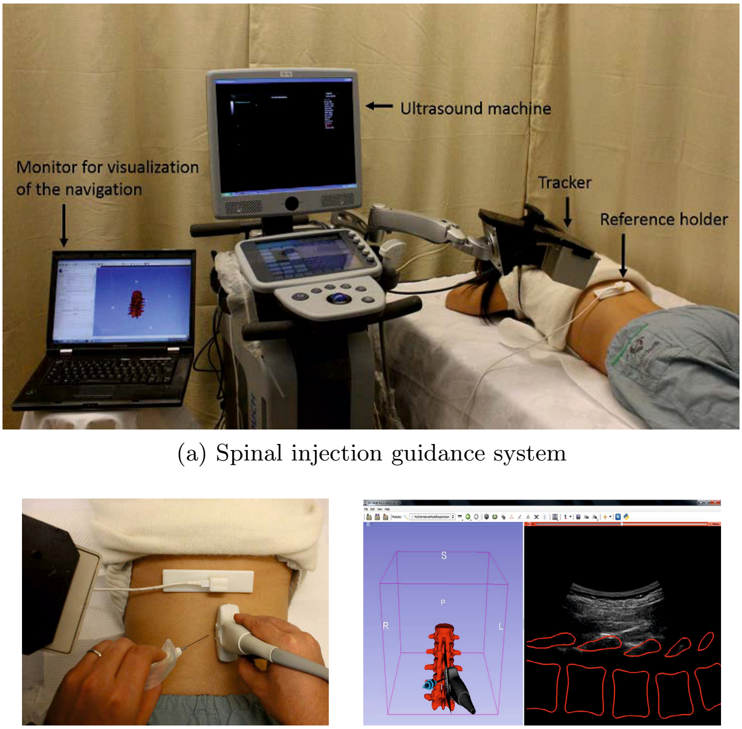
of ionizing radiation and the need for a specialized pain management clinic with access to fluoroscopy equipment. As an alternative, several ultrasound-guidance systems have been recently proposed [2, 7, 14–16], but have not become the standard-of-care mainly because of the difficulty in image interpretation by anesthesiologists unfamiliar with complex spinal sonography. A possible solution to this problem is to register a spine model to the ultrasound images and display it as an overlay. Moore *et al.* introduced an ultrasound-guided system for facet joint injections where the ultrasound transducer was tracked using an electromagnetic tracker [7]. They showed that integration of a virtual CT-based model of the spine improved the accuracy in needle placement. To perform the integration, predefined landmarks on the model were found on the target using the ultrasound, and a point-based registration was performed afterward. To visualize both the target and the needle, the ultrasound transducer has to be oriented in the same plane as the needle, but the ideal spine injection site are easily obscured by the ultrasound transducer. To address this problem, Ungi *et al.* added pre-operative ultrasound snapshots from the target to allow both the transducer and the needle to be placed at the ideal puncture site, i.e., the skin point with the shortest path to the target [15].

In the above-listed image-guided spine injection systems, models are extracted from pre-operative images such as MRI or CT. However, such pre-operative images are not usually available and expose the patient to ionizing radiation in the case of CT. Hence, the use of statistical models is a reasonable alternative.

In this paper, we introduce an ultrasound-based navigation system where the workflow is divided into two steps. Prior to the injection, tracked freehand ultrasound images are acquired from the facet joint and its surrounding vertebrae. The statistical model is then registered to those images. Next, the real-time ultrasound images, augmented with the model, are displayed for needle-guidance.

Statistical shape models have been previously generated for the vertebrae [1, 5, 10, 11]. Boisvert *et al.* studied the statistical variations of relative pose of each two adjacent vertebrae separately. They performed shape analysis of the entire vertebral column and proposed an algorithm for registration of their pose model to radiograph images. Khallaghi *et al.* built separate shape models for each vertebra and by incorporating a biomechanical model to constrain the relative pose of adjacent vertebrae, registered the shape models to an ultrasound volume [5]. This approach has certain disadvantages. Mainly, separate reconstruction of each vertebra neglects the many common shape characteristics between different vertebrae of a given subject which may decrease the accuracy of the registration and add to the computational time. To address these problems, we developed techniques for construction of a statistical multi-vertebrae model with a separate statistical analysis of shape and pose of the vertebrae [10]. The pose statistical analysis in contrast to Boisvert *et al.* are performed on the entire ensemble. We also proposed an algorithm for registration of the model to 3D ultrasound images with only a partial view of multiple vertebrae.

