

Virtual Reality Simulator for the Training of Lumbar Punctures

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Keywords

Procedure simulation, surgical simulation, visualization, virtual reality, haptic feedback, lumbar puncture

Summary

Objectives: Lumbar puncture (LP) is performed by inserting a needle into the spinal canal to extract cerebrospinal fluid for diagnostic purposes. A virtual reality (VR) lumbar puncture simulator based on real patient data has been developed and evaluated.

Methods: A haptic device with six degrees of freedom is used to steer the virtual needle and to generate feedback forces that resist needle insertion and rotation. An extended haptic volume-rendering approach is applied to calculate forces. This approach combines information from segmented data and original CT data which contributes density information in unsegmented image structures. The system has been evaluated in a pilot study with medical students. Participants of two groups, a training and a control group, completed differ-

ent first training protocols. User performance has been recorded during a second training session to measure the training effect. Furthermore user acceptance has been evaluated in a questionnaire using a 6-point Likert scale with eight items.

Results: Forty-two medical students in two groups evaluated the system. Trained users performed better than less trained users (an average of 39% successfully completed virtual LPs compared to 30%). Findings of the questionnaire show that the simulator is very well accepted. E.g. the users agree that training with such a simulator is useful (Likert grade of 1.5 ± 0.7 with 1 = "strongly agree" and 6 = "strongly disagree").

Conclusions: Results show that the VR LP simulator gives a realistic haptic and visual impression of the needle insertion and enables new insights into the anatomy of the lumbar region. It offers a new way for increasing skills of students and young residents before applying an LP in patients.

ent pain inserting the needle into bone structures. Furthermore, the liquor extracted from the spinal canal can be contaminated and therefore be unusable for the diagnosis if the puncture has been performed incorrectly. Like in most other medical procedures, experience in doing LPs may help to avoid inconveniences and risks for the patient.

LPs are usually taught using the apprenticeship method. In this method the trainee is guided by an experienced supervisor and gains his first experiences by performing the LP directly on the patient. This method has been used to educate many physicians but it has some drawbacks that affect patient and trainee. The patient is forced to take every possible failure of the trainee which can result in unnecessary pain, tissue damage or injury. The apprentice is heavily stressed by the possibility of incorrectly performing the LP and cause pain for the patient. This may lead to an increased feasibility of errors. Therefore, an untroubled learning atmosphere is hard to maintain in such a situation.

Another drawback of this method is the dependency on voluntary patients in need of an LP. In some cases medical students have to wait a long time until they can attempt to improve their experience. For these reasons an alternative for the apprenticeship method would be desirable.

Training dolls on which the LP can be performed are commercially available. These dolls can be used to give an impression of the intervention but can give no insight into the human anatomy of the lumbar region. Furthermore, an extensive evaluation of the training results can not be given and physiological and pathological variances of the lumbar anatomy can not be simulated. Recently the relevance of virtual reality (VR)-based simulators is increasing in the field of medical education (e.g. [3–5]) because with the use of simulators experience can be gained without risking the patient's health.

Singh et al. have been the first to introduce the idea of a virtual reality LP simulator with

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1. Introduction

The lumbar puncture (LP) is a complex intervention that has to be performed with great precision. The intention of the puncture is to extract cerebrospinal fluid (CSF) from the spinal canal. The CSF is used for diagnostic purposes. During the intervention a thin biopsy needle is inserted, usually between the lumbar vertebrae L3/L4 or L4/L5 and pushed in until there is a haptic feedback, a sort of

"give", that indicates the needle is inside the subarachnoidal space of the spinal canal [1, 2]. Incorrect techniques resulting from inadequate training or supervision can lead to suboptimal outcomes such as discomfort and pain or multiple LPs. Serious complications of a lumbar puncture like spinal or epidural bleeding, and trauma to the spinal cord or spinal nerve roots are rare. More often when the LP is performed without an exact knowledge of the anatomy, LPs can cause signifi-

