Tracked Ultrasound in Navigated Spine Interventions

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Abstract Ultrasound is an increasingly popular imaging modality in image-guided interventions, due to its safety, accessibility, and low cost. But ultrasound imaging has a steep learning curve, and requires significant coordination skills from the operator. It is difficult to interpret cross-sectional anatomy in arbitrary angles, and even more challenging to orient a needle with respect to the ultrasound plane. Position tracking technology is a promising augmentation method to ultrasound imaging. Both the ultrasound transducer and the needle can be tracked, enabling computer-assisted navigation applications in ultrasound-guided spinal interventions. Furthermore, the patient can also be tracked, which enables fusion of other imaging modalities with ultrasound. In this chapter, we first present the technical background of tracked ultrasound. We will review how to build research systems from commercially available components and open-source software. Then we will review some spine-related applications of tracked ultrasound modality, including procedural skills training, needle navigation for anesthesia, surgical navigation, and other potential applications.

1 Introduction

Ultrasound is becoming a ubiquitous imaging tool in many medical specialties due to its safety, portability, and low cost. Recent ultrasound devices fit in the physicians' pockets, and instantly provide real-time images of almost all anatomical regions without radiation risks to the patient or physician. Spine is, however, one of the particularly difficult areas for visualization with ultrasound. Bones and ligaments are close to the skin, and they cast acoustic shadows by reflecting the majority of the ultrasound waves, not letting through enough for visualization of deeper anatomical structures. Furthermore, stiff tissue layers of spine muscles

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attenuate the energy of the ultrasound more than other tissues with more water content. One can still find sonographic landmarks along the spine that can be used to obtain limited view of the anatomy. These landmarks are often used during interventions, as the operator finds the way of the needle based on these points.

Ultrasound combined with position tracking is a promising technology that has recently reached the clinical device market. It allows needle navigation methods that show the 3D position or projection of the tracked needle relative to the tracked ultrasound image. This visual aid enhances the accuracy of needle insertions when the target is directly visible on ultrasound. Some commercial ultrasound machines recently offer fusion of CT or MR images to real-time ultrasound, which is also a very promising avenue in computer assisted spine interventions. The real-time nature of ultrasound combined with the resolution and contrast of other image modalities may revolutionize image-guided spine interventions, enabling more procedures to be performed in a minimally invasive way. In this chapter, we will focus on the tracked ultrasound technology, and show some of its promising applications that may become routine procedures in the hands of surgeons, anesthesiologists, or interventional radiologists.

2 Ultrasound in Spinal Needle Guidance

Ultrasound has been in use for decades in guidance of invasive procedures in the spine. Although most needle insertion procedures that are commonly performed, can be completed blindly with knowledge of the anatomy. The procedural difficulty of spine interventions has a wide range depending on target structures and individual patients. For example, the most common procedure is lumbar puncture, needle insertion into the spinal canal between two lumbar vertebrae. Lumbar puncture is generally thought of as a simple procedure that every physician is able to perform without image guidance or other forms needle guides. However, in obese patients or degenerative spines, even this procedure can be so difficult that it requires ultrasound or fluoroscopic guidance. There are significantly more difficult procedures, such as selective nerve blocks, that are only attempted using CT or MRI guidance.

The most common use of spine ultrasound is to find vertebral interspaces for lumbar puncture in difficult cases. Ultrasound is helpful when the spine is covered by thick fat tissue, or when spine pathologies prevent conventional navigation by palpation. In these cases, ultrasound scanning can be done either before needle insertion, or during needle insertion to provide real time guidance as the needle approaches its target. The first technique uses landmarking. Ultrasound is used before needle insertion to find the space between two spinous processes, and marking it with a pen on the patient's skin. The needle is introduced at the marked point, which has a high probability of leading to the space between two vertebrae. In case of the second technique, imaging can be performed simultaneously during needle insertion too, to provide real time visual feedback on the needle position.

Real time guidance requires more experience and coordination skills, because the two hands of the operator are engaged in different tasks, and the attention is divided between image interpretation and needle manipulation. The difficulty in learning this complex skill is probably the only disadvantage of ultrasound-guided needle insertions in the spine region [1].

3 Tracked Ultrasound Systems

Although ultrasound has proven to be a great help in needle insertions, the combination of ultrasound imaging and position tracking, called tracked ultrasound, offers as many opportunities in the hands of interventionists as a new imaging modality. Tracked ultrasound systems have just reached the clinical market, and their future role in clinical practice will be subject to how much evidence will be found on its benefits. But the future looks promising for tracked ultrasound. It is one of the most affordable imaging modalities, and prices will drop with future generations of devices. It helps spatial coordination of the needle relative to ultrasound image position, which is one of the most challenging skills in medical interventions; therefore probably many operators will take advantage of this technology. Tracked ultrasound systems are relatively easy to build in research laboratories, and are exciting tools in experimental and clinical research. Therefore, we dedicate this section to the technical details of tracked ultrasound systems, with the goal of making them easily reproducible for a wide audience. We focus on the adaptability to existing ultrasound and tracking devices, rather than recommending a single set of hardware components. We encourage every reader who has access to an ultrasound machine and a position tracker to try assembling tracked ultrasound, because most medical specialties can take advantage of such an enhancement of ultrasound imaging in the guidance of interventions.

4 Position Tracking in Ultrasound-Guidance

Position tracking technologies evolved rapidly in the past decades, and have made it possible to track the ultrasound transducer, as well as the needle during interventions. This allowed development of navigation software for needle guidance. Medical navigation applications are much like GPS navigators developed for cars. They take advantage of position tracking by showing the user where they are on a geographical map. This makes the map extremely easy and intuitive to use. Medical navigation software enhances traditional medical images and image-guided interventions by showing the real-time positions of medical instruments on these images. Although the medical interventionist community is more careful accepting new technologies than car drivers.

Table 1 Summary of advantages and disadvantages of optical and electromagnetic tracking technologies

	Optical tracking	Electromagnetic tracking
Advantages	• Accuracy ~1–0.1 mm • Does not depend on objects in its environment • Large range (several meters) • Wireless position markers	• Can track without line of sight (inside body) • Position sensors can be small to fit in needles and catheters (~0.5 mm)
Disadvantages	• Requires line of sight • Optical markers are relatively large	• Accuracy ~1–2 mm • Limited range (typically 20–60 cm) • Affected by ferromagnetic metals in its environment • Wired position sensors

Common position tracking devices in medicine are using either optical or electromagnetic technology (Table 1). Optical tracking uses cameras and optical position markers that the computer automatically detects on the camera images. The main advantages of optical tracking are its accuracy and robustness. The main disadvantage is that the position markers need to be relatively large and in the line of sight of the cameras. An emerging alternative to optical tracking is electromagnetic tracking technology that uses an electromagnetic field generator, and wired position sensors that detect their position relative the field generator. Electromagnetic trackers generate a known changing magnetic field, and measure the currents in sensor coils that are induced by the changing magnetic field. A signature of currents in the sensor is unique to its position relative to the field generator. The main advantage of electromagnetic tracking is that it does not require line of sight, although it is less accurate and is sensitive to certain metal objects, especially electric devices in its environment.

Tracking the ultrasound transducer expands the possibilities in ultrasound-guided needle interventions. By attaching a position tracker to the ultrasound transducer and the needle, their relative positions can be computed and visualized, even when the needle is not in the ultrasound imaging plane. Such a tracked system can be further enhanced by attaching another position sensor to the patient. This allows visualization of the needle not only relative to the ultrasound image, but relative to pre-procedural CT, MRI, or other models of patient anatomy.

