Authors' accepted manuscript. Paper presented at the 42nd Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC) (Montreal, QC, Canada, 20-24 July 2020). The final published version is available at https://doi.org/10.1109/EMBC44109.2020.9176689

A freehand ultrasound framework for spine assessment in 3D: a preliminary study

Edgar García-Cano, Fernando Arámbula Cosío, Fabian Torres Robles, Zian Fanti, Christian Bellefleur, Julie Joncas, Hubert Labelle, Luc Duong

Abstract— **X-ray imaging is currently the gold standard for the assessment of spinal deformities. The purpose of this study is to evaluate a freehand 3D ultrasound system for volumetric reconstruction of the spine. A setup consisting of an ultrasound scanner with a linear transducer, an electromagnetic measuring system and a workstation was used. We conducted 64 acquisitions of US images of 8 adults in a natural standing position, and we tested three setups: 1) Subjects are constrained to be close to a wall, 2) Subjects are unconstrained, and 3) Subjects are constrained to performing fast and slow acquisitions. The spinous processes were manually selected from the volume reconstruction from tracked ultrasound images to generate a 3D point-based model depicting the centerline of the spine. The results suggested that a freehand 3D ultrasound system can be suitable for representing the spine. Volumetric reconstructions can be computed and landmarking can be performed to model the surface of the spine in the 3D space. These reconstructions promise to generate computer-based descriptors to analyze the shape of the spine in the 3D space.**

Clinical Relevance— **We provide clinicians with a protocol that could be integrated in clinical setups for the assessment and monitoring of AIS, based on US image acquisitions, which constitutes a radiation-free technology.**

I. INTRODUCTION

Adolescent idiopathic scoliosis (AIS) is a common deformation of the spine that affects 1 to 4% of the adolescent population, with a greater prevalence among females [1]. Patients are diagnosed with AIS when the Cobb angle, the angle between the two most rotated vertebrae is greater than 10 degrees. The Cobb angle is the gold standard method to measure the curvature of the spine in X-rays [2]. The advantage of X-ray imaging is that allows visualizing the full shape of spine in standing position.

The treatment of AIS depends on the severity of the curvature and progression. Generally, the curve magnitude increases over time. However, how much the magnitude increases depends on each individual patient and the treatments should be adapted accordingly [3].

There are three main limitations with the current gold standard when it comes to assessing AIS: 1) It has been reported that the Cobb angle measurement could have a variation of up to 10 degrees [4]; 2) 2D radiographs present an oversimplification of the entire 3D shape of the spine, and 3) Patients with a high risk of curve progression are usually closely monitored, with follow-ups every 4 to 6 months. This results in frequent exposure to potentially harmful ionizing radiations, and, consequently, an increased risk for breast or lung cancer [5]–[7]. Therefore, a radiation-free imaging method for assessing and following up patients would be very beneficial.

Ultrasound (US) is the most inexpensive and widely used radiation-free diagnostic image technologies in medicine. Since US in B-mode only produces one 2D image at a given time, it is not suitable for analyzing the volume of structures. However, freehand 3D US systems have been developed and applied to augment the capabilities of US. This is a non-invasive and low-cost technique that allows the generation of a 3D view of the anatomy. Recently, freehand 3D US systems have been proposed as an alternative to characterize curvatures of the spines [8]–[12]. The Scoliosis Research Society has identified the analysis of the spine in 3D space as a step forward to improve the assessment, follow-up and treatment of AIS [3].

In this paper, we investigated a freehand 3D US system without any software or hardware customization to reconstruct the shape of the spine of healthy subjects.

II. MATERIALS AND METHODS

A. *Freehand 3D ultrasound system*

The freehand 3D US system consisted of a US scanner Toshiba Xario with a linear transducer with a width of 38 mm (Toshiba PLT-704AT/5-11MHz). A USB video capture card (Dazzle DVD Recorder HD, Pinnacle) was used to save the digital images produced by the US scanner on a computer. An electromagnetic measuring system (EMS) Aurora V2 (NDI Ontario, Canada) was used to record the 3D position and orientation of the US transducer in real time. This information was synchronized with the US image acquisition. According to the information provided by the manufacturer, the tracking system generates a magnetic field in the shape of a cube measuring 50 cm per side, with a root mean square error (RMSE) of 0.70 mm for position accuracy, and an RMSE of 0.20 degrees for orientation accuracy.