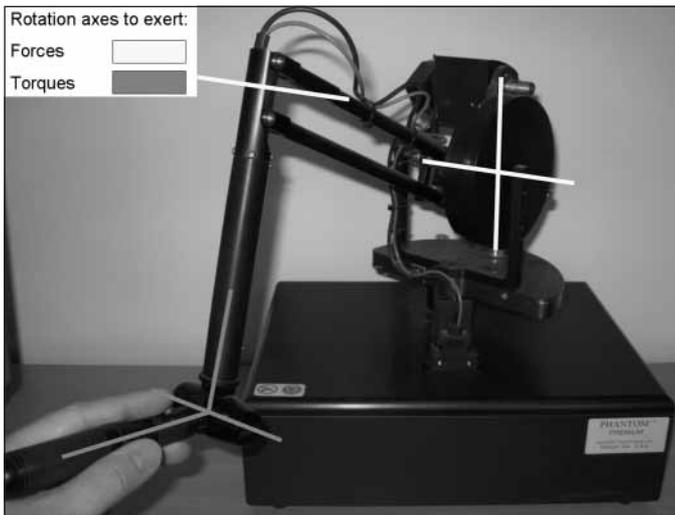


Fig. 1 Sensable's Phantom Premium device with six degrees of freedom

tactile feedback in 1994 [6]. The conceptual design included the development of a specialized force feedback device. Ra et al. presented a spine needle biopsy simulator in [7] and simulators for the virtual reality-based training of acupuncture have been introduced in [8, 9]. Forest et al. recently presented a system for the simulation of ultrasound-guided needle insertion procedures like hepatic biopsy, radiofrequency thermal ablation, prenatal examination or amniocentesis [10]. Other LP or epidural injection simulators have been announced or presented in [11–14]. These simulators use precomputed virtual haptic models generated from segmented image data. Haptic feedback of structures that have not been segmented or modeled cannot be rendered. The force feedback devices used in these systems have three degrees of freedom (3DOF) to simulate the forces that constrain the movement of the needle. If needle forces can only be rendered in three degrees of freedom, only the positioning of the virtual needle tip can be constrained and no restriction of yaw and pitch of the needle inside the virtual body can be generated unless a fixed insertion point (pivot point) is used. In this case the user is not allowed to insert the needle at arbitrarily positions to train the identification of the optimal cut-in point. In [15] a prototype system that uses a 6DOF device for the simulation before and navigation during biopsy interventions is presented. The authors developed a system that could be used in a clinical setup to train and support the physicians patient-specific in doing a biopsy. An extensive task

analysis and human performance evaluation regarding the effects of visual and haptic feedback for spine biopsy has been done in [16] using a biopsy simulation interface.

In this paper an LP training system is presented and evaluated. The system combines original CT data with label data to facilitate the haptic feedback of structures that can not be segmented with standard methods. Furthermore, the use of a haptic device with six degrees of freedom for puncture simulation enables the haptic rendering of torques and forces that resist needle rotation and transversal needle movement. While parts of this work have already been presented in [17–19] this paper presents more detail about the

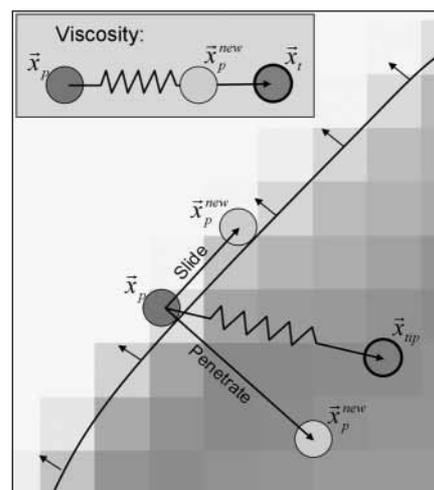


Fig. 2 Proxy-based haptic volume rendering: movement of the proxy to simulate friction forces, surface resistance and viscosity effects depending on the image gradient and the user-applied forces

haptic rendering of needle torques and new visualization techniques. It also introduces an evaluation component that rates the users' performance. It is also a pilot user study that measures the training effect and the acceptance of the training system among medical students.

2. Materials and Methods

Our virtual reality training system presents a virtual scene that consists of a user-steered virtual needle and a virtual body generated from segmented CT data. The system is split up into a haptic and a visual component.

2.1 Haptic Component

The haptic component renders the forces that affect the needle during the insertion. The forces are calculated 1000 times per second depending on needle position, needle rotation, insertion angle and local tissue properties. The haptic device is then used to return the rendered forces to the user.

2.1.1 Haptic Device

A force feedback device with six degrees of freedom (Sensable Phantom Premium 1.5) is used for the haptic I/O. This device enables haptic feedback in three directions in space and in three rotation axes of the pen-like end effector (► Fig. 1). The nominal position resolution of this device is 860 dpi (dots per inch) for translation sensing, 0.0023 degrees for yaw and pitch rotation and 0.008 degrees for roll rotation. The translational force output is limited to 8.5 N (Newton) maximum (peak force) and 1.4 N continuous force output. The maximum exertable torque is 515 mNm for yaw and pitch and 170 mNm for roll. The continuous exertable torques are 188 mNm and 48 mNm, respectively.

