Improved Spine Surgery and Intervention with Virtual Training and Augmented Reality

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ABSTRACT

Computer-aided diagnostic and therapy systems are increasingly becoming established tools for several medical procedures. In this paper, we introduce a case-based surgical training system prototype for imparting anatomical knowledge, cognitive strategies of treatment and interaction techniques for computer-aided therapy planning of spinal disorders. Patient data, image data, image analysis results and 3D models as well as annotated surgery videos and diagnostic information underlay the SpineSurgeryTrainer. Neurosurgeons or orthopedic surgeons who want to specialize in spine surgery can, in a realistic workflow, train therapeutic decisions and surgical planning. Expert opinions and their case-specific approaches support the learning process.

In addition, we integrate a prototypic add-on for enhancing the intraoperative visualization within a navigated spine surgery utilizing an augmented reality approach. In essence, operation-specific important anatomical structures are segmented from preoperative patient data and superimposed on the video stream of the operation field. In addition, slices of the anatomy data, as well as shape and depth information of targeted structures, like spinal nerves or herniated discs, can be blended, which allows for a better protection of risk anatomy and accurate identification of the structures under consideration, and thus raises the safety and accuracy factors of the intervention.

Categories and Subject Descriptors

I.3.7 [**COMPUTER GRAPHICS**]: Three Dimensional Graphics and Realism—*Virtual reality*; J.3 [**LIFE AND MEDICAL SCIENCES**]: *Training*

Keywords

Spine surgery, surgery training, augmented reality, intraoperative visualizations

1. INTRODUCTION

In recent years, complex surgical procedures mostly rely on extensive analysis and preoperative processes, including exploration and interpretation of patient image data. However, one of the challenging tasks in a surgeon's work is to transfer the information displayed in 2D diagnostic images to the 3D situation in the real world of the patient's anatomy. This challenge is mastered in a continuous learning process, still with significant obstacles. Moreover, the specific treatment decision is often based only on the clinical experience and the intervention spectrum of the surgeon.

In spine surgery, e.g., the spatial relations between neural and spinal structures and the position of the spine to the surrounding muscles, vessels and other tissues must be known. In this regard, image-guided surgery is a versatile and effective technology to improve the intraoperative orientation to the unexposed anatomy [7]. This is highly advantageous for surgeries in regions with high density of critical and vital structures. Introducing augmented reality facilitates the transfer of the diagnostic imaging to the individual patient anatomy in a straightforward fashion. Furthermore, surgical training systems enhance the experience and skills of the surgeon and related physicans.

In this paper, we extend our SpineSurgeryTrainer prototype, introduced in [3], with AR functionalities. In essence, we present two tightly-coupled prototypes: The augmented reality-based prototype improves intraoperative visualizations, whereas the training prototype supports future surgeons to develop anatomical knowledge and strategies regarding therapy decisions and planning for various diseases (e.g., disc herniation or stenosis of the spinal canal) based on actual case data. We first present the prototype for improving intraoperative visualization by augmenting the video stream of the operation field with relevant patient data from different diagnostic and intraoperative imaging modalities. This will facilitate the identification of vital structures like blood vessels and nerves or landmarks like bony structures. In section 4, we present our training system prototype. Apart from the interactive training of treatment decisions and planning of minimally invasive surgery, open surgical procedures and access trajectories, we aim to familiarize the trainee with virtual and augmented reality based tools for later therapy planning or intraoperative navigation.

2. MEDICAL BACKGROUND AND RELATED WORK

The education and training in surgery is highly dependent on the available experts and the existing case spectrum. For effective training the case spectrum must include many variants of treatment methods and their different indications. Casus [6], e.g., provides cases of chosen medical specialties for different education levels in order to train therapy findings.

Practical training includes the training with very expensive artificial models of organs, as well as mannequins, cadavers, or real patients with expert supervision. Drawbacks of mannequins include limitations in their replication of physiology and that, at best, they have a limited range of anatomical variability.