The Open-Source Toolkit for Ultrasound-Guided Intervention Systems (PLUS) [13] was used to perform the temporal and spatial calibrations between the transducer and

Edgar García-Cano and Luc Duong are with the École de technologie supérieure, 1100 Notre-Dame Street West, Montreal, Quebec H3C 1K3, Canada (corresponding author e-mail: gcano.edgar@gmail.com, luc.duong@etsmtl.ca).

Fernando Arámbula Cosío, Fabian Torres Robles and Zian Fanti are with the Instituto de Investigaciones en Matemáticas Aplicadas y en Sistemas and Centro Virtual de Computación, Universidad Nacional Autónoma de México Circuito Escolar S/N, Ciudad Universitaria, México, D.F., C.P. 04510 (e-mails: fernando.arambula@iimas.unam.mx, zian.fanti@iimas.unam.mx, fabian_torres@cvicom.unam.mx).

Christian Bellefleur, Julie Joncas and Hubert Labelle are with the [d]Research Center, Sainte-Justine Hospital, 3175 Côte-Sainte-Catherine, Montreal, Quebec, Canada. (e-mails: christian.bellefleur@recherche-ste-justine.qc.ca, julie.joncas@recherche-ste-justine.qc.ca, hubert.labelle@umontreal.ca).

the tracking sensor attached to it. This framework provides a convenient user interface to perform each of the steps involved in the calibration, contains functionalities for data acquisition from US systems and positioning devices, as well as volume reconstruction from US images, among others. In this study, we used the PlusApp-2.6-Win64 version. The software was tested on an Intel Core i7 3.6 GHz workstation with 16 GB of RAM.

B. *Study subjects*

A total of 8 healthy adults (5 females and 3 males; >= 18 years old, mean age of 30±5.13 years) were recruited for this study. The study was evaluated and approved by our institution's research ethics committee. All participants were informed of the acquisition protocol by the first author, and they signed a written consent form before being enrolled in this study.

C. *Acquisition protocol*

Acquisitions were performed in a controlled environment two days per week for two weeks; each time, they were done twice on the same day, once in the morning and once in the afternoon, for a total of 8 acquisitions per subject. The subjects were asked to use a gown to cover the front of their body, while leaving the back exposed. Prior to the first acquisition, we measured each subject's height, weight and waist circumference. Furthermore, two photographs of the trunk were taken, the first picture from the posteroanterior plane, and the second from the sagittal plane.

In this study, we performed three experiments. The first was done during the first week. We acquired the tracked US images by positioning the subject in front of a wall, at a distance of 15 cm from it (constrained setup). A vertical line was drawn on the wall, and was used as the reference to center the subject in the setup. In all the experiments, we adjusted the height of the magnetic field generator with respect to the height of the subject, positioning the former close to the subject's region of interest. Four acquisitions were performed for each subject using this setup. Since the transducer of the US was not wide enough to capture the whole vertebral body, we performed three sweeps. The first one was to the left of the centerline (L-sweep) of the spine (tip of the spinous process), the second one directly on the centerline of the spine (C-sweep), and the last one, to the right of the centerline of the spine (R-sweep).

In the second week, we performed the second and third experiments. For the second experiment, we separated the subjects from the wall. This meant that the patients were not limited by the closeness to the wall or aligned relative to any markings (unconstrained setup). We only put a red line on the floor to serve as a reference for the subjects, allowing them to know where to stand. Two acquisitions per subject were performed each day, one in the morning and one in the afternoon.

For the third experiment, we carried out the acquisitions using the same arrangement as for the constrained setup. However, in this session, the acquisitions were completed in two modes, fast and slow. The fast mode lasted approximately 20 seconds per scanning, while the slow mode took approximately 140 seconds. Only one acquisition per mode per patient was obtained.