There are other technologies for needle tracking in ultrasound-guided interventions beyond optical and electromagnetic. The most simple and oldest way is mechanical tracking is to attach a passive needle guide to the ultrasound transducer. Ultrasound guidance methods for abdominal interventions use mechanical needle guides, but they constrain the needle motion to a single line relative to the ultrasound imaging plane. This line is displayed on the ultrasound display, so the operators see where the needle will be inserted relative to the image. The needle target can be chosen by moving the transducer with the fixed needle guide. But in the spine, the target areas are only visible from a limited range of angles. And the needle usually has to go through a narrow space. Therefore, spinal interventions require more freedom of motion of both the transducer and the needle, so mechanical needle guides are typically not suitable for these procedures. Optical and electromagnetic position tracking, however, allows any position and angle of the needle relative to the ultrasound transducer. Using the tracked position information, navigation software can display the needle relative to the ultrasound image in real time.

5 Hardware Components

Experimental tracked ultrasound systems have been studied for over a decade in spinal needle guidance applications. But the first products approved for clinical use only appeared recently on the market. In this section we describe the architecture of tracked ultrasound systems in general, and how research prototypes can be built from low-cost components.

Tracked ultrasound hardware systems are composed of a conventional ultrasound machine and an added position tracker. In an experimental setting, there is often a dedicated computer for tracked ultrasound data processing, because ultrasound machines either restrict installation of research software or their hardware is not powerful enough for running additional applications. We will discuss a system design with a dedicated computer for our research application, because it can be easily built from existing components in any research laboratory (Fig. 1).

The majority of tracked ultrasound systems use electromagnetic technology for position tracking. Although optical tracking can also be used, the line of sight often breaks when the transducer is moved around the patient. This causes loss of

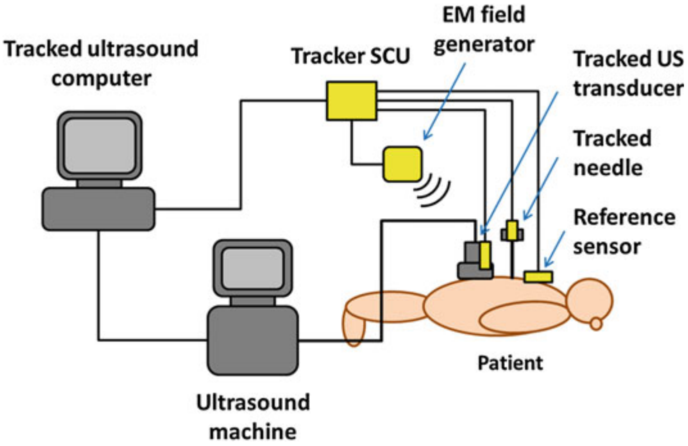


Fig. 1 Schematic layout of tracked ultrasound systems using electromagnetic (*EM*) position trackers

tracking signal, which is inconvenient for the operating staff. Electromagnetic trackers do not need line of sight, and—if the field generator can be placed close enough to the operating region—it is usually accurate enough.

When choosing an ultrasound machine for a tracked ultrasound system, we should first consider systems that are already integrated with position tracking, and have research interface that provides real-time access to the ultrasound image and tracking data streams. If tracking is not already available in the chosen ultrasound machine, an external tracker needs to be attached to the transducer. Even if the ultrasound machine does not offer digital access to the images and imaging parameters, most ultrasound machines have a standard video output that can be tapped into using a video grabber device.

Fixing the tracking sensor on the ultrasound transducer is not difficult using glue or a rigid clip. If sterile environment is needed, the transducer along with the sensor can be placed in a sterile bag. The reference position sensor needs to be fixed to the patient as rigidly as possible. Since the reference sensor provides the link between the patient and the navigation coordinate system, it makes the system more convenient to use if anatomical directions are marked on the reference sensor, so it can be placed in the same orientation. A reference sensor holder can provide the anatomical markers, along with an interface that can be firmly attached to the skin using an adhesive sheet (Fig. 2). Tracking the needle is the most challenging task, especially if the needle is thin (smaller than about 17 Ga) and bends during insertion. A larger, more accurate sensor can be clipped to the needle using a disposable plastic interface. But when the needle bends, a clipped sensor at the hub will not give accurate information on the tip position. Smaller sensors can be integrated in the needle stylet to provide direct tip tracking. Some companies offer electromagnetically tracked stylets approved for clinical use. However, such small sensors have a very limited (around 200 mm) usable range around the field generator, which can make the system hard to set up around the patient.

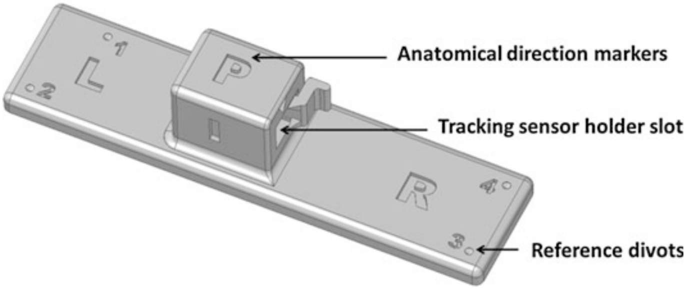


Fig. 2 Reference sensor holder

6 System Calibration

Ultrasound imaging differs significantly from other imaging modalities traditionally used in image-guided interventions. Both the contents and the positions of ultrasound images change rapidly in time, while CT and MRI images have static content and well-defined positions. Therefore ultrasound tracking requires special practices to ensure a maintainable navigation software design. We describe the coordinate systems that need to be represented in tracked ultrasound systems, and best practices in finding the transformations between the coordinate systems. In other words, we discuss calibration between components of the system.

In a full featured navigation system, there are three dynamic and three static coordinate transformations (Fig. 3). The dynamic transformations are shown in orange color, and the static ones in blue. The dynamic transformations change rapidly as the tracking sensors move relative to the Tracker coordinate system. The Tracker coordinate system is most commonly the electromagnetic field generator. The static transformations are equally important, but they do not change significantly during the intervention.

All transformation chains eventually end in a common Right-Anterior-Superior (*RAS*) anatomical coordinate system. When a CT or MRI image is loaded in the needle navigation scene, their *RAS* coordinate system is used. In ultrasound-only cases, the *RAS* can be defined at an arbitrary position with the coordinate axes directions matching the patient anatomical directions.