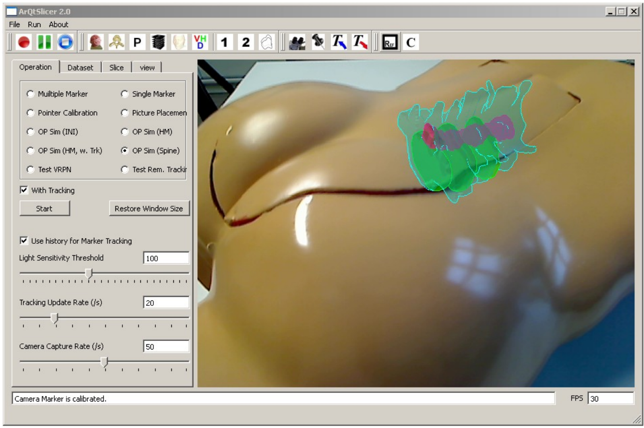
An alternative approach that makes an impact on the medical community are computer simulation systems, which can train practitioners on a virtual patient whilst critically analyzing skills and providing feedback on the performed procedure without the presence of an expert trainer. Of the human sensory modalities, the two cues most frequently used in virtual simulators are *vision* and *touch*. Combining 3D display devices and haptic devices is commonly used, such as in the prototype of a telerobotic surgical simulation system for training spine surgery [21]. PalpSim is another example of a visio-haptic medical training environment based on augmented reality technology [2]. Training systems, such as the KISMET-based Virtual Endoscopic Surgery Training system VSOne [9], provide simulation techniques which allow the modeling of "virtual tissue" based on a data-model which reflects the physical characteristics like mass, stiffness and damping of real tissue. The degree of reality is associated with a specialization of a simulator for a certain training task. This process requires customized hardware and time-consuming and costly preparations (e.g., force measurements carried out in vivo) or deformation simulations in terms of the tissue or the instrument movements (e.g., [4]). Training or simulation of several training tasks with one system bears a challenge. For the training of planning surgical and interventional procedures, the anatomical knowledge and development of planning strategies based on anatomical landmarks are crucial. A simulation of realistic device steering is not required.

In order to support the surgeon during surgery, medical navigation systems are used to establish correspondences between locations in an acquired patient dataset and the patient's physical body. In the last two decades, many research works aimed at enhancing image-guided surgery with AR technologies. Some works provided enhanced endoscopic views that are paired with synthesized virtual renderings generated from the same view, e.g. [10]. Other systems tried to modify the design of operating binoculars [1] and microscopes [5] to allow for data augmentation. Augmented reality has also been introduced as a training tool for surgical procedures [14, 13].

3. AR-ASSISTED SPINE SURGERY

In this section, we adapt and extend our intraoperative visualization method [18] for the use in navigated spine surgery. Figure 1(a) depicts the hardware setup of our prototype, in which we use a model of the upper body with an integrated model of the lower part of the spine. We also adapt a tablet PC with a high resolution built-in camera to simulate a surgical microscope or endoscope. In a first step, we compute the camera intrinsic parameters using MATLAB's Camera Calibration Toolbox.

(a)



(b)

Figure 1: Prototype of the intraoperative extended reality visualization system: (a) Hardware setup; (b) visualization module.

For tracking, we implement a marker-based optical tracking server, which continuously captures a video stream of the trackable region with a calibrated high resolution camera. At each frame, the system searches for predefined markers and, for each detected marker, computes its pose in the camera coordinate system. Pose information of all detected markers are transmitted to the tablet PC over a WLAN con-

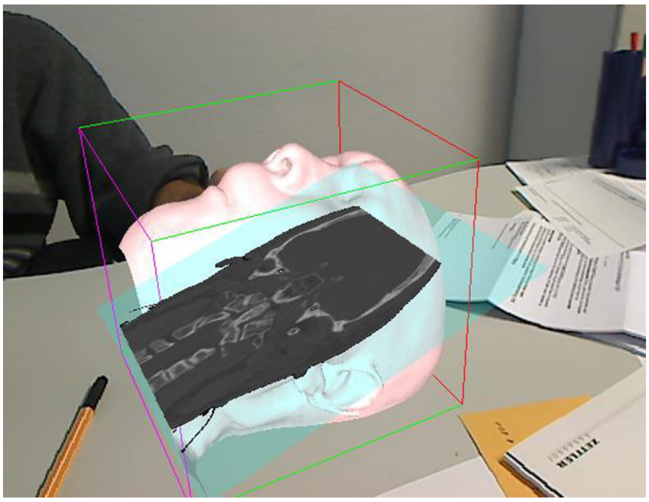


Figure 2: Interactively selected tomographical slices.

