Portable optically tracked ultrasound system for scoliosis measurement

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Abstract Monitoring spinal curvature in adolescent kyphoscoliosis requires regular radiographic examinations; however, the applied ionizing radiation increases the risk of cancer. Ultrasound imaging is favorable over X-ray because it does not emit ionizing radiation. It has been shown in the past that tracked ultrasound can be used to localize vertebral transverse processes as landmarks along the spine to measure curvature angles. Tests have been performed with spine phantoms, but scanning protocol, tracking system, data acquisition and processing time has not been considered in human subjects yet. In this paper, a portable optically tracked ultrasound system for scoliosis measurement is presented. It provides a simple way to acquire data in the clinical environment with the aim of comparing results to current X-ray-based measurement. The workflow of the procedure was tested on volunteers. The customized open-source software is shared with the community as part of our effort to make a clinically practical system.

Keywords. Adolescent Idiopathic Kyphoscoliosis, Scoliosis, Kyphosis, Tracked sonography, Tracked ultrasound snapshot

Introduction

1.1 Adolescent idiopathic scoliosis

The most frequent form of spinal deformities is adolescent idiopathic scoliosis. Studies conducted in different countries found its prevalence between 1% and 5%, therefore, it is considered a common disease in children [10, 13, 20]. The etiology of this disease has not yet been fully discovered, however, genetic factors influence both the incidence and the severity of scoliosis [19]. It is most commonly diagnosed in early adolescence (9-12 years of age) and progresses until the spine reaches full development, around the age of 18-20 years.

Symptoms of adolescent idiopathic scoliosis include lateral curvature of the spine in straight standing position, kyphosis, and permanent vertebral rotation around the axis of the spine. The severity of scoliosis is characterized by the angle of curvature between vertebrae above and below the curvature (Cobb angle). Therapeutic proto-cols are

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based on Cobb angle: i) curvatures less than 20 degrees require X-ray moni-toring every 3-6 months, depending on the rate of progression; ii) scoliosis between 20-40 degrees is treated with bracing; and iii) scoliosis over 40 degrees, or if chest deformation causes breathing difficulties, is treated surgically, permanently fusing the vertebrae in a straight position. Scoliosis monitoring continues after surgical treatment as well using regular spine imaging. About 10% of adolescent scoliosis cases progress to a state when they require therapy.

Although screening children in the early adolescent age for scoliosis would be nec-essary for optimal treatment and optimal use of clinical resources, currently afforda-ble screening methods are inaccurate [1]. Therefore, patients may be diagnosed when scoliosis progressed in an advanced stage.

Once diagnosis is confirmed, it is important to frequently monitor all cases to make sure progression is detected early and appropriate therapy is started. However, frequent X-ray imaging in children can lead to increased risk of cancer. Girls who undergo regular spine X-ray, have a nearly twofold risk of breast cancer as adults [4, 7]. Another study found that repeated X-ray exams in childhood significantly contribute to leukemia and prostate cancer [12]. Further studies may be needed to establish accurate estimates of the risks of X-ray, but a safe scoliosis monitoring method would improve the health of this young patient population.

1.2 Scoliosis monitoring techniques

Radiation-free scoliosis monitoring methods have been investigated in the past, but none of them have been successful in replacing X-ray in the clinical practice. The optimal method needs to be: free of ionizing radiation, accessible to the patient population, and accurate for therapeutic decision making.

Magnetic resonance imaging (MRI) is a safe and accurate alternative to X-ray. Open MRI machines permit scanning from a standing patient position, making these images suitable for scoliosis angle measurement. Unfortunately, MRI is less accessible than X-ray due to its high cost and the patient has to stand motionless for several minutes while the scanner captures the entire spinal column, which further limits its use for routine monitoring in an adolescent population [3].

Inspection will yield visual signs of scoliosis on the back of the patient. Visual signs of spinal curvatures have been measured using computerized topographic scans of the skin surface using laser scanners and stereo camera technology [6]. However, surface scans are not informative enough to support therapeutic decisions [5] .

Ultrasound does not have a large enough field of view to directly visualize spinal curvatures. There have been attempts to use indirect ways of measuring spinal curvatures with ultrasound. A correlation between vertebral rotation and scoliosis angles in untreated patients was discovered [14] but this correlation is unreliable and completely lost in patients receiving therapy [9].

One of the recently emerging imaging modalities is tracked ultrasound: a combination of conventional ultrasound and position tracking technology. With tracked ultrasound it is possible to create a 3D reconstruction from 2D ultrasound images. Position tracking of the ultrasound transducer allows to display the whole spine region in 3D. Experimental results have confirmed that landmarks on reconstructed image volumes could be used to monitor spine curvature angles [2, 11]. Tracked ultrasound appears to be the only alternative to X-ray that fulfills all three requirements: safety, accessibility and accuracy.