Before scanning the subjects, an identification and marking of the vertebrae was performed by the operator through a palpation of the spinous process. First, the subject was sitting on a chair with their head bent forward, exposing the C6 and C7 vertebrae, which were identified and marked with a water-based marker. These vertebrae have the most prominent spinous process in the cervical section of the spine. Then, the subject curved the spine and, by palpation of the iliac crest bones, the intervertebral space between vertebrae L4 and L5 was marked. By counting downward from the C7 vertebra, the tips of the thoracic (T1 to T12) and lumbar (L1 to L4) vertebrae were identified and marked. Later, to validate the initial markings, a counting upward from the vertebra L4 to C7 was performed. This procedure was validated by two physicians.

Temporal and spatial calibrations between the US and the EMS were carried out prior to the acquisitions, and all the acquisitions were performed by the same operator. The US data was acquired in B-mode, with the subject in a natural standing position, barefoot, and without any support or platform that could alter their standing stability. Since the probe is tracked by the EMS, it must be always inside the magnetic field (50cm cube), hence, the back of the patient must be also within the same magnetic field, otherwise, the position and orientation will be lost. Due to natural respiratory and involuntary movements of subjects, their position could change during the acquisition, a reference tool that is part of the tracking system was attached to the subject. The reference tool is used to capture any unintentional shifting, and its location is used to correct the position and orientation of the tracked data. This reference tool was set three inches to the left of the intervertebral space between the vertebrae L4 and L5 on each subject.

Once all the vertebrae were identified with a water-based marker, the operator applied US gel on the region of interest to ensure image quality. He then requested that the subject stand still behind one of the red lines (depending on the experiment) on the floor, to be centered according to the vertical line on the wall (only for the constrained setup), to breathe shallowly, and to hold their sight forward, with arms relaxed. Prior to the acquisition, the subjects were also requested to remove any metallic objects. For long-haired subjects, we asked them to arrange their hair in an updo in order to allow an unobstructed view of the spine.

The calibration of the probe's frequency was set at 6.6 MHz, and the depth at 6 cm. The gain and the dynamic range were adjusted depending on the subject to enhance the quality of the images of the vertebrae. During each scanning, the operator moved the probe upward, starting at the fourth lumbar (L4). The position of the transducer was always adjusted to ensure that the spinous process was visible in the images. At the end of each acquisition, all subjects were questioned to see if they had experienced any inconvenience or discomfort during the procedure.

D. *3D reconstruction of the spine*

The data of each sweep was saved in a file containing the raw images with the transformations required to perform the volume reconstruction. As part of the pre-processing, all the data that belonged to the US configuration was removed from each of the images acquired, and only the region of interest was saved. PLUS library uses a customized version of the MetaIO image format to save the data [13].

The collected sweeps were used to generate a freehand 3D reconstruction. The reconstruction consists in arranging every US image into a 3D volume. Then, the value of each voxel is determined by the weighted average of all the coinciding pixels, or simply by the last coinciding pixel. A method based on the interpolation of nearby voxels was included to compute hole filling. This process was computed using the image utilities of the PLUS software with default parameter values [13].

E. Anatomical landmark identification

Once the reconstruction was generated, the volume was displayed in 3D Slicer [14] using the volume rendering module. Then, the spinous processes were manually identified on the volume reconstructions as anatomical landmarks. When the US waves go into the body, most of them are absorbed, and the rest are reflected to the transducer, which are used to generate the images. In the case of vertebrae, these reflect most of the sound waves, producing a bright section on the image. Also, since the waves cannot penetrate osseous matter, an acoustic shadow is presented behind each vertebral body.

From the sagittal view, we divided the reconstruction into two by identifying the inflexion point dividing the lumbar and thoracic sections of the spine. Vertebra L4 was the starting point at the bottom of the reconstruction. To recognize the spinous process, we looked for the acoustic shadows on the reconstruction. From the three sweeps, we used sweep 1 or 3 to locate the vertebrae in the sagittal plane (see **Fig 1a**). By modifying the volume rendering of sweep 1 or 3, we were able to see the structure of the surface of the vertebrae in greater detail. **Fig 1b** and **c** show the depth of the spinous process in the sagittal view by modifying the display values in 3D Slicer. Finally, using sweep 2, we aligned the landmarks to the centerline of the spine (see **Fig 1d**).