This paper has the following main contributions: first, we implement above mentioned registration technique [10] in a parallelized scheme and adapt it with



(a) Spinal injection guidance system

(b) Needle and transducer orientation

(c) Navigation display

Fig. 1. a) System setup. b) Visualization of the needle and the transducer on the subject's back. c) Guidance system interface. Live ultrasound images are augmented with the registered model, the needle and the transducer.

a navigation system that guides facet joint injections with tracked freehand 2D ultrasound images. As opposed to our earlier work with 3D probes [10], the use of tracked 2D probes is clinically more relevant due to their widespread availability in anesthesiology clinics. Second, experiments are performed on ultrasound data obtained from nine patients who had prior CT images as the gold-standard. This is particularly helpful to determine the accuracy of the registration and the final shape against CT images. Third, current study is performed on patients scheduled for facet joint injections as apposed to our previous study which was on healthy volunteers.

2 Methods

2.1 The Image-Guided System

Figure 1 shows the guidance system. Ultrasound images are tracked by an electromagnetic tracker (Ascension Technology Corporation, Shelburne, VT, USA)

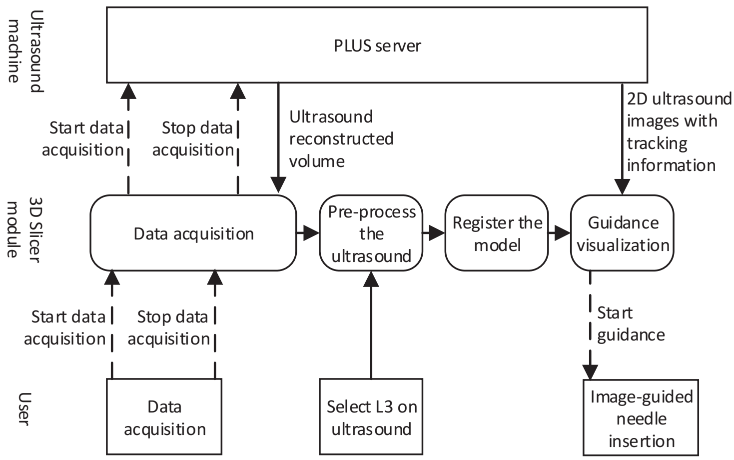


Fig. 2. Overview of the software

and are acquired using an Ultrasonix SonixTouch (Ultrasonix, Richmond, BC) at 30 frames per second. A curvi-linear C5-2 transducer is used which contains a built-in electromagnetic sensor at the tip. The probe is calibrated temporally and spatially at different depths with an average RMS error of 0.94 mm. A reference electromagnetic sensor is attached to the subject skin above the L1 vertebra. The needle tip is also tracked using an electromagnetic sensor. For facet joint injection, no loss-of-resistance is used to guide the placement of the needle, so the EM sensor can be placed directly at the needle tip.

Figure 2 shows an overview of the software design. This software is written on top of the open source library PLUS (Public Library for UltraSound) published by the Perk Lab at Queen's University, Canada [6]. PLUS provides access to ultrasound images, tagged with corresponding transformations of the ultrasound transducer, needle, and the reference sensor in real time. It also provides the reconstruction of the ultrasound volume in real time. 3D Slicer (Harvard Medical School, Boston, MA) is used as the interface for visualization and transmitting the user requests to the plus server [3]. Previously developed application in 3D slicer, called OpenIGTLink Remote, is used for communication with the PLUS server [13].