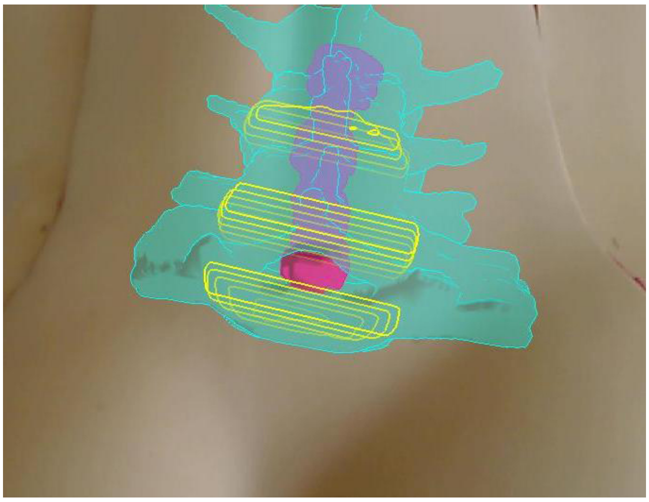


Figure 3: Shape information of intervertebral discs is emphasized by a set of contour lines.

nection. However, the design allows for connecting to other commercial tracking systems.

Prior to the operation, a one-time hand-eye calibration step is performed. In essence, the tablet PC camera is calibrated with respect to the tracker using a common reference marker that is visible (only at the calibration step) to both cameras. A second tracked marker is fixed to the tablet PC, where the goal of the calibration is to compute the spatial transformation between the tracked marker and the video camera of the tablet PC. After calibration, the transformation remains valid as long as the marker does not move with respect to the video camera.

To register the patient/phantom with the scanned dataset, and hence with the anatomical models reconstructed from it, the reference marker is attached to a rectangular plastic board that is scanned with the patient or phantom model. The corners of the marker are interactively selected from the scanned dataset, and their absolute positions are calculated considering image spacing, and defined as registration points. 3D positions of the corresponding points in the patient coordinate system are precisely defined using the tracking system. The two sets of points are finally registered adapting a paired-point rigid registration scheme, applying a least square fitting approach.

The rendering module (Figure 1b) running on the tablet PC continuously captures a video stream and renders it as a background. At each frame, relevant virtual objects are rendered/overlaid using a two-pass rendering algorithm that highlights object silhouettes for better shape perception. Several objects can be overlaid according to the current operation conditions. These include 3D reconstructions of segmented structures from the anatomy dataset.

Additionally, tomographical slices can be superimposed. For this purpose, we adapt an optimized slicing algorithm [17] to compute tomographical slices at the desired position and orientation. The generated slice image is then blended in the real scene with the correct pose (see Figure 2). Here, the dimension and spacing of the 3D dataset and the generated cross section are considered to correctly adjust the physical proportion with the patient and environment. For certain structures, such as the yellow colored vertebral discs in Figure 3, an enhanced visualization of shape and depth information can also be provided. This is achieved by extracting the planar contours of the (herniated) disks at successive depths perpendicular to the viewing direction. Depth information is conveyed via depth cueing by defining the transparency of a contour as a linear function of its depth. In minimally-invasive endoscopic or microscope-based spine surgery, augmentation should be performed on the video stream of the endoscope/microscope camera. However, this requires tracking these devices and a more complicated calibration of their cameras.

4. VIRTUAL TRAINING SYSTEM

To develop a successful training system, the integration of potential users in the design is crucial. As described in [3], we used the informal specification method of scenarios to involve them actively into the conceptional process. Furthermore, the conceptional design of the SpineSurgeryTrainer is based on the Four-Component Instructional Design Model (4C/ID-Modell) [11]. According to this model, four components are necessary to realize complex learning: learning tasks, supportive information, procedural information, and part-task practice. Initially, the prototype provides some cases of various degenerative diseases of the neck and lumbar spine. Based on these cases, the process of treatment decision and the relevant planning of conventional therapy (e.g., physiotherapy), epidural injection or access planning in minimally invasive surgery can be trained.