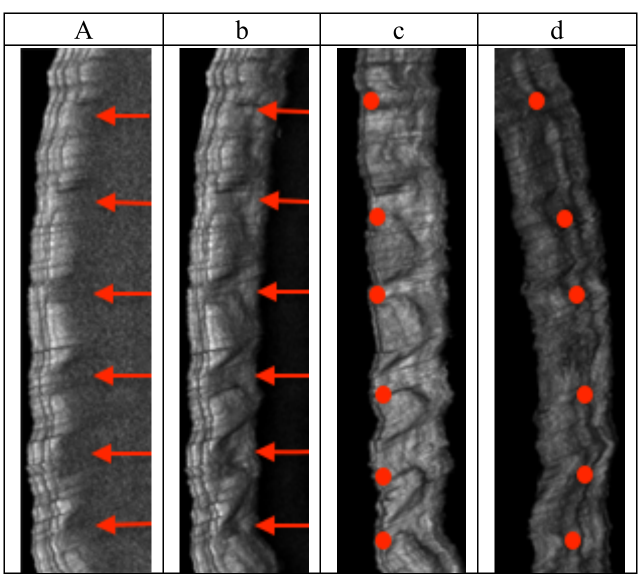

Fig. 1 Identification of spinous processes

A 3D point-based model of the spine's centerline was formed after all the processes were marked. All models were represented according to the reference frame defined by Stokes [2]. The horizontal axis x runs from the rear to the front of the subject; the horizontal axis y runs from right to the left, and the vertical axis z from the bottom upwards to the head of the subject. A rigid transformation was performed to align the 3D models, considering vertebra L4 as the origin of the reference frame.

III. Results

Each acquisition comprised three sweeps. In total, there were eight acquisitions per subject. The average time for the first acquisition was 20 minutes. For the following acquisition, the average time was 12 minutes, since no anthropometric characteristics or pictures were taken. Preparing the subject for each acquisition took around 5 minutes. This time included providing initial instructions, changing upper clothes for a gown, marking the vertebrae, positioning the subject and applying US gel. Table 1 shows the averages of the acquisition time and frames per sweep in three different setups, as well as the average of the disk space used to save the reconstruction data.

TABLE I. Statistics per sweep in different setups. As part of the acquisition, time, number of frames and disk space used are presented. Also, reconstruction time and disk space needed for each computed reconstruction is shown.

Setups	Average acquisition time (seconds)	Average frames	Average reconstruction time (seconds)	Average reconstruction (disk space in MB)
Exp 1†	40	1460	27	2
Exp 2‡	40	1370	27	2
Exp 3†	20	691	30	1.8
Exp 3†	140	3800	50	2.1

† constrained setup

‡ unconstrained setup

IV. Discussion

In this study, we model the shape of the spine by using a freehand 3D US system. The objective is to examine the challenges of these alternative systems in characterizing the spine in 3D space. There is no agreement regarding the characteristics of the hardware needed to set up these systems to scan the spine. However, in most studies, linear transducers [8], [12] are more frequently used versus convex ones [11]. Also, magnetic trackers [8], [12] are more recurrent than optical trackers [15]. In most of these studies, a custom-made software is implemented for the acquisitions and processing of the data; the exception is the work of Ungi et al. [16], who used the PLUS library [13].

The patient is required to be in standing position when modeling the shape of spine. This position is the gold standard in clinical practice to evaluate the spine morphology in the 3D space. Compared to X-rays, acquiring US images from the spine takes more time. When sweeping the spine, an involuntary motion is produced, either by the operator when pushing the transducer on the spine, or by the subject's natural breathing movements and while trying to maintain a stable position. Zheng et al. [11] used a support frame to fix the shoulders and the hips during their acquisitions. However, Bellefleur et al. [17], showed that fixing the hips or shoulders produces a change in the natural position of the subject. Hence, we preferred to adopt a natural position in our experiments.

