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Visual aid for identifying vertebral landmarks in ultrasound

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ABSTRACT

PURPOSE: Vertebral landmark identification with ultrasound is notoriously difficult. We propose to assist the user in identifying vertebral landmarks by overlaying a visual aid in the ultrasound image space during the identification process.

METHODS: The operator first identifies a few salient landmarks. From those, a generic healthy spine model is deformably registered to the ultrasound space and superimposed on the images, providing visual aid to the operator in finding additional landmarks. The registration is re-computed with each identified landmark. A spatially tracked ultrasound system and associated software were developed. To evaluate the system, six operators identified vertebral landmarks using ultrasound images, and using ultrasound images paired with 3D spine visualizations. Operator performance and inter-operator variability were analyzed. Software usability was assessed following the study, through questionnaire.

RESULTS: In assessing the effectiveness of 3D spine visualization in landmark identification, operators were significantly more successful in landmark identification using visualizations and ultrasound than with ultrasound only (82 [72 – 94] % *vs* 51 [37 – 67] %, respectively; $p = 0.0012$). Time to completion was higher using visualizations and ultrasound than with ultrasound only 842 [448 – 1136] s *vs* 612 [434 – 785] s, respectively; $p = 0.0468$). Operators felt that 3D visualizations helped them identify landmarks, and visualize the spine and vertebrae.

CONCLUSION: A three-dimensional visual aid was developed to assist in vertebral landmark identification using a tracked ultrasound system by deformably registering and visualizing a healthy spine model in ultrasound space. Operators found the visual aids useful and they were able to identify significantly more vertebral landmarks than without it.

KEYWORDS: Image-Guided Therapy, Spine, Scoliosis, Ultrasound, Visualization, Visual aid, 3D Slicer, SlicerIGT, PLUS Toolkit.

1. PURPOSE

Adolescent idiopathic scoliosis is a spinal deformity occurring in 1 – 3% of adolescents and is associated with coronal spine curvature greater than 10 degrees [1]. Scoliosis is generally diagnosed in young adolescents (10 – 14 years old) and monitored through full development of the spine (16 – 22 years old). In clinical settings, radiography is used as the gold standard for visualization and quantification of scoliosis and is, at present, the most widely used imaging modality for monitoring the disease. Progression of scoliosis is generally monitored with radiographs acquired every 4 – 12 months [2]. This monitoring can require, on average, 25 radiographs per patient from the beginning of treatment, through to any final follow-up visits [2]. Accumulation of ionizing radiation exposure becomes a concern when screening or assessing pediatric patients with radiographs. Due to an increased risk of diseases such as leukemia, breast and prostate cancer [3], infrequent monitoring may often occur in-place of monitoring with alternate imaging modalities. Furthermore, radiographic assessment is limited to the coronal and sagittal planes. These limitations may present clinicians with an over-simplified view of the spine and its true deformities [4].

Associated health risks and radiographic limitations for visualization and quantification of scoliosis have provoked research into monitoring through alternate imaging modalities. Ultrasound may be favorable to radiography for use in spinal curvature measurement as it does not emit ionizing radiation. Studies have previously validated ultrasound for

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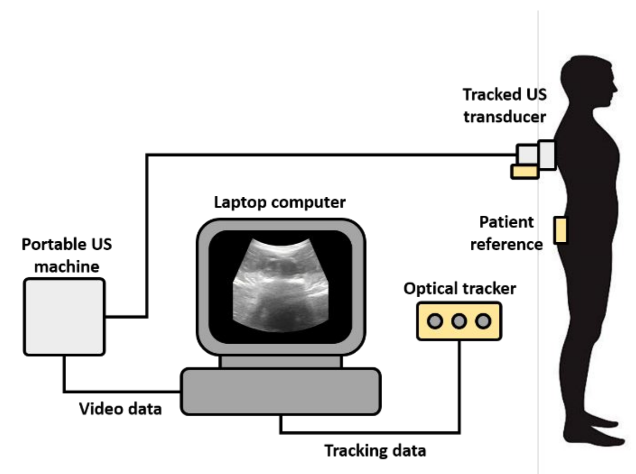
screening and assessment of scoliosis and other spinal deformities [4, 5]. From these studies, we find that spatially tracked ultrasound is capable of providing precise identification of vertebral landmarks [5]. Additionally, we see that spatially tracked ultrasound is able to produce accurate spinal curvature measurements [5].