A new method for scoliosis measurement has been developed previously, and tested on phantom models [17]. Tracked ultrasound (TUS) has been successfully used in medical imaging and image-guided interventions. In particular, it has been tested in spinal injection navigation [16] and vertebra localization for spine surgery [18].

1.3 Objectives

Our goal is to develop a clinically practical system for scoliosis monitoring. As part of this translational effort we build upon of the proof of concept phantom system proposed by [17] and present a portable TUS system based on a new ultrasound machine and optical tracking. We streamline the workflow of the procedure so it can be easily replicated by other researchers and operated without deep technical background. The workflow is implemented as an open-source module of the 3D Slicer[1] application, and can be conveniently installed from the 3D Slicer extension manager (app store). We evaluated the usability of the developed TUS system.

Materials and Methods

2.1 System design

The TUS system has three main components. An optical tracker (Micron Tracker, Claron Technologies Inc., Toronto, Ontario, Canada), a portable ultrasound scanner with USB connection (General Purpose 99-5914 Probe, Interson Corporation, Pleasanton, CA, USA), and a laptop computer (Fig. 1).

Contrary to [17] we use an optical tracker instead of an electromagnetic tracker. Optical trackers can use wireless markers, are generally more accurate and are not affected by metallic or electronic objects in the environment. Sensors used as reference markers are made of paper, which is very cheap and also makes feasible the tracking of multiple reference markers. This can be used for patient motion detection and to be more robust to markers occlusions.

Hardware interfaces are implemented in the PLUS software[2] [8]. PLUS implements an abstraction layer over tracker and imaging devices, and provides calibration and synchronization methods for tracked ultrasound. It transmits tracked images to 3D Slicer through the OpenIGTLink protocol [15].

The interface for the portable Interson ultrasound probe was implemented in PLUS. Nevertheless, the system can be used with any of the ultrasound machines and trackers supported by PLUS, which makes reproducibility of the system convenient.

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[1] www.slicer.org

[2] www.plustoolkit.org

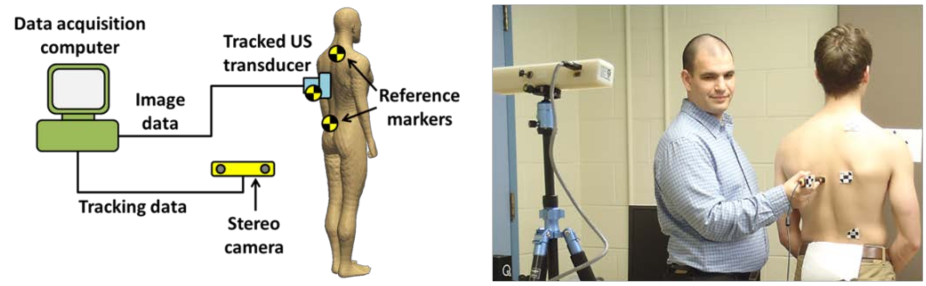

Fig. 1 Schematics of the TUS system (left panel), and the prototype system in use (right panel)

2.2 System setup

The hardware described in previous section was integrated using the PLUS library. Configuration files to connect different acquisition systems are provided in PLUS website. In particular, sample configuration files used to connect the Interson Probe and the Micron Tracker can be found in the PLUS website.

As with any TUS system, it requires a calibrated probe. If US imaging parameters are not changed, the calibration can be done once and saved in the configuration file. We found that 10 cm depth is adequate for this application.

When the patient comes in, at least one reference marker is attached to his back. This reference marker is used because the patient may move during the acquisition. The assumption is that the relative position between the transverse processes and the reference marker is the same during the whole scanning.

The tracker should be facing a wall where a reference marker must be attached. During the acquisition, the patient will be asked to place in front of the wall. The reason why a marker is attached to the wall is to be able to project the transverse processes positions to the wall. This makes the angle measurements compatible with the traditional procedure done on frontal X-ray radiographies.

2.3 Slicelet implementation for spinal curvature measurement

We designed and implemented a custom workflow and user interface, called a slicelet, based on the 3D Slicer application platform and its SlicerIGT extension[3]. Slicelets are custom user interfaces programmed for the 3D Slicer application that typically support a single clinical workflow without the complexity of the full 3D Slicer user interface. Our slicelet helps in the localization of vertebral transverse processes as landmarks along the spine to measure curvature angles. We build upon [17] and added new features and interfaces to streamline the procedure, reducing the lengthy analysis time.