Spatial calibration of the system entails the computation of the static transformations. *Reference* to *RAS* transform is typically obtained by landmark registration. In this method the transform is determined by minimizing the difference between points defined in the pre-procedural CT or MRI image and the same points marked

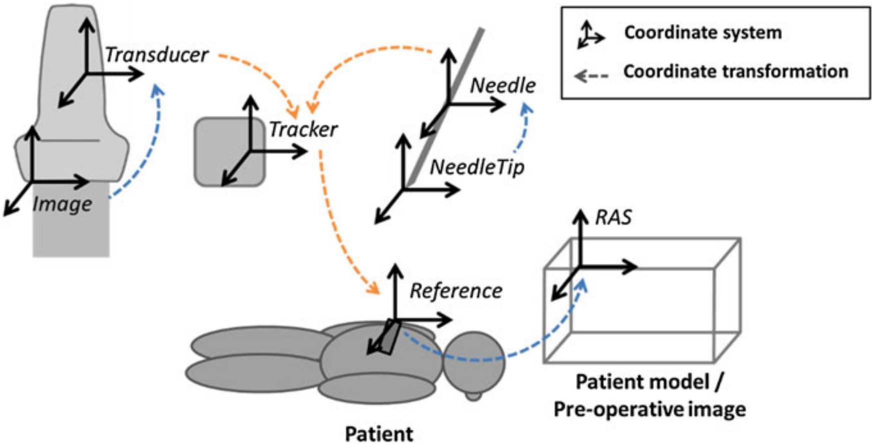


Fig. 3 Coordinate systems and transformations in a tracked ultrasound-guided needle navigation scene

on tracked ultrasound images. The method is very simple, the computation is immediate, and usually accurate enough, but finding the corresponding anatomical locations on different imaging modalities requires experience. Although there have been promising attempts to automate this process by image-based registration. Automatic methods may require less skills from the users and might be more accurate (by matching large number of points or surface patches), but so far these methods do not seem to be able to match the speed, simplicity, and robustness of the manual registration method.

Computation of the *NeedleTip* to *Needle* transform is straightforward, typically performed using a simple pivot calibration. The tracked needle is pivoted around its tip for a couple of seconds and the transform that minimizes the dislocation of the needle tip is computed. Usually the calibration has to be performed only once for each needle type that may be used in the procedure.

Determining the *Image* to *Transducer* transform (also known as *probe calibration*) accurately is a difficult task, mostly because of the 3D point localization by ultrasound is inherently inaccurate, due to the “thickness” of the ultrasound beam (Fig. 4). Beam width causes objects to appear in the ultrasound image that are several millimeters away from the ideal imaging plane and blurring of object boundaries on the images.

The *Image* to *Transducer* transform can be determined by moving a tracked pointing device (such as a needle or stylus) to various points in the image and recording the pointer tip position in both the *Transducer* coordinate system and the *Image* coordinate system (Fig. 5). The transform can be determined by a simple landmark registration. The advantages of the method are that it is simple, reliable, requires just an additional tracked stylus, and can be performed in any medium where a needle can be inserted. However, positioning the pointing device’s tip in the middle of the image plane and finding the tip position in the image requires an experienced operator and therefore the accuracy and speed of the calibration heavily depends on the operator.

Automatic methods have been proposed to reduce the operator-dependency and increase the accuracy of the probe calibration. These methods extract features (such

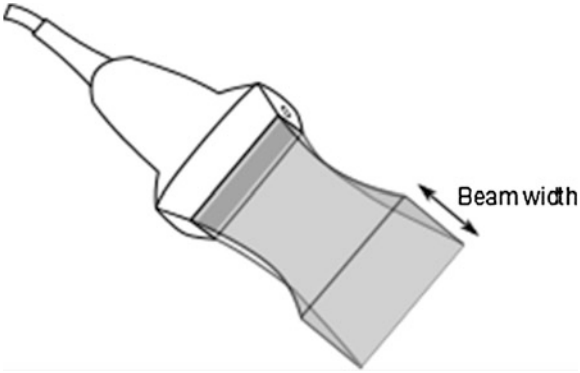


Fig. 4 Anything inside the thick ultrasound beam will appear in the acquired ultrasound image

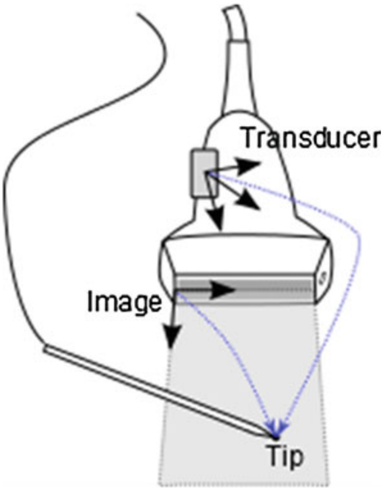


Fig. 5 Spatial calibration of the transducer can be performed by recording the pointer tip position in the *Transducer* coordinate system and marking them in the image

as intersection points or lines) from the image automatically, then compute the transform that minimizes the difference between the expected and the measured positions of the features.

Intersection of a thin linear object (such as a wire or needle) and the image plane show up on the image clearly, as a bright spot. Automatic detection of small bright spots in an image is a relatively simple task and the position of the spot usually can be determined very accurately, therefore many calibration phantoms contain a number of wires at known positions. A particularly interesting setup is when wires are arranged in multiple N-shaped patterns (Fig. 6), because if the wire positions are known in 3D and the relative distances of the intersection points in the image are known in 2D, the position of the middle wire intersection can be computed in 3D [2]. Arranging wires in planes have the additional advantage that the intersection points in the image are collinear, which can be used for automatically rejecting bright spots in the image that do not correspond to an actual wire intersection point (Fig. 7). Having 3 N-shaped wire pattern is shown to be enough to reach submillimeter calibration accuracy [2]. Fully automatic, open-source implementation of the N-wire-based probe calibration is available in the Plus toolkit [3]. The advantage of the method is that is fully automatic, therefore a large number of calibration points can be collected and so the effect of random errors can be reduced, the results not depend much on the operator, and the calibration can be completed within a few minutes. The disadvantage of the method is that it requires measurement of the wire positions in the tracker coordinate system (typically by landmark registration of the calibration phantom), requires phantom fabrication, and attention has to be paid to set imaging parameters that allow accurate automatic detection of the wire intersections.

Other automatic methods have been proposed that use a simpler calibration phantom. For example, it is possible to compute the probe calibration just by imaging a flat surface while completing certain motion patterns with the transducer. This method is called *single-wall calibration*. The advantage of the method that it

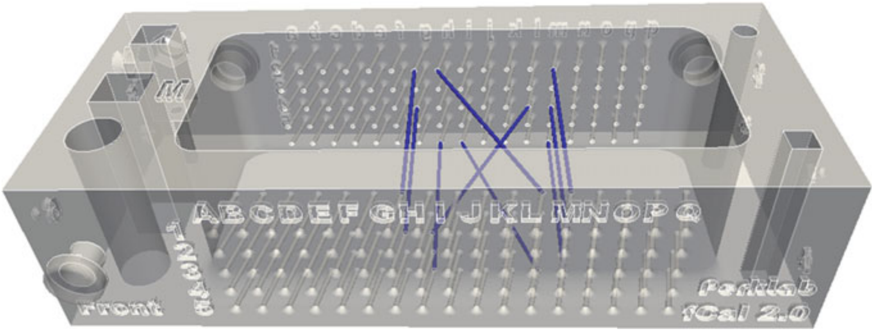


Fig. 6 Calibration phantom containing 3 N-wires. 3D-printing-ready CAD model, instructions, and calibration software are all available in the Plus toolkit [3]

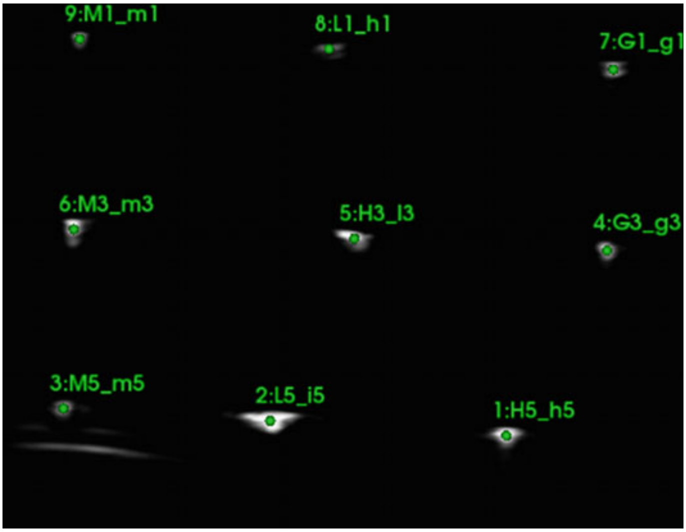


Fig. 7 Ultrasound image of the calibration phantom containing 3 N-wires with an overlay showing the results of the automatic marker detection algorithm

just require a simple flat diffusively reflecting surface as calibration phantom, however the method is not very robust and can provide very inaccurate results if the motion patterns are not completed carefully or not optimal imaging parameters are used.