Each of the three sweeps for each acquisition can be reconstructed individually, or they can be put together to generate a unique volume. The disadvantage of a unique volume is that with it, identifying the structure of the vertebrae is more time-consuming and less evident, as compared with the three individual reconstructions. For this reason, we decided to use the three separate reconstructions to perform the vertebral-level identifications.

Landmark identification is not a trivial task. The thoracic section contains the ribs, which produce similar reflections to those of the vertebrae. The lumbar section contains more muscles than does the thoracic section, and therefore, the muscles tend to occlude the vertebrae. In contrast to radiographs, in US images, only the surface of certain regions of the vertebrae are visible.

In this study, we were able to mark the spinous processes to generate a 3D point-based model of the spine. This was performed manually by the operator using the volume-rendering module of 3D Slicer.

During the acquisition, the subjects reported that they felt more comfortable in the constricted setup, since they had a reference while looking forward, and could maintain their position. Also, the operator indicated that the motion of the subject during the acquisitions with the unconstrained setup was more noticeable. Thus, we used the constrained setup for experiment 3. For the acquisitions in this experiment, the operator put extra marks on the backs of the subject. These marks helped the operator control the motion of the transducer and cover regions of the spine equally in both the fast and slow sweeps.

The number of frames per sweep (greater or smaller) had an impact on the resolution of the volume reconstruction. Since the operator could not keep the same pace during the sweeps, the number of slices varied in different regions of the spine. When the spacing between slices was large, the resolution of the volume was low. On the other hand, when the slices were close, a higher resolution volume reconstruction could then be generated. Since the errors were similar in all three experiments, we considered that 40 seconds per acquisition allows a good compromise between time, the comfort of the subject and of the operator, and the number of frames per sweep (around 1400).

For our approach, we used a volume reconstruction and marked the spinous processes to generate a 3D representation of the spine. Although the landmark identification is a time-consuming process, we were able to identify the spinous processes in the 3D space.

V. Conclusion

The proposed method is promising for the non-invasive assessment and monitoring AIS. This assessment could be performed by analyzing the landmarks detected on the 3D reconstruction of the spine, which is generated by tracking US images from the back of the subject, and provide more information about the morphology of the spine than 2D measurements. For such an assessment, we consider that the constrained setup would favor the evaluation of patients holding still in a stable natural position. The acquisition could be performed in 40 seconds. This time represents a decent trade-off between the number of frames per acquisition and the comfort of patients and operators. Since this framework uses a radiation-free technology, patients could be examined more frequently and be subjected to fewer X-rays for follow-ups, which could help clinicians adapt patients' treatments more effectively.

In future work, we will use a wider transducer to perform only one sweep per subject, which will reduce the acquisition time. Also, the transducer should have a higher penetration capability, to allow an evaluation of whether landmarks can be extracted from freehand 3D reconstructions on overweight subjects. Other tracker systems will be evaluated to capture the full shape of the spine.

Acknowledgment

This research was funded by a scholarship from CONACYT CVU 323619 in Mexico and the Fonds de recherche du Québec – Nature et technologies (FRQNT), file 194703, and the Ministère des Relations internationales et de la Francophonie.

References

[1] J. C. Cheng *et al.*, "Adolescent idiopathic scoliosis," *Nat. Rev. Dis. Prim.*, vol. 1, p. 15030, 2015.

[2] I. A. F. Stokes, "Three-dimensional terminology of spinal deformity. A report presented to the Scoliosis Research Society by the Scoliosis Research Society Working Group on 3-D terminology of spinal deformity.," *SPINE*, vol. 19, no. 2. pp. 236–248, 1994.

[3] H. Labelle, C.-E. Aubin, R. Jackson, L. Lenke, P. O. Newton, and S. Parent, "Seeing the spine in 3D: how will it change what we do?," *J. Pediatr. Orthop.*, vol. 31, no. 1 Suppl, pp. 37–45, 2011.