4.1 Workflow

The training procedure of the SpineSurgeryTrainers, depicted in Figure 4, is based on a high-level clinical workflow. After selecting the training case, the process of diagnosis follows. At first, the relevant patient data is provided including age, sex, weight, and family anamnesis, the assessment of the professional environment, case history and previous treatments. The results of clinical and physical examinations and medical images are then presented and have to be assessed just as the anamnesis. Afterwards, the trainee interactively explores the MRI image slices and a polygonal

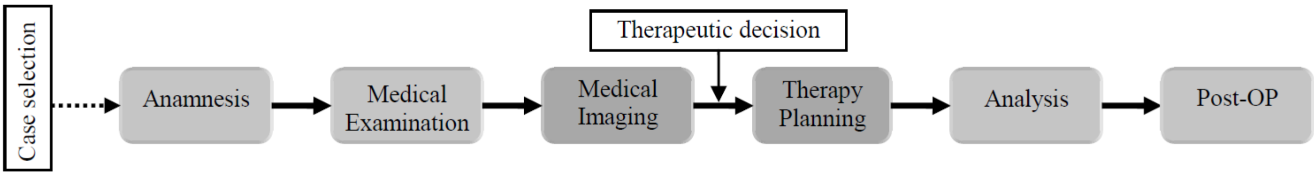


Figure 4: Training workflow of the SpineSurgeryTrainer (based on clinical workflow).

3D model reconstructed based on those image data, in order to finalize a therapy decision. The provided data and exploration tools and interaction techniques are described in more detail in the subsequent sections. After the treatment decision, the trainee can plan the selected therapy virtually. The focus is on the interactive planning of interventions and surgical procedures based on the image data and the 3D model. After completing the therapy planning, the result will be compared with those of experts in the analysis step. Finally, the user can learn about the progress of the real operation and the follow-up. Subsequently, he/she has the option to train another variant of this case.

4.2 Data

For the generation of polygonal 3D models, the slice data (mostly MRI) ideally need to exhibit a standard resolution of minimally 1mm and a slice thickness of maximally 3mm. In general, a training case contains the following 3D models: vertebras, intervertebral discs, spinal cord, large vessels and nerves, muscles, and the skin, which is relevant for access planning. Neck cases additionally contain tissues of the respiratory tract and the esophagus.

4.3 Exploration of Medical Image Data

To explore medical image data, the user can switch between two views, as shown in Figure 5. One view allows for displaying data in a traditional slice-oriented manner, where the grey value window can be defined. Zooming through individual slices is also possible to allow for more exact inspection of the data. Moreover, semitransparent colored overlays of segmented structures can also be blended, whereas 3D representations of these structures are displayed in a second 3D viewing widget, which supports the cognitive connection between the two views as well as the spatial perception of the anatomy. For this purpose, the 2D slice can also be integrated into the 3D view, as Figure 5 shows.

The system is intended to be used with a six degree of freedom (6DOF) input device to slice through the data, analogous to the marker-based augmented reality approach described in Section 3 [17]. Instead of the tracked marker (see Figure 2), a 6DOF input device from the SensAble Technologies PHANTOM product line of haptic devices[1] is used to manipulate the slice within the 3D scene. We used a PHANTOM Omni® and PHANTOM Desktop® from SensAble for the implementation and evaluation of our 6DOF interaction methods.

Using a force feedback Phantom device, differences in haptic material properties (e.g., stiffness) help to distinguish between critical and less critical tissues for minimally invasive procedures at the spine. This classification is performed by our medical experts during the examination of the 3D reconstructions. An injury of vulnerable risk structures such as nerves and large vessels must be avoided, while impenetrable structures (e.g., vertebras) may serve as landmarks. Injury of fat and muscle tissue is unavoidable. Principally, the haptic material properties are used to detect collisions of the 3D cursor with surfaces instantly (by force feedback), even if the view is blocked. Thus, the trainee can quickly identify and correct errors during, e.g., a trajectory planning (see Section 4.4). Indirectly, this extends the trainee's knowledge of the underlying three-dimensional spinal anatomy.

Free navigation in 3D space by rotation (with one or all three degrees of freedom), translation and zooming is difficult for untrained persons. Thus, in addition to the traditional views (axial, coronal, and sagittal) predefined favorable views are provided in order to support the user in navigation to crucial views of the 3D scene. Interfering structures are already masked out in those selectable views. Moreover, automatically generated camera paths guide the user through the 3D scene and therefore simplify the exploration task [12]. The camera tour can be arbitrarily interrupted by the user to interactively explore a certain region, and thereafter the animation can be resumed.