The ultrasound imaging system is typically only loosely coupled to the position tracking system and there can be temporal misalignments between tracking and imaging data that is recorded at the same time. The goal of *temporal calibration* is to detect and compensate such temporal misalignments. Accurate temporal calibration is needed when images are acquired while moving the transducer. High accuracy and reliability is achievable using hardware triggers. If hardware-based

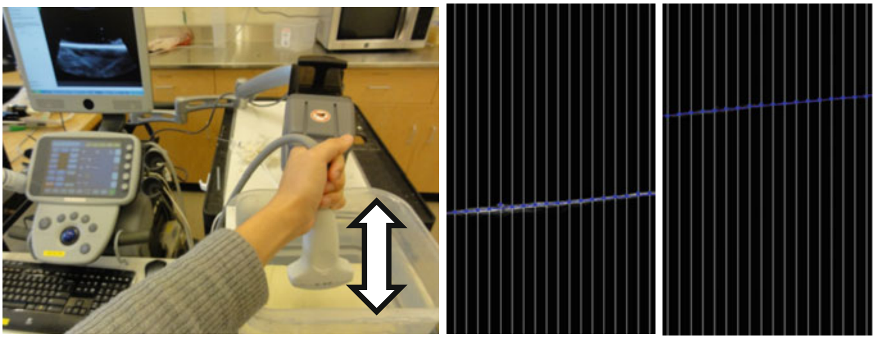


Fig. 8 Moving the transducer up/down repeatedly for acquiring tracking and imaging data for temporal calibration (*left*). Position of the water tank bottom is automatically detected in the ultrasound image and used as position signal for the image data. Position of the water tank bottom is shown for the *top* and *bottom* positions (*center, right*)

synchronization is not available but the acquisition rate and latency is constant in both the imaging and tracking device then software-based method can be used to compute the fixed time offset. Methods based on detecting certain events (such as sudden motion) have been proposed. These methods are easy to implement, but inaccurate or require lengthy data acquisition, because acquisition of a single measurement sample takes a few seconds. Correlation-based methods require the operator to perform quasi-periodic motion with the transducer for a few seconds and during this time imaging and tracking data is recorded (Fig. 8). Then position signal is extracted from the data and the time offset is computed that results in the highest correlation value between the position signals (Fig. 9). Position signal from the 3D pose information can be computed as position along the first principal axis of the motion. Position signal from the image data can be retrieved by detecting the position of a feature (such as the bottom of the water tank) and use the position along a chosen axis. The correlation-based temporal calibration method is accurate, reliable, and a free, open-source implementation is available in the Plus toolkit [3].

7 Volume Reconstruction of Tracked Ultrasound

Position of recorded ultrasound images can be used to reconstruct 3-dimensional ultrasound volumes. Reconstructed volume data can be in the same format as other volumetric images (CT or MRI), but the intensity values of voxels still highly depend on the direction of sound propagation. Therefore, processing and visualization of such volumetric images are difficult. Intensity values in ultrasound are not characteristic to tissue types, and are often attributed to artifacts (including scatter and shadow), rather than anatomical structures. Image quality and parameters also depend on the settings of the ultrasound scanner, the size of the patient, and motion patterns of the transducer during image recording.

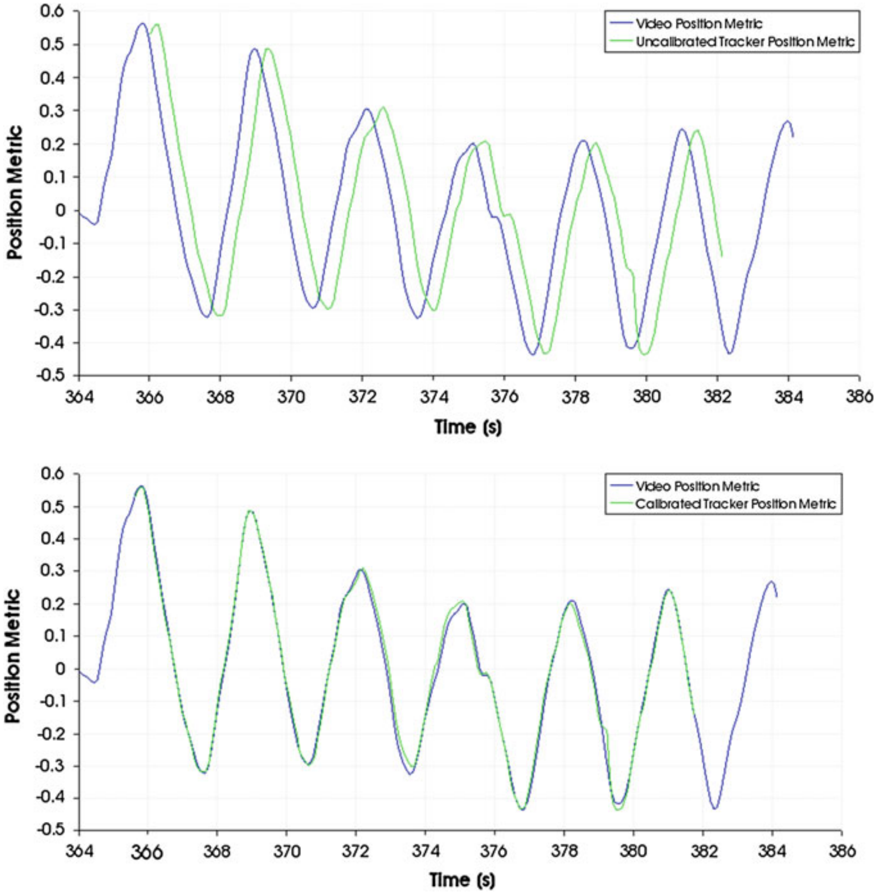


Fig. 9 Without temporal calibration the video and tracking data are misaligned (*top*). Temporal calibration minimizes the misalignment (*bottom*)

Reconstructed image volumes are often used in cross-modality image registration for fusion of ultrasound with pre-procedural CT or MRI images. These promising applications are still in research phase, but they may have a significant role in clinical practice in the future, as they combine the excellent tissue visualization features of other modalities with the safety, portability, and accessibility of ultrasound.

The quality of reconstructed ultrasound volumes depend on many factors, including the quality of the input images, calibration accuracy of the transducer tracker, the accuracy of temporal synchronization between image acquisition and position tracking, and the algorithms applied for filling voxels in the reconstructed volume where a recorded image is not available. Fortunately, there are a number of open-source implementations for ultrasound volume reconstruction algorithms.