Conventional 2D ultrasound is used to localize the L1 vertebra by counting-up from the sacrum. The reference sensor is attached to the skin, 3.5 cm above the spinous process of L1. The reference sensor was stabilized in a plastic holder which determines the orientation of the sensor. Therefore, the tracker measurements are mapped into approximately anterior-posterior, lateral, and superior-inferior directions, respectively. Image acquisition for volume reconstruction of the entire lumbar spine is started and terminated by a foot pedal. The ultrasound volume is reconstructed incrementally as the images are acquired. Next, the user is asked to locate the L3 vertebra in the ultrasound volume using a single click in the 3D Slicer interface. The alignment of the model to the volume is performed next, as detailed in the following section. Then, the system automatically switches into real-time guidance by visualizing the live ultrasound images and the needle together with the registered model. The accuracy of needle localization with respect to the ultrasound is mainly determined by the EM-tracker and ultrasound calibration. The EM system used in our research has a static accuracy of 1.4 mm and 0.5 degrees RMS (Ascension Technology Corp, Milton, VT). These should be considered lower limits, since accuracy in vivo will also include some distortion of the EM field.

2.2 Construction of the Multi-vertebrae Model and Its Registration to Ultrasound Volumes

We refer the reader to a detailed description of the model and its registration to ultrasound volumes [10]. Here, we briefly describe the method. The statistical multi-vertebrae shape+pose model is generated from a training set which includes surface points of multiple vertebrae over a range of the population (n=32). Pose statistics are separated from the shape statistics since they are not necessarily correlated and do not belong to the same space [9]. Poses are presented by similarity (rigid+scale) transformations which form a Lie group where linear analysis is not applicable. To address this issue, the transformations are projected into a linear space by logarithmic mapping. Next, Principal Component Analysis (PCA) is performed to extract main modes of variations of poses. A separate PCA analysis is also used to compute the shape statistics. Note that these analyses are performed on the entire ensemble (including all lumbar vertebrae) which results in common statistics of multiple vertebrae. Such analyses result in a mean shape, μ_s, a mean pose, μ_p, and their modes of variations, v_s^k and v_p^k. Linear combination of these modes of variations with the mean shape and mean pose results in a new instance of the ensemble:

$$S = \mathcal{T}(\mu_s, \mu_p, v_s^k, v_p^k, w_s^k, w_p^k), \tag{1}$$

where w_s^k and w_p^k are the weights associated with the corresponding modes of variations. Prior to the registration, ultrasound images are processed to enhance the bone surface. We follow the technique proposed by Foroughi *et al.* where pixels with large intensity and shadow beneath them are considered as bone surface [4]. The registration of the model to enhanced ultrasound images is performed using a GMM-based registration method. In this iterative technique, the previously generated model boundary points are defined as the centroids of the GMM. The target, i.e. the bone surface enhanced in ultrasound images, is considered to be an observation generated by the GMM. The registration is then defined as estimation of proper weights of the modes of variations and a rigid transformation applied to the entire ensemble, to maximize the probability of the GMM centroids generating the target.

The algorithm is parallelized at CPU level, using the Intel Math Kernel Library (Intel, Santa Clara, CA, US). Using this parallelization, the registration, together with the ultrasound pre-processing, takes approximately 10 seconds.

3 Experiments

3.1 Initial Ultrasound Acquisition

Ultrasound images were acquired from a prone subject. To provide maximum similarity to the supine position (subject's posture during CT acquisition) with respect to spine curvature, and also for the subject comfort, a small pillow was placed under the abdomen. Prior to the data collection, brief sonographic study was performed by the sonographer to tune the imaging parameters such as focus and depth. The sonographer also examined the best possible probe trajectory for data collection by marking the spinous processes of L1 and S1. For each experiment, three different scans were performed and corresponding volumes were reconstructed afterward (see Figure 3 for a graphical illustration):

1. Side-sweep scanning was collected from the subject's top-left to bottom-left and back to the top-right ($\sim$ 30 seconds). The transducer angled toward midline and in the transverse plane, 2 cm away from the midline.
2. Transverse midline volume was acquired from top to bottom in the transverse plane ($\sim$ 15 seconds).
3. Sagittal zigzag data collection was performed by moving the transducer laterally in the sagittal plane ($\sim$ 50 seconds).

For the remaining experiments, each of these tracked ultrasound images were reconstructed into a volumetric representation [15].

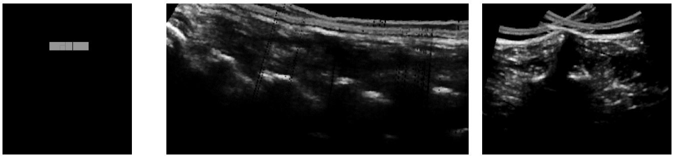
The standard-of-care for the subjects in this study includes a CT-scan taken several months before the injection session.