4.4 Virtual Therapy Planning

In addition to the exploration task, the 2D medical image slices (with overlays) and the 3D model are provided for the interactive treatment planning. On request, an introductory animation (illustrated in Figure 6) shows only the spine with the highlighted pathology and transforms the view from the initial coronary view into the operation view, showing all segmented structures.

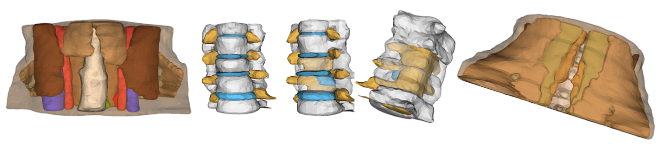


Figure 6: Intro sequence from coronary view to one operation view

In the following subsections the proceeding of trajectory planning, and tools to enhance visibility of important shapes or to verify the planing result are explained.

4.4.1 Trajectory Planning

Planning of a trajectory to the operation field in a minimally invasive procedure, a target area of injections, or setting of screws for spinal fusions are, by default, marker-based. That is to say, the user has to place a marker for the puncture and the target point of the virtual needle, dilator (tubular retractor) or screw. Those two markers can be defined via 2D mouse on the 2D image slices (CT or MRI)

[1]http://www.sensable.com/products-haptic-devices.htm

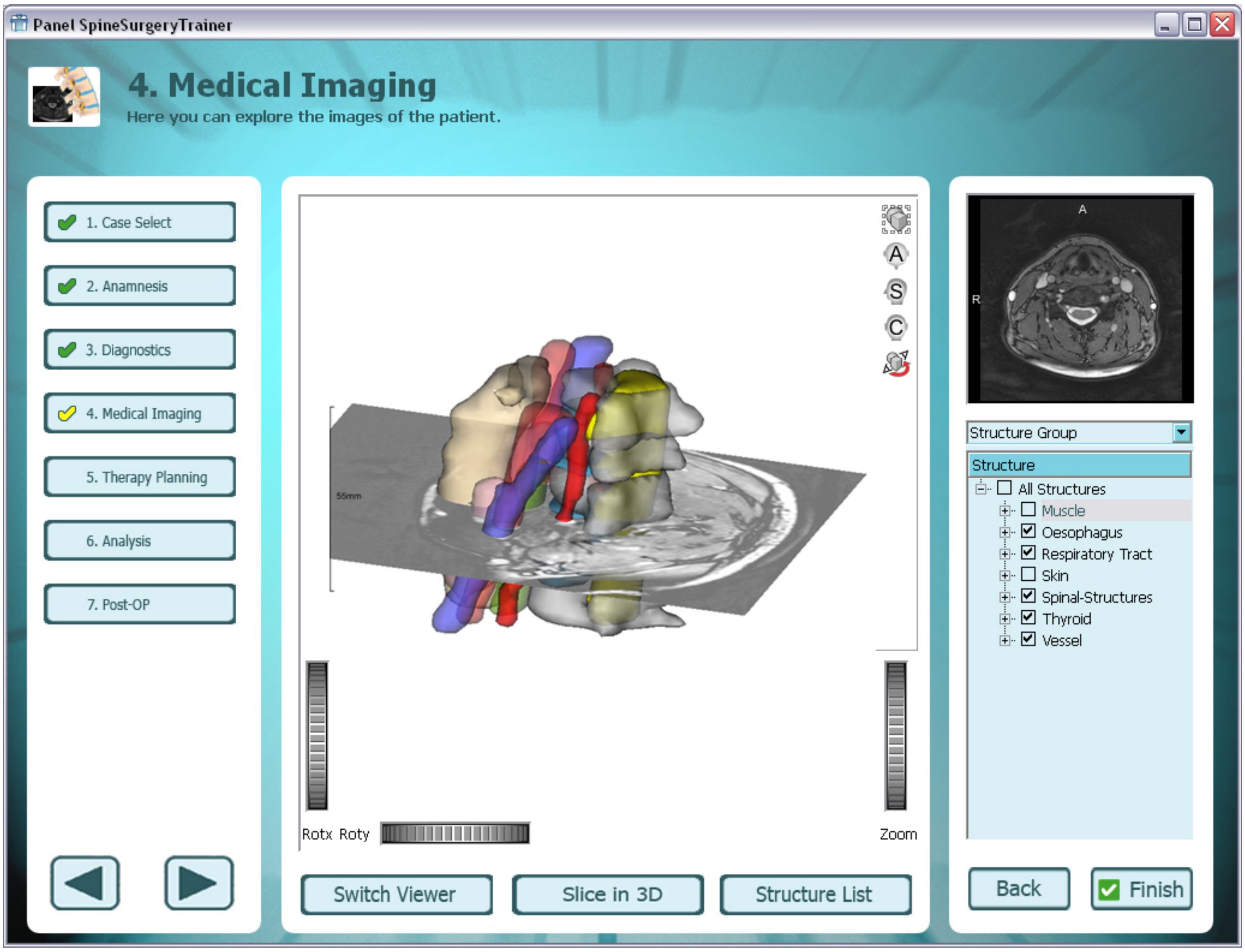


Figure 5: User interface for the exploration of medical image data and 3D model of the patient's anatomy. The currently displayed slice (top-right) is integrated in the 3D scene of a cervical vertebrae dataset. The colored overlays in the slice view correspond to the 3D representations of segmented structures. Structures (or groups of structures) can be selected by the structure tree on the right side. The current training workflow is displayed on the left side, where jumping to individual steps is possible.

or on the reconstructed 3D model of the patient anatomy. An animation visualizes the puncture of the virtual puncture device in 3D along the resulting trajectory between the markers. Since it is only implicitly defined by the two markers, the estimation of this trajectory bears a high mental effort. Therefore, we provide a more intuitive alternative taking advantage of the haptic 6DOF input device (depicted in Figure 