The slicelet currently consists of the steps depicted in Fig. 2: communication with acquisition devices, tracked ultrasound snapshots and continuous tracked ultrasound

[3] www.slicerigt.org

video acquisition, localization of vertebral transverse processes in the acquired images and computation of angles between vertebrae.

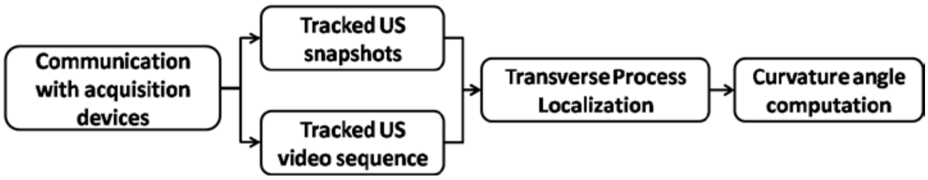

Fig. 2 Workflow of the slicelet

Communication with acquisition devices

Images and tracker positions are provided by the PLUS server. Once the PLUS server is running, the status of the communication can be seen in the slicelet as shown in Fig. 3. A tool viewer, with a convenient color code, shows markers and tools visibility. This tool is very useful when working with optical trackers.

At this point of the procedure, it is important to check the working volume and also to make sure that the markers and the probe are visible in the region of interest. The wall reference marker does not need to be visible during the acquisition, but it is assumed that the relative position between the tracker and the wall does not change during patient scanning.

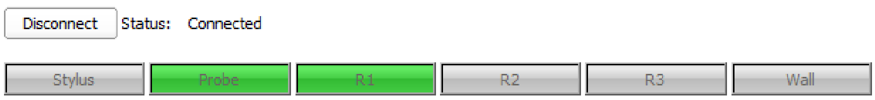

Fig. 3 The tool viewer shows the visibility of the markers. The spatial position of the US probe (Probe), three references markers (R1, R2 and R3) attached to the patient, a Stylus and a marker attached to the wall that faces the patient are acquired by the software. Currently, only the Probe, R1 and the Wall are used to compute the angle between the vertebrae but in the future we plan to explore the use of the others to improve the workflow

Tracked US images acquisition

The scoliosis monitoring slicelet can be used to measure vertebral angles using both: tracked ultrasound snapshots and video sequences. We decided to offer both possibilities because transverse process localization is easier with snapshots, while time occupied during patient scan is lower when video sequences are acquired. In both cases, data can be saved to be inspected afterwards and can also be used to build a database.

If the physician feels comfortable using snapshots, he must scan the patient until he finds a transverse process and then a snapshot is acquired with the aid of the table shown in Fig. 4. To reduce patient waiting time, a quick scan may be preferred. The software offers the possibility to acquire sequences for the left and right side of the spine. Those video sequences are stored, and used afterwards, to localize the images where the transverse processes are visible.

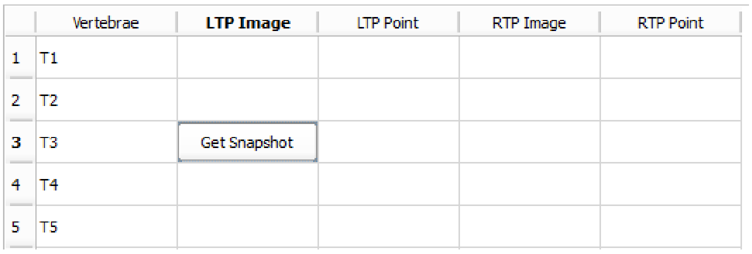

Fig. 4 The table is used to acquire the Left Transverse Process (LTP) and Right Transverse Process (RTP) images and to mark the LTP and RTP points.

Transverse processes localization

Regardless of the method used to acquire the images, left and right transverse process must be manually marked in the corresponding images. When the left and right transverses processes of a vertebra are already located, the software automatically computes and shows the segment determined by the two transverse processes in a 3D Scene. When the transverse process points that define two vertebrae lines are already acquired, it is possible to compute the angle between them as shown in Fig. 5.

Fig. 5 When the transverse processes points that define a vertebra line are already acquired the corresponding row in the table is shown in green. When two lines are already defined is possible to compute the angle between them

Curvature angle computation

The segments that determine the angle between two vertebrae are projected to the wall that faces the patient and then the angle between the projected segments is computed. The segments are projected to the wall to simulate the X-ray projection and to have an angle comparable with the Cobb angle.