Patients with deformed or diseased spine may have landmarks which are hidden from view or difficult to identify with ultrasound – partially due to the fact that ultrasound cannot penetrate bone, rendering only bone contours visible. Discerning spinal geometry from ultrasound is a perennially difficult problem that has motivated sizable research. Much existing work requires patient specific magnetic resonance imaging or computerized tomography, which is not practical for scoliosis monitoring, and even less for scoliosis screening [6, 7]. Semi-manually defined image regions undergoing maximum intensity projection on the coronal plane has been shown in scoliosis measurement [4]. These results were obtained using a high-end externally-tracked ultrasound machine. Significant time was also spent manually marking of each recorded ultrasound sequence. Local filters, such as directional Hadamard features [8], can successfully assist in segmenting spinal landmarks, but the operator must scan the region and place a filtering window over the landmark. The question remains how to guide the operator to the vicinity of a vertebral landmark, which is the issue we aim to address in this paper.

We propose an approach inspired by clinical practice. When assessing spines with ultrasound, clinicians often first scan and segment vertebral landmarks that are easy to find, such as transverse processes in the T1 and T2 vertebra, to orient themselves, although these landmarks are not always found in clinically relevant regions of interest for patients with scoliosis. We use these landmarks to digitally overlay a "visual aid" on the ultrasound images to orient the clinician in further scanning and landmark segmentation in the more difficult and clinically relevant regions of the spine. We present the methodology and implementation this "visual aid" and a comparison of vertebral landmark identification with and without visual aids. Inter-operator variability and time to task completion were also analyzed and qualitative operator feedback on usability was gathered to supplant the quantitative analysis.

2. METHODS

The operator performs a tracked ultrasound scan along the centerline of the spine, starting from the most superior thoracic vertebra to the most inferior lumbar vertebra. Using Church's method [9] and applying the centerline's length and curvatures as constraints, we deformably register a generic model of a healthy spine to the ultrasound coordinate system. With this approximate model, we can display for the operator the estimated locations of transverse processes in the ultrasound images by intersecting the model in the plane of the current ultrasound frame. Thus, we display an



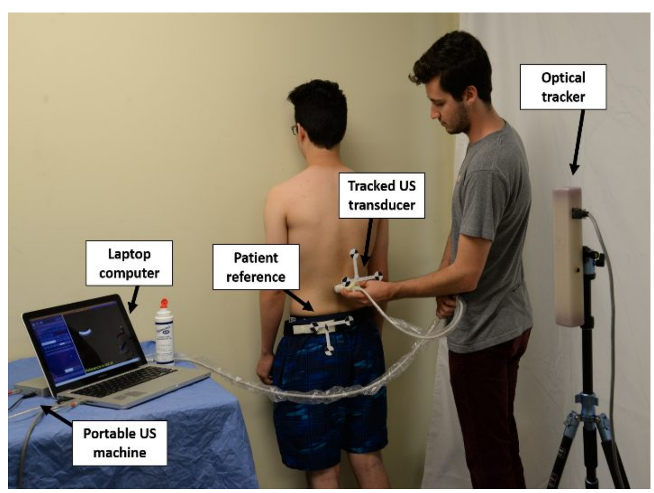


Figure 1. *Left*: Schematic diagram of the spatially tracked ultrasound imaging system.
Right: The spatially tracked ultrasound imaging system in use. US = ultrasound.

intuitive and qualitatively accurate model that aids operators in orienting themselves, which would otherwise be difficult from the ultrasound images alone. Guided by the superimposed model, the operator can more easily scan and identify vertebral landmarks in the deformed regions of the spine. With each new landmark that the operator identifies, the deformable registration is re-computed, thus increasing the accuracy of the superposition of the model spine.

2.1 Tracked sonography system

The spatially tracked ultrasound system used to acquire images used for this study consisted of an optical tracker, a tracked ultrasound transducer, a tracked patient reference, and a laptop computer (Figure 1). Optically tracked markers were fixed rigidly on the transducer and around the patient's waist to determine the location of the transducer with respect to the patient. Tracking information and ultrasound images were captured in real-time on the laptop computer.