7) which is specified in [8]. Here, the puncture task is separated into three individual phases (placement of the device tip, orientation, and insertion), whereas each phase contains a specific set of haptic constraints to simplify their respective performance. While working on the image slices corresponds to the clinical routine, the 3D models provide a better perception of spatial relations.

4.4.2 *Enhancement of Visual Perception*

For better visibility of the target area or to check for possible injury risks, structures can be masked out or shown interactively via a tree structure (see the right side of Figure 5a). Additionally, we integrated the isoline-based method of our augmented reality module described at the end of Section 3 in order to optionally support the trainee with more depth cues without occluding important structures. In Figure 3, e.g., the shape of intervertebral discs is emphasized by a set of yellow contour lines. Thus, the shape and therewith the lumbar disk herniation is clearly visible within the virtual vertebras and spinal canal and the video captured skin of the mannequin phantom.

4.4.3 *Verification of User Planning*

To verify the planning, the 3D scene including the virtual surgical instruments can be explored. An optional animation can also visualize the planned process. In case of a minimally invasive access planning, the animation conveys the whole process of extending the aperture with dilators to the point of the insertion of tabular retractors. For the purpose of verification as well as initial assistance, it is possible to automatically superimpose predefined insertion regions

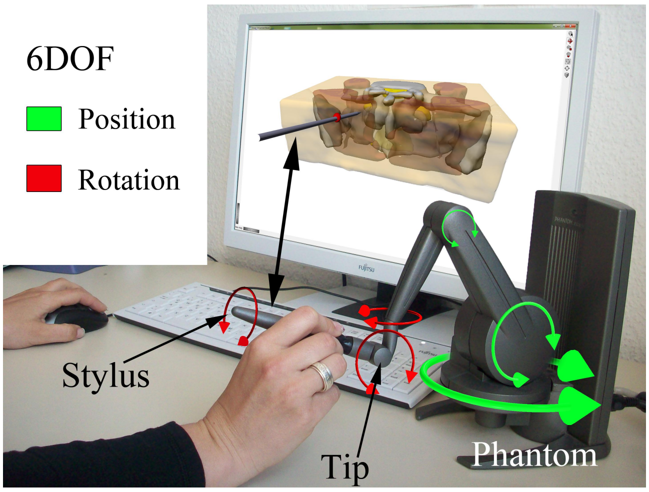


Figure 7: Manipulating the puncture device with a 6DOF PHANTOM Desktop ® device (using force feedback).

on the skin, similar to the method in [19]. Furthermore, this gives an impression of the very limited operation field in spine surgery. Such insertion regions also designate regions in which risk structures like blood vessels might be injured, where impenetrable bony structures might hamper the opening, or regions with too long instrument paths or bad angles.