8 Open-Source Software Tools for Rapid System Development

The complexity of image-guided needle navigation systems requires continuous software development and maintenance. Regular tasks include fixing errors, adding features, modifying the user interface, and adding support for new imaging and tracking hardware. Reliable software requires so much resources that it can only be achieved through a collaborative common platform that is shared between research groups and commercial partners. A medical engineering research group, or a medical device company would not develop a computer operating system, a programming language, or a computer graphics library. Similarly, they do not need to spend efforts on re-implementing device interfaces, calibration algorithms, or visualization methods, etc. To maximize productivity, they should focus on implementing new methods, building on previous results. Unfortunately previous results are typically published in journal and conference papers, which are not suitable to archive software methods. These publication are most effective if they are accompanied by an implementation of the published methods in an open-source software platform.

A commonly used software platform for tracked ultrasound system consists of two main parts (Fig. 10). The Public Software Library for Ultrasound Research (PLUS) implements lower level software components, including device interfaces,

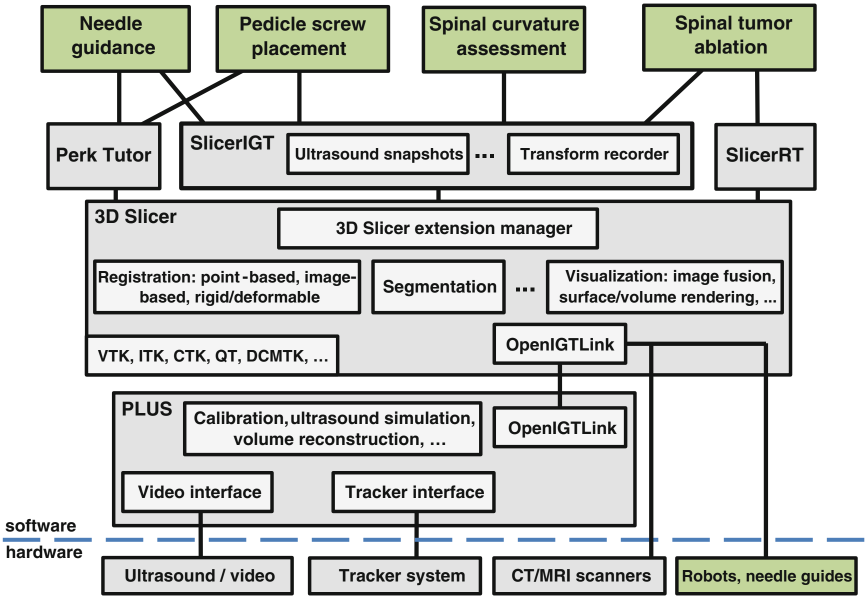


Fig. 10 Architecture overview of image-guided spinal disease diagnosis and treatment systems made from reusable software components

calibration methods, data acquisition, and data processing methods (e.g. 3-D volume reconstruction) [3]. PLUS is distributed under a permissive open-source license that allows both academic and commercial use without restrictions (www.plustoolkit.org). PLUS provides real-time data streams to end-user applications. Applications can be rapidly prototyped in the 3D Slicer framework (www.slicer.org). The advantage of 3D Slicer is that hundreds of medical image processing algorithms are implemented and deployed in this framework. They are readily available, and can be used for visualization that best helps intervention navigation.

9 Tracked Ultrasound in Interventions Training

Long learning curve is probably the only disadvantage of ultrasound guidance in spinal needle placement procedures [1]. The interpretation of musculoskeletal ultrasound images is difficult, and the operator has to do it in real time during interventions, while manipulating the ultrasound transducer in one hand and insert a needle with the other hand. This challenge is largely related to visuospatial coordination skills. Ideally, these necessary skills are learned before they are first performed on patients. Learning in a simulated environment on phantom models is not only safer for patients, but is also shown to improve the learning process [4]. Phantom models are proven tools in teaching spinal needle insertions to prepare medical residents for patient encounters [5]. Needle coordination skills in difficult procedures can be improved by providing augmented reality visual feedback while practicing the procedures on phantom models [6, 7].

Objective measurement of operator skills is of utmost importance in procedural skills training. Medical training is currently transforming according to the principles of competence-based medical education. The goal of this trend is to assure proper acquisition of skills before physicians perform interventions on patients. This demand requires simulation-based training and quantitative performance feedback for the trainees, as well as quantitative evaluation of skills. Teaching of ultrasound-guided spine interventions can greatly benefit from tracked ultrasound technology, both as an augmented reality system for improving visuospatial skills, and using tracking to objectively analyze hand motion data for skills evaluation. Systems with position tracking are inherently able to record motion trajectories that can be analyzed for qualitative and quantitative measures of procedural proficiency. Algorithms borrowed from artificial intelligence are shown to be able to classify motion gestures [8] and skill levels of the operator [9, 10].

Sonographic anatomy of the spine is difficult to master due to poor visibility and the complex shape of vertebrae. Tracked ultrasound along with tracked needle offers an excellent augmented reality training system. 3-D anatomical models of the training phantoms can be registered to the navigation scene to show what structures are responsible for characteristic features on the ultrasound image. When the needle is inserted incorrectly, the 3-D scene shows the trainee the exact relation of the actual needle position and the target point in relation to the spine anatomy. The

Fig. 11 A simulator with tracked ultrasound, tracked needle, and registered 3-D anatomical model for learning spatial coordination in spinal interventions

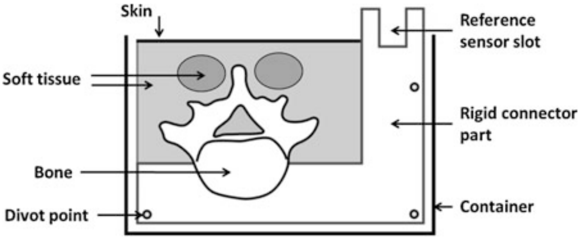


Fig. 12 Components of an ultrasound-guided spine intervention training phantom

spatial relations of tools and anatomy can be learned with such tracked systems [11] to improve needle coordination skills (Fig. 11).

The rest of this section gives an overview of how to build augmented reality training systems using position tracking to develop the skill of mental projection of the ultrasound image and needle trajectory on the patients in clinical procedures.

Commercial suppliers offer more and more spine simulation training models, but they can also be prepared from low-cost components (Fig. 12). A spine model can be rapid prototyped, or purchased from a supplier. It should be rigidly fixed by a connecting part to a reference tracking sensor holder, and some divot points should be marked on this rigid part for landmark registration. The space around the spine can be filled with organic or soft plastic gel, and the skin can be simulated by a rubber sheet.

Although there are several commercial and free products for ultrasound-guided spinal interventions, finding the best ways to teach and evaluate these skills is still subject to intensive research. Open-source platforms allow fast setup of research prototypes that can be modified for new visualization techniques or evaluation metrics with minimal additional development work, such as the Perk Tutor platform [11].

Skill levels and performance scores of trainees are essential in any training program. Access to position data in tracked ultrasound and needle systems can be used to record tool trajectories, which correspond to hand motions of trainees. Recorded tool trajectories can be used in many ways to compute objective performance metrics. The most common performance metrics are total procedure time and needle insertion time. The latter corresponds to the total amount of time when the needle was inside the phantom. An important motion economy parameter is total needle path inside the phantom. Longer needle paths add up from multiple reinsertions and probing. These are clinically proven risks for infection and bleeding complications, therefore they are always good to be treated as primary measures of skill. Novice operators often do sideways or rotating motions with the needle, which is not recommended because the needle inside the tissue bends, which cannot be directly seen, so aiming at the correct target becomes more difficult. Sideways needle motion can be measured using the *potential tissue damage* parameter [7]. Procedures have specific success criteria that can be measured or observed during practice insertions to compute success rate. In case of lumbar puncture phantoms, the artificial spinal canal is usually filled with water, so the backflow of that water through the needle defines successful completion of the procedure. In facet joint injections or other nerve blocks the position of the needle tip may define success or failure. These metrics are readily implemented in the Perk Tutor platform.