The end-user application, ScoliUs (Verdure Imaging, Stockton, California, USA), was built using the 3D Slicer platform (www.slicer.org), with modules from the SlicerIGT (www.slicerigt.org) [10] and Sequences extensions [11]. 3D Slicer is a medical image processing, analysis and visualization software platform which allows for the development of additional medical imaging applications [11, 12]. A MicronTracker H3 - 60 (Claron Technology Inc. Toronto, Ontario, Canada) passive optical tracking camera and Telemed MicrUs portable ultrasound machine (Telemed Medical Systems, Milan, Italy) were connected to a laptop computer through the PLUS Server Application software interface for hardware components (www.plustoolkit.org) [13]. Tracking data from the optical tracker and images from the ultrasound were streamed from PLUS to the OpenIGTLink network protocol [14]. Data is brought into ScoliUs via OpenIGTLink to acquire, record, and replay the tracked ultrasound images (Figure 2).

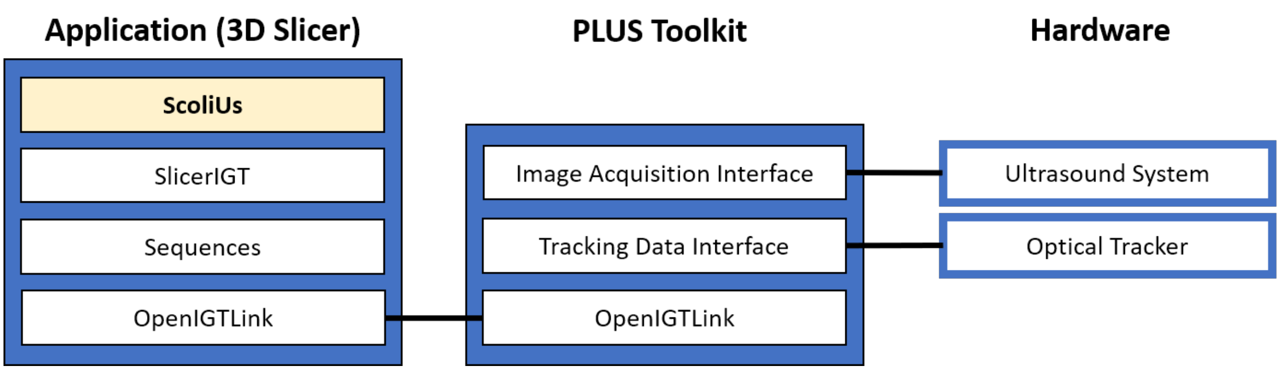


Figure 2. Software architecture of the tracked sonography system using ScoliUs, 3D Slicer, and PLUS. The Telemed portable ultrasound machine and the MicronTracker optical tracker are hardwares.

2.2 Sonography protocol

Four male subjects (mean age 22.8 years) had transverse ultrasound images taken left and right of centerline from their superior thoracic to inferior lumbar region while in a natural standing position. Images were acquired directly from the transducer by an experienced sonographer. There were no filtering algorithms applied to any acquired images in the study. Standard water-based ultrasound transmission gel was used for acquiring all images. Images were collected at a frequency of 3MHz, with an imaging depth of 90 mm and focus of 64 – 80 mm. Dynamic range and gain were adjusted to create a clear visual contrast between bone surfaces and soft tissue. Other imaging parameters were set to the defaults which are provided by the ultrasound manufacturer.

2.3 Experimental design

To determine the effectiveness of additional visual aids in ultrasound landmark identification, six operators were tasked with identifying transverse processes in ultrasound images independently. Transverse processes on the left and right sides of the thoracic and lumbar regions provide up to 34 landmarks for operators to identify in each image series. Operators were randomly assigned two series of images for landmark identification from a group of four. In one series, landmarks were identified using only ultrasound images (Figure 3 *Left*). In the other series, landmarks were identified using an augmented view comprised of a manipulable 3D view displaying a spine model and ultrasound transducer alongside ultrasound images with overlaid spine model intersections (Figure 3 *Right*). After the study, operators answered a questionnaire on the usability of the end-user application and effectiveness of the augmented view.