4.5 Utilizing Augmented Reality

In order to take advantage of and familiarize the trainee with our AR-based approach (recall Section 3), we combine both the intraoperative prototype and our virtual training prototype.

As stated in Section 4.3, we adapt the optimized slicing algorithm as an exploration tool, utilizing advantages of a 6DOF input device. A further step is to use it (as originally intended) with a video captured physical marker, as shown in the upper part of Figure 5b, using the prototype setup.

In the advanced stage of training, the trainee can familiarize with AR-aided therapy planning methods, like the one described in [15]. For this purpose, the case data of the training system is expandable by new but incomplete cases (e.g., without anamnesis). Thus, the MRI or CT data of locally available mannequins, cadavers or real patients with the relevant reconstructed polygonal 3D models can be explored and used to make a virtual therapy planning.

Using our AR-based prototype, the virtual planning results (e.g., insertion point and incidence angle of a puncture device) will be overlaid on the real patient body, mannequin or cadaver. Afterwards, the trainee performs the usual training on the real body object supported by the AR technique. Of course, any other virtual object can be mapped on the body as well. Similar to [15], our training system can also be used for real therapy planning, and using the augmented reality technique the physician will be supported in real surgery. In this way, the trainee can first develop planning strategies at a home PC/workstation before he/she starts to train the procedure with a training object. Supported by his/her own virtual planning results mapped on the real training object, the trainee learns not only performing an intervention, but also the use of emerging intraoperative medical visualization technology.

4.6 User Guidance and Support

The user is (optionally) directed through the whole training process by offering information for each step on functionality and interaction possibilities (textually, and sometimes by videos). The user may also request expert support for both the treatment decision as well as for therapy planning. Thus, the trainee learns possible treatment suggestions and their respective indications from different experts. These are presented textually and by displaying the relevant 2D image slices as well as by a static or animated 3D visualization of the patient anatomy. During the therapy planning process, proposals of several experts are available in the form of videos of the experts' planning processes and the interactive explorable resulting 3D scenes. In the analysis step, the comparison with the planning of the experts is firmly integrated. The simultaneous presentation of the learner's therapy planning and processing and the recommendations of several experts enable the learner to check his/her results and get an impression of the variety of surgical and therapeutical strategies for a particular case. It is also planned to run the planning process of the experts as an interactive animation in order to communicate solution strategies and approaches.

5. IMPLEMENTATION

The system has been developed on an Intel® Xeon® quad-core Processor with 3.06 GHz, 8GB RAM and an NVIDIA GeForce GTX 460graphics card with 768MB memory supporting 3D graphics. For the development of the virtual training system, the prototyping environment MeVisLab [16] was used, incorporating the visualization toolkit (VTK) for geometry handling and graphics rendering, and the Open Haptics Toolkit [20] for accessing the phantom device and haptics rendering.

We use a modular software design that fits to the framework of MeVisLab. Each step of the workflow, outlined in Figure 4, is implemented in one macro module with python script. With this design, the relevant software modules of the AR-assisted spine surgery system could be well incorporated into the training prototype.

The software modules (tracking, calibration, registration, slicing, and rendering modules) of the prototype for AR-assisted spine surgery have been implemented with C++, OpenGL, VTK, and Qt. For the current implementation, the tracking module relies on marker-based tracking provided by the ARToolkit, which allows for multiple marker tracking in real time. However, due to the inaccurate calibration, we calibrate camera parameters using MATLAB. As a result, the new calibration was significantly more accurate regarding marker detection and pose estimation.

6. RESULTS

Figure 5 depicts a snapshot of the GUI of the medical imaging module within the training prototype. With a few buttons the user can define the view that is represented in the main window and which exploration tools are used. In the screenshot, e.g., a plane widget is added to the 3D scene that represents the relevant medical image slice. The GUI is reduced to the suitable control elements or widgets in respective to the content of the current main view and to the current training task (here exploration). Additionally to the current module interface, the training workflow is displayed continuously on the left side. Thus, the user keeps track of the current interaction possibilities. With the optional use of a 6DOF input device with force feedback, interaction tasks, such as the control of a virtual puncture device, are simplified, and the training is therewith improved.