The bone surface was also manually segmented from each 2D ultrasound image. The segmentation was then transformed to the subject's coordinate space using the calibration and tracking information. The result is a set of point resembling the surface of the vertebrae in subject's coordinate space. As expected, only some of the posterior aspects of the vertebrae were visible, i.e. laminae, transverse processes, spinous process, and posterior part of the vertebral body.

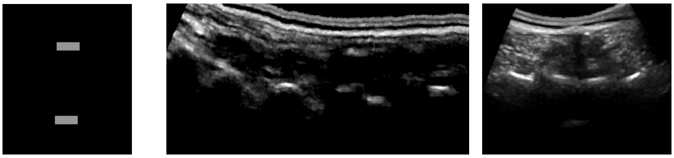
3.2 Accuracy Validation

For each registration of the model to ultrasound volumes, the following measurements were made:

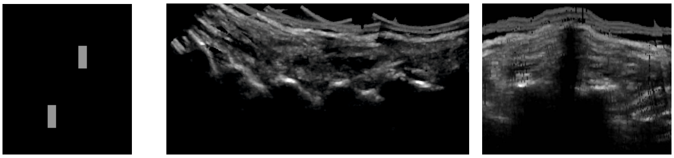
1. The RMS distance of the manually segmented ultrasound points to the model. Although the manual segmentation does not provide a full representation of the vertebrae, it is used to provide a measure of how well the multi-vertebrae model is registered to the ultrasound features.
2. The RMS distance between the model and the manually segmented CT images. This measure is calculated to estimate how well the patient-specific shape of the vertebrae registered to the ultrasound data matches the patient's anatomy observed in CT images. To this end, each vertebrae of the registered model is separately aligned to the corresponding vertebrae from the segmented vertebrae, using the coherent point drift registration method [8]. Then the RMS surface distance is reported as the shape error.



Side sweep: sagittal slice and axial slice



Transverse midline: sagittal slice and axial slice



Sagittal zigzag: sagittal slice and axial slice

Fig. 3. Three different scans were performed on each subject

Experiments were also performed to measure the sensitivity of the algorithm to the initial point selection, i.e. a point around the center of L3, which was marked by the user. To this end, the model is manually well-aligned to the target. The center of mass of the L3 vertebra in the model was extracted. Next, a displacement ranging from 0 to 30 mm, in a random direction, was added to the model, followed by registration. Initial displacements were divided into bins with 5 mm width. For each bin, five experiments were performed for each subject and each ultrasound volume. The mean distance error between the registered model surface to the manually segmented bone surface points in the ultrasound volumes was reported.

4 Results

4.1 Model Construction

The training set for the statistical model was a set of segmented lumbar vertebrae acquired in our previous studies for a total of 32. Manual CT segmentation was performed interactively using ITK-SNAP (www.itksnap.org). 95% of the shape and pose variations are captured by first 25 and 7 modes, respectively. The model is capable of reconstructing an unseen observation with distance error below 2 mm with using the first 20 modes of the variation.

4.2 Registration of the Multi-vertebrae Model to Ultrasound Images

Examples of the registration of the multi-vertebrae model to ultrasound volumes are shown in Figure 4. Distance errors are given in Tables 1. The results for side sweep are significantly better than the other two scans ($p < 0.05$), makes it a preferred scanning protocol. An RMS error of 2.3 mm (maximum 8.4 mm) is adequate for helping to correctly identify the key features in the ultrasound