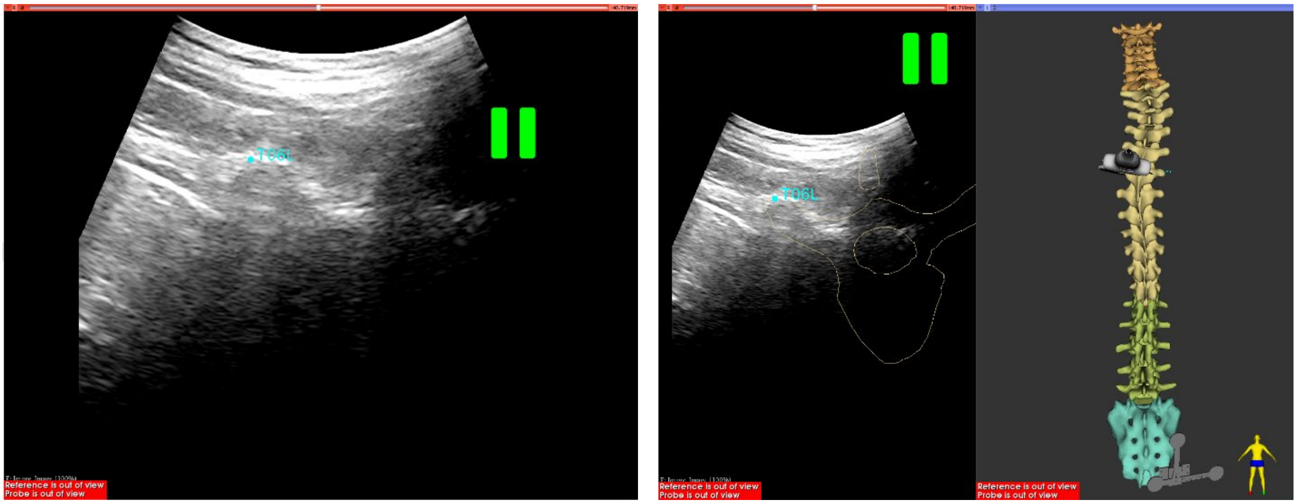


Figure 3. *Left*: Ultrasound image of T6 vertebrae shown during landmark identification.
Right: Augmented Ultrasound image of T6 vertebrae shown during landmark identification.

2.4 Statistical analysis

Operator performance metrics were determined to be the primary outcomes of this study. A one tailed Student's t-Test for independent unpaired samples was used to compare the mean landmark identification rate between all operators. A similar analysis of inter-operator variability and time to task completion are also presented. Results are presented as mean [interquartile range].

3. RESULTS

During the landmark identification study, the mean landmark identification rate was significantly higher with the augmented view than with ultrasound only (82 [72 – 94] % *vs* 51 [37 – 67] %, respectively; $p = 0.0012$, n = 6 in both categories) (Figure 4). Additionally, mean time to task completion for operators was significantly higher with the augmented view than with ultrasound only (842 [448 – 1136] s *vs* 612 [434 – 785] s, respectively; $p = 0.0468$, n = 6 in both categories) (Figure 4).

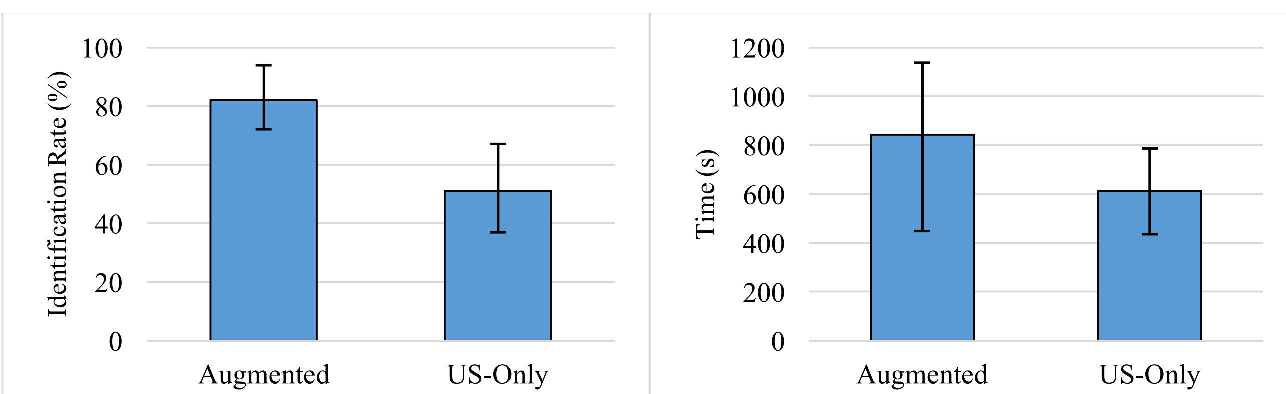


Figure 4. Mean and interquartile range plot of mean landmark identification rate (*Left*) and mean time to task completion (*Right*).