Cost of the training system can be reduced by simulated ultrasound. Low cost training simulators are important because none of the training enhancement technologies substitute a good amount of hands-on practice. Trainees should ideally be given opportunity to deliberately practice until leaning objectives are met. Trackers are typically an order of magnitude less expensive devices compared to ultrasound machines. And ultrasound compatible training phantoms wear out over hundreds of needle insertions, which deteriorate ultrasound image quality. Simulated ultrasound can be generated from the tracked position of a needle and a non-functional ultrasound transducer. Simulated ultrasound has been shown to be useful in learning ultrasound skills usable with real ultrasound [12]. An open-source ultrasound simulator is available in the PLUS software library.

10 Extending Needle Navigation Techniques

Position tracking of the ultrasound and the needle extends the possibilities in ultrasound-guided needle insertion techniques. Direct visual aiming is only possible with conventional ultrasound when the needle is parallel to the ultrasound imaging plane. This is called the in-plane insertion technique (Fig. 13a). The out-of-plane technique (Fig. 13b) is more challenging, because the transducer needs to be moved back and forth, and the needle position needs to be assessed mentally from multiple

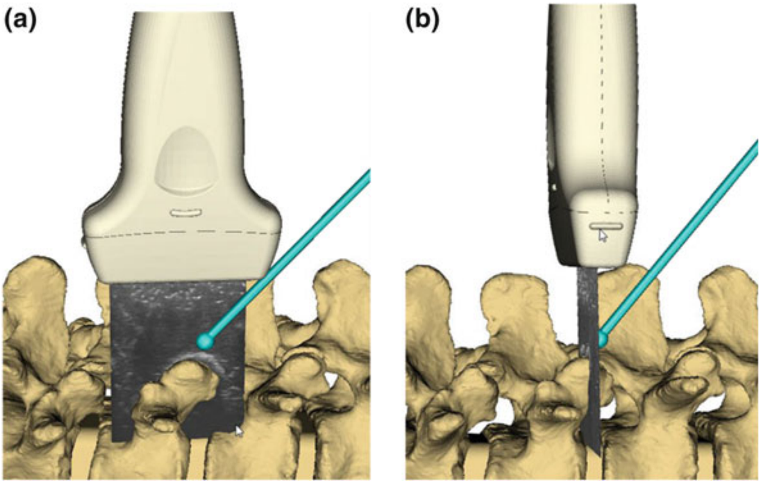


Fig. 13 In-plane and out-of-plane techniques in ultrasound-guided needle insertions

scanned images. But position tracking allows 3-dimensional visualization of both the ultrasound and the needle, allowing accurate needle aiming regardless of the ultrasound image orientation (Fig. 13).

11 Tracked Ultrasound Snapshot Technique

Simultaneous handling of the ultrasound transducer and the needle has two main disadvantages. It requires significant hand coordination skills, and the transducer physically limits the range of motion of the needle. The acoustic shadows of vertebrae limit angles and positions of the ultrasound transducer. The ideal, shortest path for the needle is often blocked by the transducer in real time ultrasound guidance. Therefore, the operator may sacrifice the ideal needle path for real time imaging. But tracked ultrasound offers separation of imaging and needle insertion in time. The optimal ultrasound image can be recorded relative to the patient anatomy. This image can be displayed for navigation when the transducer is removed from the patient, and the tracked needle can be guided along the recorded ultrasound snapshot. This technique, called tracked ultrasound snapshot (TUSS) guidance simplifies the hand coordination task, because the operator has to do only one thing at a time, imaging or needle insertion. TUSS also allows needle insertion at the same location that was used for imaging.

12 Facet Joint Injections with Tracked Ultrasound Snapshots

Facet joint injections are done routinely on a relatively large patient population with chronic back pain. The current standard of practice is either fluoroscopic or CT-guided needle placement. Ultrasound offers a radiation-free alternative to image guidance [13, 14], but it has not become a routine clinical procedure due to its difficulty. Tracked ultrasound improves the accuracy of needle placement when it is fused with a previous CT scan [15]. However, a CT scan is not always available for these procedures. In this section we describe the TUSS-guided facet joint injections, which potentially facilitates ultrasound-only guidance in facet joint injections.

Since needles can access the facet joints only in a constrained range of angles, real-time ultrasound guidance is inconvenient. TUSS allows the procedure to be separated in an imaging phase and a needle insertion phase. Initially, the operator finds the target facet joint, and records one or more ultrasound snapshots at the target. Then the ultrasound transducer is not needed during needle insertion, as the operator guides the needle tip to the targets defined on the snapshots.

Operator performance in TUSS-guided facet joint injections was compared to conventional ultrasound guidance in a cadaveric lamb model [16] (Fig. 14). Success rate and insertion time improved significantly in a pilot study (Table 2).

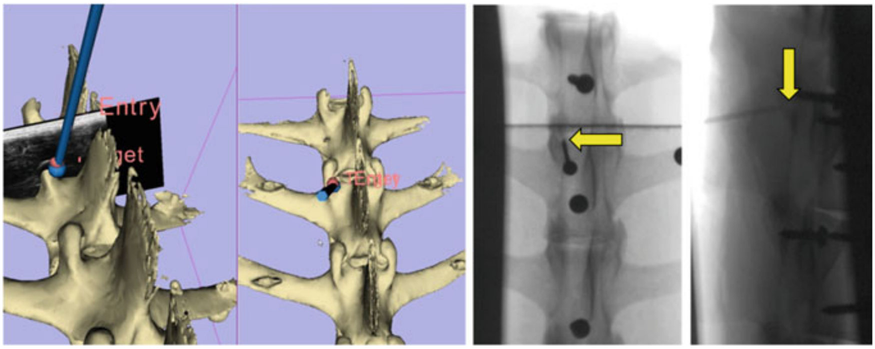


Fig. 14 Dual 3-D navigation scene for facet joint injection with registered CT-derived spine model in a lamb specimen. Radiographs on the right confirm the needle position (*arrows* point at the needle)

Table 2 Operator performance in TUSS-guided versus conventional US-guided facet joint injections in a lamb model

	TUSS guidance	US guidance
Number of insertions	50	50
Success rate (%)	*94	44
Insertion time (s ± SD)	*36.1 ± 28.7	47.9 ± 34.2

*$p < 0.05$ versus Freehand US guidance

The most important limitation of ultrasound and TUSS guidance in the spine is limited visibility of bone structures in ultrasound images. Visual enhancement of the spine could be achieved by fusion of a previous CT image to the tracked ultrasound [17], however, ultrasound-only procedures are preferred to reduce radiation risks and cost. Vertebra visibility could be improved in the needle navigation display by fitting a deformable general vertebra shape model to automatically detected bone contours [18]. Although shape model fitting is still in the experimental phase, and will likely have limitations in certain pathological cases, it may greatly enhance the potentials in ultrasound guidance in the spine.