[4] Y. Majdouline, C.-E. Aubin, M. Robitaille, J. F. Sarwark, and H. Labelle, "Scoliosis Correction in Adolescent Idiopathic Scoliosis," *J. Pediatr. Orthop.*, vol. 27, no. 7, pp. 775–781, 2007.

[5] M. M. Doody, J. E. Lonstein, M. Stovall, D. G. Hacker, N. Luckyanov, and C. E. Land, "Breast cancer mortality after diagnostic radiography: findings from the U.S. Scoliosis Cohort Study.," *Spine (Phila. Pa. 1976).*, vol. 25, no. 16, pp. 2052–2063, 2000.

[6] C. M. Ronckers, M. M. Doody, J. E. Lonstein, M. Stovall, and C. E. Land, "Multiple diagnostic X-rays for spine deformities and risk of breast cancer.," *Cancer Epidemiol. Biomarkers Prev.*, vol. 17, pp. 605–613, 2008.

[7] C. M. Ronckers, C. E. Land, J. S. Miller, M. Stovall,

J. E. Lonstein, and M. M. Doody, "Cancer mortality among women frequently exposed to radiographic examinations for spinal disorders.," *Radiat. Res.*, vol. 174, no. 1, pp. 83–90, Jul. 2010.

[8] C. W. J. Cheung, Siu-Yin Law, and Y.-P. Zheng, "Development of 3-D ultrasound system for assessment of adolescent idiopathic scoliosis (AIS): And system validation," *2013 35th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, pp. 6474–6477, 2013.

[9] C. J. Cheung, G. Zhou, S. Law, and T. Mak, "Ultrasound Volume Projection Imaging for Assessment of Scoliosis," *IEEE Trans. Biomed. Eng.*, vol. 34, no. 8, pp. 1760–1768, 2015.

[10] F. Ibrahim, J. Usman, M. S. Mohktar, and M. Y. Ahmad, "Quantitative Evaluation of Spinal Coronal Curvature for Scoliosis Using a Fast 3-D Ultrasound Projection Imaging Method," *IFMBE Proc.*, vol. 56, pp. 313–317, 2016.

[11] Y.-P. Zheng *et al.*, "A reliability and validity study for Scolioscan: a radiation-free scoliosis assessment system using 3D ultrasound imaging," *Scoliosis Spinal Disord.*, vol. 11, no. 1, p. 13, 2016.

[12] C. W. J. Cheung, G. Q. Zhou, S. Y. Law, K. L. Lai, W. W. Jiang, and Y. P. Zheng, "Freehand three-dimensional ultrasound system for assessment of scoliosis," *J. Orthop. Transl.*, vol. 3, no. 3, pp. 123–133, 2015.

[13] A. Lasso, T. Heffter, A. Rankin, C. Pinter, T. Ungi, and G. Fichtinger, "PLUS: Open-source toolkit for ultrasound-guided intervention systems," *IEEE Trans. Biomed. Eng.*, vol. 61, no. 10, pp. 2527–2537, 2014.

[14] A. Fedorov *et al.*, "3D slicer as an Image Computing Platform for the Quantitative Imaging Network," *Magn. Reson. Imaging*, vol. 30, no. 9, pp. 1323–1341, 2012.

[15] T. K. Koo, J. Y. Guo, C. Ippolito, and J. C. Bedle, "Assessment of scoliotic deformity using spinous processes: Comparison of different analysis methods of an ultrasonographic system," *J. Manipulative Physiol. Ther.*, vol. 37, no. 9, pp. 667–677, 2014.

[16] T. Ungi *et al.*, "Spinal curvature measurement by tracked ultrasound snapshots.," *Ultrasound Med. Biol.*, vol. 40, no. 2, pp. 447–54, Feb. 2014.

[17] C. Bellefleur, J. Dansereau, A. Koller, and H. Labelle, "Evaluation of the efficiency of patient stabilization devices for 3D X-ray reconstruction of the spine and rib cage," *Stud. Health Technol. Inform.*, vol. 88, no. Figure 1, pp. 127–131, 2002.