The training system has been developed in cooperation with orthopedic surgeons, and it includes six cervical and eight lumbar vertebrae cases with indication for peridural injection and operative interventions. Modeling of single cases partially prerequisites clinical expertise and is extensive regarding data/material acquisition and processing, which includes anonymization, segmentation, generation of case variants, and editing of operation video clips. It is often necessary during the real operation of a case to decide whether it is suitable for the surgery training system.

As stated before, the hand-eye calibration requires minimal user interaction and is performed only once prior to the operation. Registration is similarly a one-time step that is performed during setting up the system. The slicing algorithm allows for on-the-fly computation and rendering of slices at a near real-time rate.

For the OP training scenario, a phantom model of the upper body is scanned with the mounted reference marker. After extrinsic calibration of the video camera, the mannequin phantom model is registered to the scanned data, using the corners of the reference marker as the set of correspondence point pairs. From a co-registered patient dataset, three vertebrae, intervertebral discs, and the spinal canal are segmented and 3D models are reconstructed. Finally, the visualization module starts the video stream augmentation.

Figure 1b depicts a snapshot of the GUI of the visualization module in a simulated spine surgery scenario. The widget shows a right posterior oblique (RPO) view, with augmented models of the lumbar vertebrae L2-L4 (cyan), intervertebral discs (green), and spinal canal (pink). Object silhouettes are slightly highlighted for enhanced shape perception. In Figure 8, a side view with an additional transparent overlay of a tomographical slice from the patient data is shown.

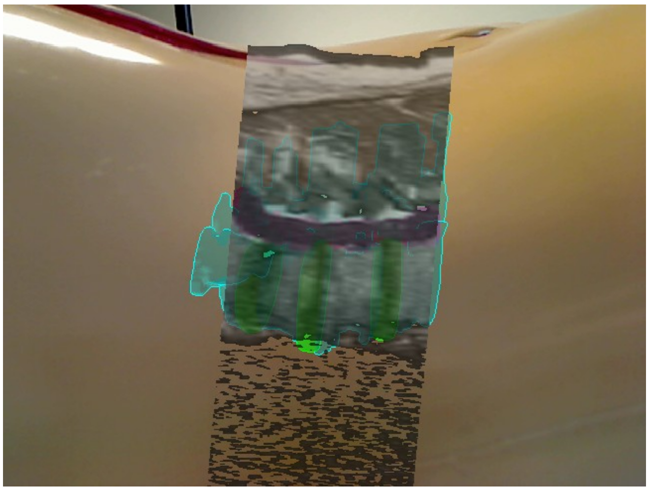


Figure 8: Side view with augmented vertebra (cyan), discs (green), and spinal canal (pink) in addition to a blended MRI cross section.

7. CONCLUSION AND FUTURE WORK

The SpineSurgeryTrainer is a case-based interactive training system, which provides training for the complete clinical workflow in spine surgery. With the current prototype future surgeons are able to acquire and improve their anatomical knowledge concerning spinal and surrounding structures, and they can train diagnosis and therapy decisions on the basis of several cases and case variations. Available expert recommendations and explanations as well as the analysis of the planning results help the user to plan the therapy self and to understand the planning processes of the experts. The difficulty varies according to the optionally provided assistance and expert proposals. An AR extension does not only support the trainee performing a planned intervention on a real training object, but also the use of AR technology in a real surgery. We aim at raising the safety and accuracy factors of the intervention by superimposing relevant operation-specific anatomical structures on the video stream of the operation field, which obviously allows for the protection of risk structures like spinal nerves, blood vessels, and the spinal canal. Thus, we introduced a prototypic tablet PC based add-on for enhancing intraoperative visualization, with the focus on spine surgeries. In addition, targeted structures like tumors or herniated discs are better localized and information about the shape and extent of such structures can be conveyed at different depth levels. From a surgical point of view, we have received positive feedback regarding the relevance and applicability of the presented approach.

Our future work concerning the intraoperative visualizations will focus on evaluating the applicability of the concept to other surgery scenarios. In a following development phase of the Spine Surgery Trainer, the effectiveness of further interaction tools, e.g., distance measurements or virtual removal of bony structures, will be examined. In addition, the system will be extended with further scenarios (e.g., placement of artificial discs or implants) and new operation cases. Therewith, a representative set of different planning processes will be provided and the trainee would obtain an overview of the possible disease patterns and treatments. Otherwise, a continuous evaluation of the systems regarding the usability and learning success will be conducted.

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