13 Spinal and Epidural Anesthesia with Tracked Ultrasound Snapshots

Spinal and epidural anesthesia are similar procedures; the needle is just pushed a little further in case of spinal anesthesia. Both are performed to numb the lower body for surgery while the patient remains awake. These procedures are preferred over general anesthesia, having lower risks and the contributing to faster recovery after surgery. Spinal and epidural needles are both placed in the spinal canal. Spinal anesthesia is injected inside the dura sac, where the medicine takes effect immediately, and is usually used in shorter and simpler procedures. Epidural injections are placed just outside the dura sac. A catheter can be left in the epidural space to provide continuous administration of medicine for longer procedures. From the needle guidance point of view, the needle should be similarly navigated in the spinal canal between two lumbar vertebrae in both cases (Fig. 15).

Spinal and epidural anesthesia is routinely performed without image guidance, as the vertebral interspaces are palpable in the average patient. However, some pathological conditions may cause the narrowing of the interspaces, making it difficult or impossible to lead a needle to the spinal canal. In less severe cases, conventional ultrasound may help identify the interspaces where needle insertion can be attempted with higher probability of success, but in extreme cases, only a CT image-based guidance may provide enough information for needle navigation. Tracked ultrasound offers the accuracy of CT-guided navigation, using a pre-operative CT image, registered to the patient using landmarks visible on ultrasound images.

The most intuitive display for needle navigation is when vertebrae and the needle are represented with surface models. Surface models can be generated from CT images using a threshold-based segmentation, but pathological spines may require manual slice-by-slice contouring, especially in the presence of metallic implants. The CT-derived surface models can be registered to the needle navigation coordinate system using landmark points. The landmarks should be rigidly fixed to the vertebrae, and should be easy to identify on ultrasound images. Natural landmarks can be the facet joints, or transverse processes. In case of implanted vertebral screws, the screw heads are excellent landmarks (Fig. 16).

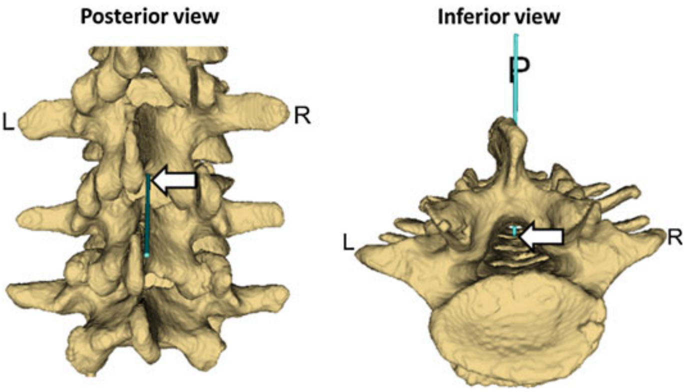
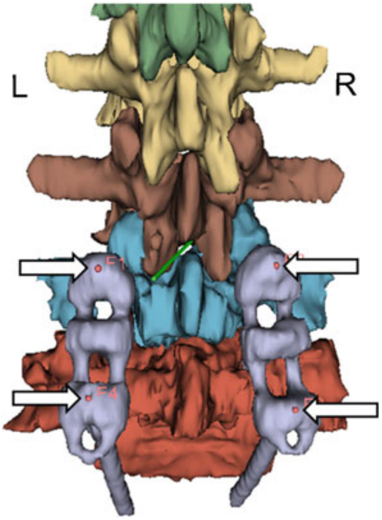


Fig. 15 Illustration of needle position in spinal and epidural injections relative to the lumbar spine in posterior and inferior views. The *arrow* points at the needle tip in both images

Fig. 16 Needle navigation scene for spinal anesthesia. In this patient, vertebral screws provide landmark points (*arrows*) for registration. The *green stick* shows the operator the ideal direction of needle insertion. In such degenerative spines, different colors for individual vertebra models make image interpretation easier



14 X-ray Dose Reduction in Pedicle Screw Navigation

One of the most popular subjects for computer-aided surgical navigation techniques is pedicle screw placement. There is an abundance of evidence that computerized navigation of surgical tools improves the outcomes of the surgeries, and reduces the probability of complications. Different navigation techniques share a common task, which is the spatial registration of the actual patient with the virtual model of the patient. The pedicle screw position is typically planned with respect to a pre-operative CT image. But the CT image needs to be registered with the patient on the surgical table, so the navigation system knows where the screws positions are planned with respect to the patient.

Ultrasound can be tracked using the same tracking system that is used for surgical navigation. This allows ultrasound to identify landmarks for registration of the pre-operative plan to the surgical navigation system. The vertebra anatomy offers many unique surface landmarks, but few are convenient to identify in ultrasound images. The spinous process is hard to localize with ultrasound because of the prominent echo signal from the supraspinous ligament. The second closest structure to the skin that has a face perpendicular to the ultrasound propagation direction is the set of articular processes. The four articular processes are relatively easy to find in ultrasound images, and they surround the vertebra, therefore are excellent points for landmark registration.

The pre-operative CT can be accurately registered to intraoperative tracking using the articular processes as landmarks [19]. More landmarks can be defined to further reduce the effect of landmark position errors (Fig. 17), although at the cost if increasing the total procedure time.

15 Spinal Curvature Monitoring with Tracked Ultrasound Snapshots

Kyphoscoliosis is a condition with pathological curvatures of the spine. The most common cause of this condition is a disease called adolescent idiopathic kyphoscoliosis. It affects 1 individual in 1,000, and is typically discovered in the early adolescent age. It requires regular monitoring of the pathological curvatures, to be able to decide on treatment options in time. Spinal curvature measurement may also be needed during surgery to provide feedback on achieving the surgical plan. Spinal curvature measurements are currently performed on X-ray images in the clinical practice. However, regular examinations with X-ray have been linked to an increased risk of cancer [20–22]. Therefore, an alternative measurement method without ionizing radiation would be ideal for monitoring kyphoscoliosis angles.

In the current clinical practice, measurements are made on X-ray radiographs. The reader selects two vertebrae that are most angled at the superior and inferior end of the curvature. A line is drawn on superior end-plate of the superior vertebra, and on the inferior end-plate of the inferior vertebra. The angle between these lines is called the Cobb-angle, which is the most common measure of spinal curvatures. Minor curvature angles can also be defined besides the most prominent major angle. However, lots of factors cause variance in the Cobb-angle. The posture of the patient, the angle of X-ray imaging, and these curvatures are reported to increase within a day, begin up to 5° larger in the afternoon compared to measurements in the morning [23]. Since variability between different readers is reported to be 2°–7° even on the same images, spinal curvature differences less than 5° are generally not considered significant when estimating disease progression [24, 25].