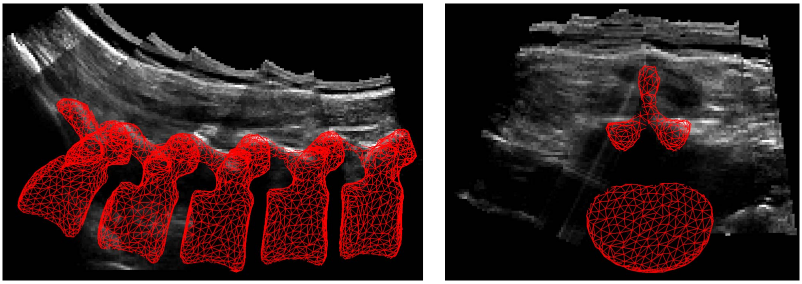


Fig. 4. Example of the registered model to an ultrasound volume

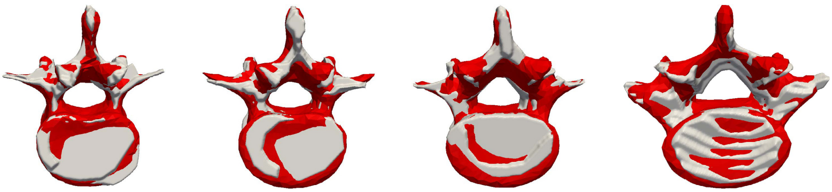


Fig. 5. A comparison of registered model to ultrasound images and the model from CT images. The registered model is highlighted in red and the white surface shows the CT manual segmentation.

Table 1. RMS distance (in mm) between the segmented ultrasound and the registered model. Results for side sweep are significantly better ($p < 0.05$).

	side sweep	transverse midline	sagittal zigzag
RMS distance error	2.3±0.4*	3.2±0.9	3.0±0.5
Maximum distance error	8.9±4.2*	10.6±4.4	13.4±4.9

Table 2. RMS distance (in mm) between the shape of the manual segmentation of the CT and the shape of the registered model to the ultrasound images

	side sweep	transverse midline	sagittal zigzag
L2	1.3±0.3	1.3±0.3	1.3±0.3
L3	1.5±0.4	1.4±0.2	1.3±0.3
L4	1.5±0.4	1.5±0.4	1.5±0.4
L5	1.5±0.3	1.5±0.3	1.5±0.3
All	1.5±0.4	1.4±0.3	1.4±0.3

image. The goal is to interpret the ultrasound and rely on the ultrasound features, not solely the model.

The RMS distance errors between the manual segmentation of the CT and the registered model is given in Table 2. Interestingly, there is no significant differences between the ultrasound acquisition techniques. All vertebrae give errors of ~ 1.5 mm, suggesting that all registered models can accurately generate patient specific vertebrae anatomical shapes.

Results on capture range experiment shows that the error remains the same for variations under 10 mm. This covers a reasonable area (20 mm) within the vertebrae, suggesting the method is robust to initialization errors.

5 Discussion and Conclusion

Our image-guided system can be considered as the evolution of the method presented by Moore *et al.* [7] and Ungi *et al.* [15] by providing the augmentation of the ultrasound with a statistical model. Additionally, the alignment of the model to the ultrasound volume requires minimal interaction, i.e. selection of the L3 vertebra in the ultrasound volume. In the two above mentioned studies, registration is performed by selection of multiple fiducials in both CT and ultrasound. The registration technique used in this work is superior to the one presented by Khallaghi *et al.* [5] in terms of computational time (10 seconds vs. 45 minutes). Additionally, we validate our technique on *in vivo* data.

There are some limitations to this study. Mainly, the training data for reconstruction of the model are segmented vertebrae from the CT images, which are all captured in a supine position. Therefore, the model may not be able to capture all possible spine curvature especially the curvature, when ultrasound and needle insertions are performed.

Future work will be focused on evaluation of the needle injection using this image-guided system and its potential improvement over the conventional manual or fluoroscopy-based technique.

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References

1. Boisvert, J., Cheriet, F., Pennec, X., Labelle, H., Ayache, N.: Articulated spine models for 3-d reconstruction from partial radiographic data. IEEE Transactions on Biomedical Engineering 55(11), 2565–2574 (2008)
2. Chen, E.C.S., Mousavi, P., Gill, S., Fichtinger, G., Abolmaesumi, P.: Ultrasound guided spine needle insertion. In: Proc. SPIE, vol. 7625, pp. 762538–762538–8 (2010)