Operators identified 80 (51%) transverse processes using only ultrasound images. With visual aids operators identified 129 (83%) transverse processes. With only few exceptions (T1L, T1R, T12L, and T12R), the identification rate for each individual vertebra when using the visual aid was always greater than or equal to the identification rate of the same vertebra using only ultrasound images (Figure 5, Figure 6). This trend was visible in thoracic and lumbar regions of the spine.

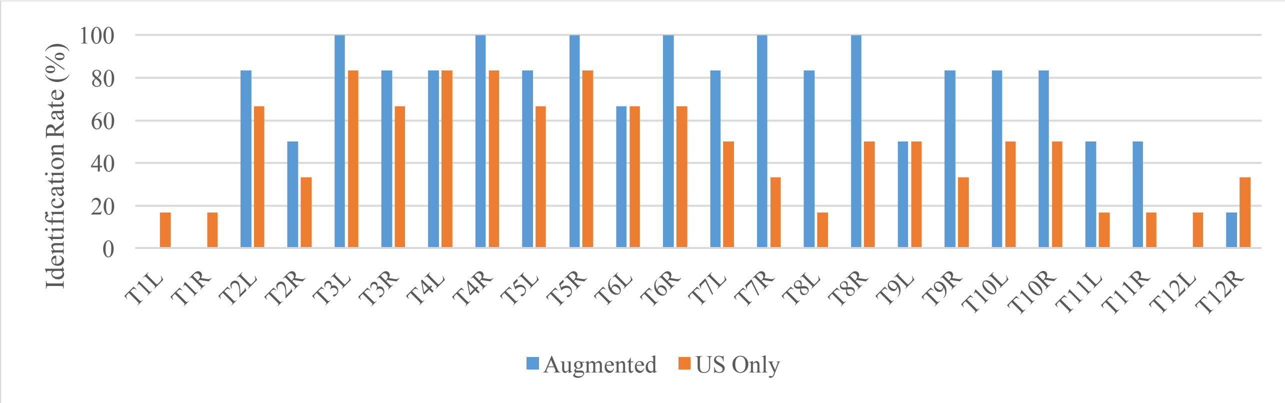


Figure 5. Mean landmark identification rate plot of thoracic vertebrae. L = Left, R = Right.

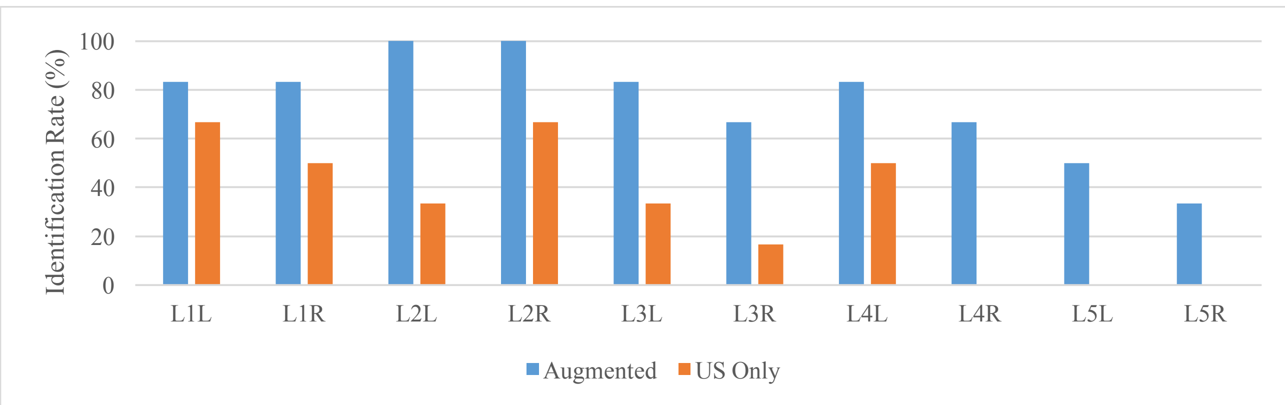


Figure 6. Mean landmark identification rate plot of lumbar vertebrae. . L = Left, R = Right.

Once operators had used ScoliUs to identify vertebral landmarks, they responded to a series of questions using a Likert scale, with 1 being strongly disagree, and 5 being strongly agree. The questions solicited feedback on the software's usability in general and using each respective identification method (Figure 7). Responses showed that operators agreed or strongly agreed it was easy to learn to use ScoliUs, and it was easy to navigate through ultrasound images with ScoliUs. Operators strongly agreed it was easy to use ScoliUs to place landmarks. Additionally, operators felt that the 3D spine model visualization helped them identify landmarks, and visualize the spine and vertebrae.