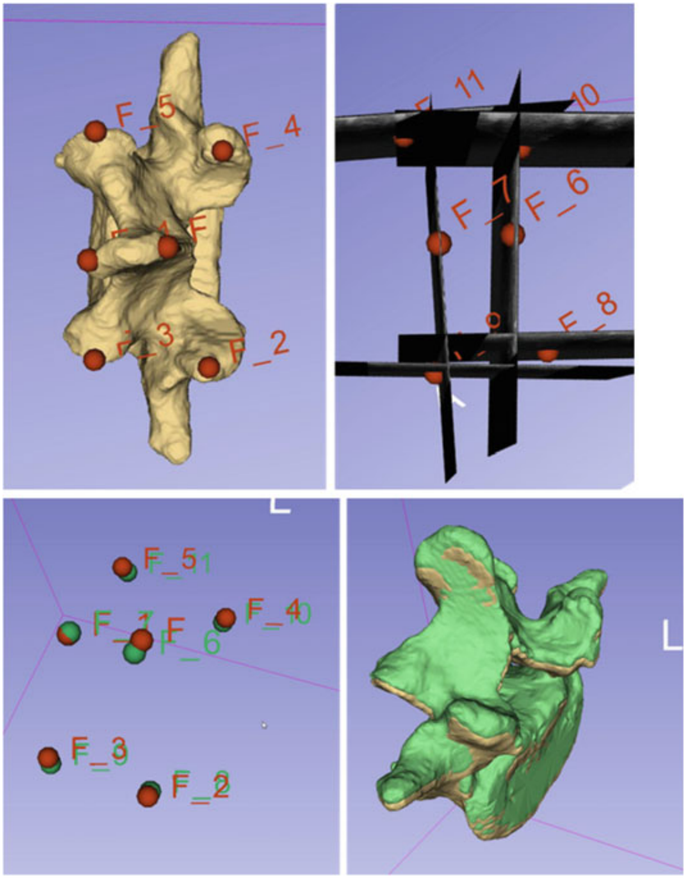


Fig. 17 Landmarks defined for registration on the CT-derived model of a lumbar vertebra (*top left image*), and the same landmarks defined on tracked ultrasound snapshots (*top right image*). The two sets of landmarks are registered (*lower left image*), and the registered vertebra position (*green*) is localized close to the ground truth position (*yellow*) in the *lower right image*

Tracked ultrasound offers accurate spatial localization of vertebra landmarks visible on ultrasound images. These landmarks are suitable for measurement of spinal curvature and vertebra rotation without ionizing radiation. Spinal curvatures are measured between two vertebrae that are rotated in the coronal plane at the largest angle. The angle is defined between two lines in the coronal plane. Both lines can be defined by two symmetric points on each vertebra. The points can be transverse processes on tracked ultrasound snapshots, as these points are visible on ultrasound images along the entire spinal column (Fig. 18).

Tracked ultrasound technique can provide as accurate spinal curvature measurements as X-ray images [26]. Although this method needs further clinical testing, as the conventional anatomical landmarks, the vertebral end-plates, cannot be

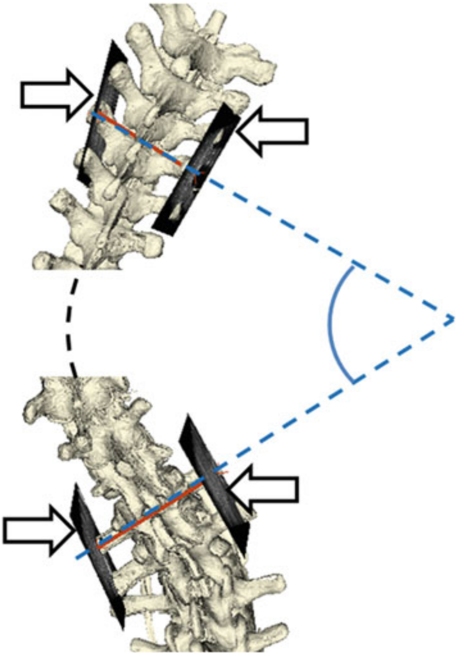


Fig. 18 Spinal curvature measurement using four landmark points from four tracked ultrasound snapshots (marked by *white arrows*). The 3D spine model illustrates the measurement principle, but it is not available in the clinical setting

used for ultrasound-based measurement that is used for X-ray measurement. The vertebral end-plates cannot be seen in ultrasound due to the acoustic shadow of the lamina and vertebral processes. Anatomical features that are accessible by ultrasound imaging and also visible in X-ray are transverse processes (Fig. 19).

Two potential advantages of using tracked ultrasound for spine curvature angle measurements are safety and accessibility. Radiation-free monitoring method in

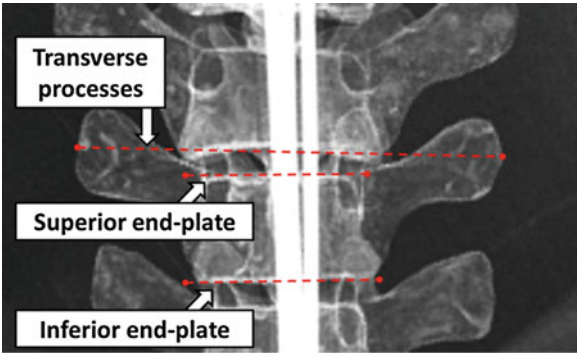


Fig. 19 Anatomical features for spinal curvature measurement. Superior and inferior end-plates are conventionally used in radiographic measurements. The transverse processes are also visible in ultrasound

adolescent kyphoscoliosis reduces the risk of cancer in these patients, as ultrasound has no known adverse side effects. Tracked ultrasound machines are also more accessible tools than X-ray machines. Portable ultrasound machines allow screening and monitoring in remote areas where permanent medical imaging facilities are not available. Therefore, tracked ultrasound may become the clinical standard for kyphoscoliosis monitoring in the future.

16 Ultrasound Image Fusion with Other Modalities

Ultrasound imaging lacks important features of CT or MRI modalities, including characteristic image intensity values for different tissues. Intensity values are relative on ultrasound due to attenuation, acoustic shadowing, and other artifacts. The ideal image guidance for the interventionist would have the standard image quality of CT and MRI, and also the convenient accessibility of ultrasound. Therefore, a great challenge for researchers and engineers is to fuse preoperative CT and MRI with ultrasound in real time during ultrasound scanning. If these preoperative images are registered to the patient anatomy, tracked ultrasound images can be enhanced by showing a corresponding slice from CT or MRI, either fused with the ultrasound, or side-by-side. Tracking ensures that both images show the same slice respective to the patient anatomy. Even though perfect spatial registration between preoperative images and intraoperative ultrasound cannot be achieved due to soft tissue deformations around the spine, and due to patient motion, physicians can mentally correct for these deformations, so the image fusion can help both even when the registration accuracy is limited.

CT-to-ultrasound or MRI-to-ultrasound fusion could also be used to eliminate needle tracking from interventional procedures. Ultrasound can be used to directly visualize the needle, and preoperative images show the target anatomical structures. Therefore, fusion of the two modalities may provide real time needle navigation in preoperative images. This potentially reduces the cost of disposable needle trackers, and extends the applicability of tracked ultrasound to interventional tools (e.g. tissue ablators) that are currently not equipped with position tracking.

Significant effort has been made to implement fusion of preoperative images with intraoperative ultrasound. The registration methods are either based on common image features between CT and ultrasound [27], or they use the surface model of the spine, which requires segmentation of the vertebrae [28]. A common problem in image registration is that the CT image is usually taken in supine patient position, while needle insertions are done while the patient is bent forward. This requires non-rigid registration of the CT image. Biomechanical constraints can be applied to account for the typical deformation of the spinal column. Unfortunately, rate of failed spine CT to ultrasound registration is reported to be significant, even under experimental conditions, both with image-based [17] and with surface-based algorithms [29]. Reported success rates are below 90 %, and clinical cases would probably result lower success rate compared to the experimental environment, therefore, automatic registration of CT and ultrasound images require further research and development.

Ultrasound image fusion with other modalities has significant potential in transforming image-guided therapy applications. Its benefits are not limited to navigation of needle interventions. Other image-guided therapies including radiation therapy may also benefit from real-time, accurate localization of organs and pathological tissues.

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