3. Fedorov, A., Beichel, R., Kalpathy-Cramer, J., Finet, J., Fillion-Robin, J.C., Pujol, S., Bauer, C., Jennings, D., Fennessy, F., Sonka, M., et al.: 3D slicer as an image computing platform for the quantitative imaging network. Magnetic Resonance Imaging 30(9) (2012)
4. Foroughi, P., Boctor, E., Swartz, M., et al.: 2-D ultrasound bone segmentation using dynamic programming. In: IEEE Ultras. Symp., pp. 2523–2526 (2007)
5. Khallaghi, S., Mousavi, P., Gong, R.H., Gill, S., Boisvert, J., Fichtinger, G., Pichora, D., Borschneck, D., Abolmaesumi, P.: Registration of a statistical shape model of the lumbar spine to 3D ultrasound images. In: Jiang, T., Navab, N., Pluim, J.P.W., Viergever, M.A. (eds.) MICCAI 2010, Part II. LNCS, vol. 6362, pp. 68–75. Springer, Heidelberg (2010)
6. Lasso, A., Heffter, T., Pinter, C., Ungi, T., Chen, T.K., Boucharin, A., Fichtinger, G.: Plus: An open-source toolkit for developing ultrasound-guided intervention systems. In: 4th NCIGT and NIH Image Guided Therapy Workshop, vol. 4, p. 103 (2011)
7. Moore, J., Clarke, C., Bainbridge, D., Wedlake, C., Wiles, A., Pace, D., Peters, T.: Image guidance for spinal facet injections using tracked ultrasound. In: Yang, G.-Z., Hawkes, D., Rueckert, D., Noble, A., Taylor, C. (eds.) MICCAI 2009, Part I. LNCS, vol. 5761, pp. 516–523. Springer, Heidelberg (2009)
8. Myronenko, A., Song, X., Carreira-Perpinan, M.: Non-rigid point set registration: Coherent point drift. In: Advances in Neural Information Processing Systems - NIPS, pp. 1009–1016 (2007)
9. Pennec, X.: Intrinsic statistics on riemannian manifolds: Basic tools for geometric measurements. Journal of Mathematical Imaging and Vision 25, 127–154 (2006)
10. Rasoulian, A., Rohling, R.N., Abolmaesumi, P.: Augmentation of paramedian 3D ultrasound images of the spine. In: Barratt, D., Cotin, S., Fichtinger, G., Jannin, P., Navab, N. (eds.) IPCAI 2013. LNCS, vol. 7915, pp. 51–60. Springer, Heidelberg (2013)
11. Roberts, M.G., Cootes, T.F., Pacheco, E., Oh, T., Adams, J.E.: Segmentation of lumbar vertebrae using part-based graphs and active appearance models. In: Yang, G.-Z., Hawkes, D., Rueckert, D., Noble, A., Taylor, C. (eds.) MICCAI 2009, Part II. LNCS, vol. 5762, pp. 1017–1024. Springer, Heidelberg (2009)
12. Rubin, D.I.: Epidemiology and risk factors for spine pain. Neurologic Clinics 25(2), 353–371 (2007)
13. Tokuda, J., Fischer, G.S., Papademetris, X., Yaniv, Z., Ibanez, L., Cheng, P., Liu, H., Blevins, J., Arata, J., Golby, A.J., et al.: Openigtlink: an open network protocol for image-guided therapy environment. The International Journal of Medical Robotics and Computer Assisted Surgery 5(4), 423–434 (2009)
14. Tran, D., Kamani, A.A., Al-Attas, E., Lessoway, V.A., Massey, S., Rohling, R.N.: Single-operator real-time ultrasound-guidance to aim and insert a lumbar epidural needle. Canadian Journal of Anesthesia/Journal canadien d'anesthésie 57(4), 313–321 (2010), http://dx.doi.org/10.1007/s12630-009-9252-1
15. Ungi, T., Abolmaesumi, P., Jalal, R., Welch, M., Ayukawa, I., Nagpal, S., Lasso, A., Jaeger, M., Borschneck, D., Fichtinger, G., et al.: Spinal needle navigation by tracked ultrasound snapshots. IEEE Transactions on Biomedical Engineering 59(10), 2766–2772 (2012)
16. Yan, C.X., Goulet, B., Pelletier, J., Chen, S.J.S., Tampieri, D., Collins, D.L.: Towards accurate, robust and practical ultrasound-ct registration of vertebrae for image-guided spine surgery. International Journal of Computer Assisted Radiology and Surgery 6(4), 523–537 (2011)