Results

The workflow described in previous section has been implemented; it provides all of the required capabilities for scoliosis monitoring using tracked ultrasound snapshots and video sequences.

As an example, Fig. 6 shows the tracked ultrasound snapshots acquired during a procedure. Red points correspond to the transverse processes locations in the ultrasound images. The red lines connect two transverse process that belong to the same vertebra.

The software can be installed from the extension manager of the latest version of the 3D Slicer application. The extension manager is a plug-in mechanism that allows reasearchers and developers to add extensions to the core 3D application. Those extensions can be installed by the user after installing the main 3D application without any programming required. The name of the slicelet is Scoliosis Monitoring and is part of the Scoliosis extension. All software used in this study is open-source, freely available for research or commercial use without any restrictions. This allows incremental reasearch, and focus work on unsolved problems like transverse process automatic segmentation or spine volume reconstruction.

The whole procedure can be tested with various ultrasound and tracker systems supported by PLUS. This includes the most popular tracking systems (Polaris, Micron, Aurora, Ascension) and the Interson USB and Ultrasonix ultrasound machine. Besides, Epiphan or Imaging Control frame grabber can be used to acquire the images of any ultrasound machines with video output.

The workflow was implemented with the portable USB ultrasound probe, which shows sufficient image quality for this application. The size and weight of the acquisition systems that were used allows to pack and move the system, which will make this a portable solution for scoliosis measurement in future clinical applications.

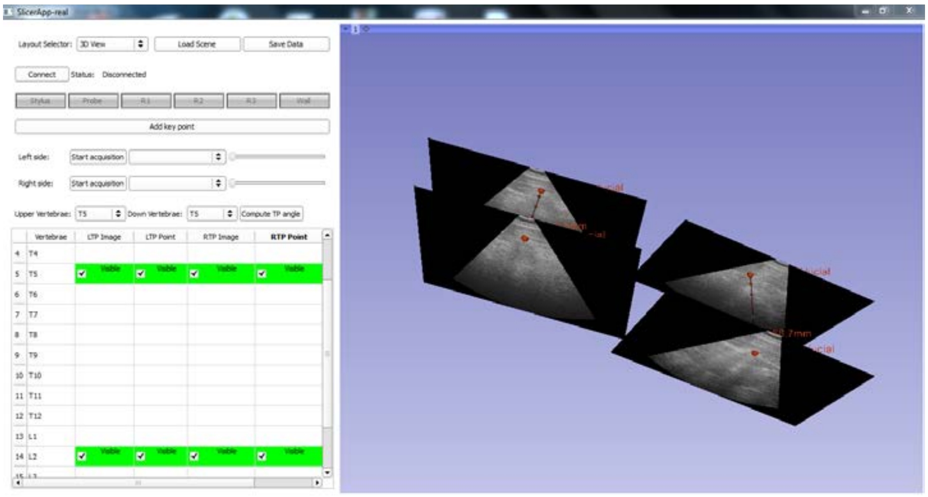

Fig. 6 The vertebral lines are shown in the 3D scene. In this case the transverse processes corresponding to L2 and T5 vertebrae were acquired

Discussion

Although some previous works have shown the feasibility of tracked ultrasound to localize vertebral processes to measure spinal curvature, the problem is still open. We believe we are sharing a valuable tool that can be very useful to show physicians the potential of the methods and also to identify the main challenges we need to tackle in order to bring scoliosis monitoring with ultrasound into routine clinical use.

The portable optically tracked ultrasound system can save ultrasound video sequences along with tracking data. This enables the acquisition of experimental studies from volunteers and patients looking forward to building the essential dataset for the research in the field. Currently, vertebral transverse processes are marked manually by the physician and the data is used to compute the curvature angle. This expert segmentation can also be saved in the application and this valuable information will enable testing future automatic segmentation algorithms.

The tool is integrated into the Slicer platform and the Slicer-IGT extension. This Slicer platform can be freely used by the research community and it enables an easy manipulation of the tracked ultrasound studies and the integration with other modalities such as X-ray, CT or MRI. Future developments in the field can also be rapidly integrated into Slicer as extensions (its plug-in mechanism) and shared through the Slicer app-store.

Our next step in this ongoing project will be to study the correlation between the radiography and sonographic curvature measuring methods in real patients. Another future research line will be related to the segmentation of the transverse processes. In some patients it is hard for the physician to correctly identify some transverse processes. We plan to explore the feasibility of using tracked ultrasound volume reconstructions of the spine in conjunctions with models of the spine. A nice 3D model of the spine might give the physician some spatial information that could greatly facilitate the transverse process localization procedure.

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