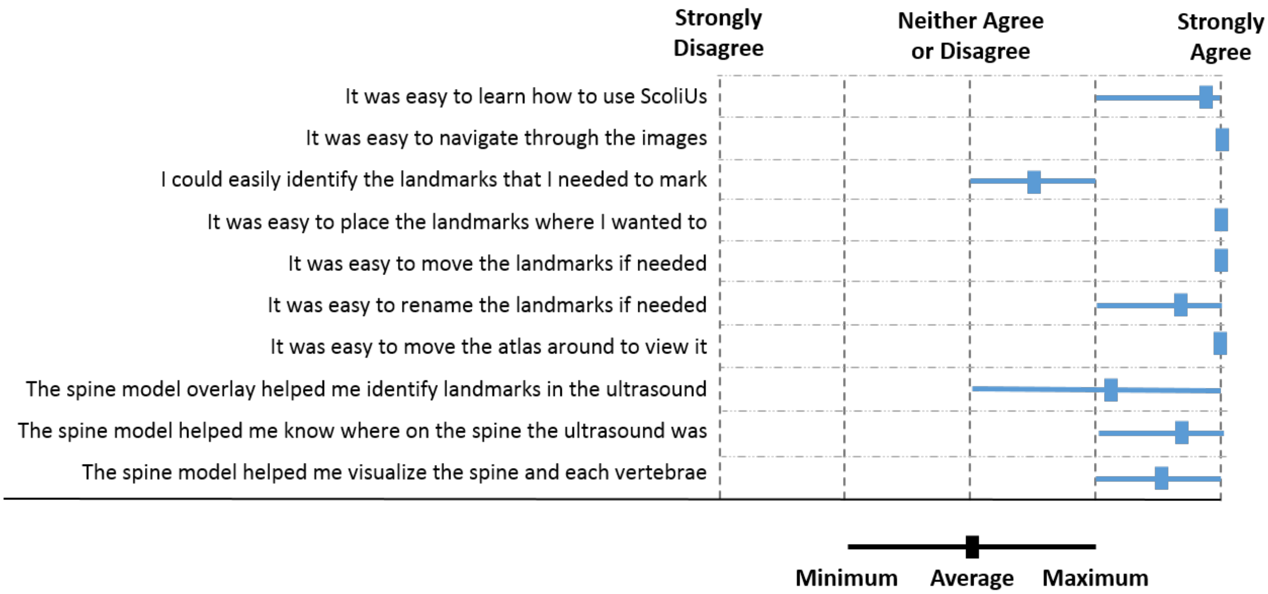


Figure 7. Min-Max-Average chart assessment of usability questionnaire responses.

4. DISCUSSION

Operators generally reported some difficulty in distinguishing landmarks from each other, and from other anatomical landmarks, such as ribs, when in the thoracic regions (Figure 7). Given than ultrasound cannot penetrate bone tissue, rendering only bone contours visible, the task of identifying intricate vertebral landmarks was non-trivial. The majority of the errors in the thoracic region, when using only ultrasound were associated with misinterpretation of the images. This occurred where the operators mistakenly identified the ribs, and not the transverse processes, most notably between T6 and T12 (Figure 5). When using the augmented view in these same regions, operators repeatedly attained higher identification rates when they were guided by the superimposed model and accompanying visual aids.

As operators progressed into the lower lumbar region of the spine (L3, L4, and L5), image quality and identification rates decreased (Figure 6). This is likely due to the subjects used in the study, with a mean age of 22.8. Typically, visibility in ultrasound images decreases with age, and as soft tissues thicken with increased body mass. As adolescent idiopathic scoliosis generally diagnosed in young adolescents (10 – 14 years old) and monitored through full development of the spine (16 – 22 years old), we do not perceive these issues to be as prevalent in pediatric patients.

5. CONCLUSION

A three-dimensional visual aid was developed to assist in vertebral landmark identification in tracked ultrasound by deformably registering and visualizing a healthy spine model in ultrasound space. Operators were able to identify significantly more landmarks with the visual aid than without it. Operators also found the visual aid to be helpful in identifying skeletal landmarks. Our results demonstrated the effectiveness and usefulness of the three-dimensional visual aid in vertebral landmark identification in tracked ultrasound images.

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