2.1.2 Proxy-based Haptic Rendering

The use of virtual proxies [20] or god-objects [21] is a common approach for haptic surface rendering, because it allows smooth shaded feedback from unprocessed polygons. The basic idea behind proxy-based methods is that a virtual spring damper with damping

constant k connects the haptic instrument to a virtual proxy. This way the representation of the instrument tip in cyberspace does not directly interact with the virtual object. The proxy acts as an interface. By the restriction of proxy movement forces are indirectly (by the spring) applied to the haptic instrument using Hooke's law

$$\vec{f} = k \cdot \vec{d} \quad (1)$$

where \vec{d} is the distance between proxy position \vec{x}_p and instrument tip position \vec{x}_i . The new proxy position \vec{x}_p^{new} is calculated in every time step (approx. 1000 times per second).

2.1.3 Proxy-based Haptic Volume Rendering

An approach for haptic volume rendering [22, 23] has been adapted to enable haptic feedback from unsegmented structures in CT data during a lumbar puncture. While in haptic surface rendering planes defined by surface normals restrict the proxy from moving through surfaces, in proxy-based haptic volume rendering the proxy is constrained to move only perpendicular to the direction of the image gradient vector at the proxy position $\vec{\nabla}V(\vec{x}_p)$ (► Fig. 2). Therefore, this method enables haptic feedback directly from volumetric density data (e.g. CT data).

The movement is split-up into three steps that correspond to the simulation of penetrability, friction, and viscosity. Figure 2 illustrates the proxy movement as described in [23]. The proxy is moved (or not moved) in direction of the surface normal to simulate penetrability. Alternatively it is moved (or not

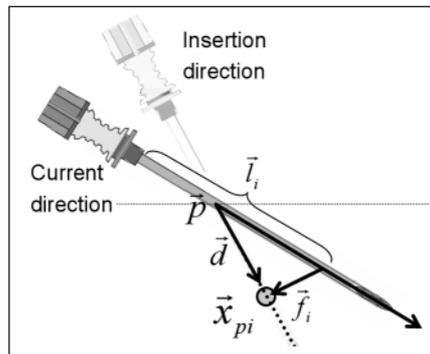


Fig. 3 Generation of torques by restricting the needle shaft proxies to follow the insertion vector defined by \vec{p} and \vec{d}

moved) perpendicular to the surface normal to generate the friction effect. In absence of a strong image gradient viscosity is simulated by delaying the proxy movement. A set of constants and transfer functions can be used to define tissue properties like friction, stiffness, viscosity, and penetrability.

2.1.4 Needle Model

The user-controlled virtual needle is modeled as a rod. To allow for the generation of needle tip forces and needle body forces 15 proxies are attached to the virtual needle (multiproxy approach) with the first proxy at the tip of the needle and the others equidistantly located between tip and handle of the needle.

2.1.5 Needle Tip Forces

The surface resisting force, that prevents the needle from piercing a surface, surface fric-

tion that can be felt when the needle slides over a surface, and viscosity, that impedes free needle movement inside of an organ, affect the needle tip and are calculated using the haptic volume rendering approach for the first proxy \vec{x}_{p0} . As described in 2.1.3 this allows the user to feel the resistance and friction of structures that have not been segmented. Haptic volume rendering forces depend on the pixel values $V_{CT}(\vec{x})$ and gradients $\vec{\nabla}V(\vec{x})$ of the structures and manually adjusted transfer functions and parameters. During an LP some structures (e.g. ligaments, bones, skin) are pierced by the needle. To ensure, that the important structures (especially the ligaments) contribute realistic force sensations these structures have been labeled during the insertion. If the first proxy is about to enter a labeled structure the haptic volume-rendering forces are temporarily ignored until the part of force directed against the needle's direction exceeds a predefined threshold or the needle moves back again. This way the forces needed to pierce important structures like the ligamentum flavum can be directly defined depending on the virtual patient.

2.1.6 Needle Body Forces

The realistic behavior of the needle is improved by restricting rotation and transversal motion of the needle inside of the body. The needle position and needle direction vectors \vec{p} and \vec{d} are stored when the needle pierces the skin to calculate correction forces that restrict the user from rotating the needle inside the body and transversal needle move-

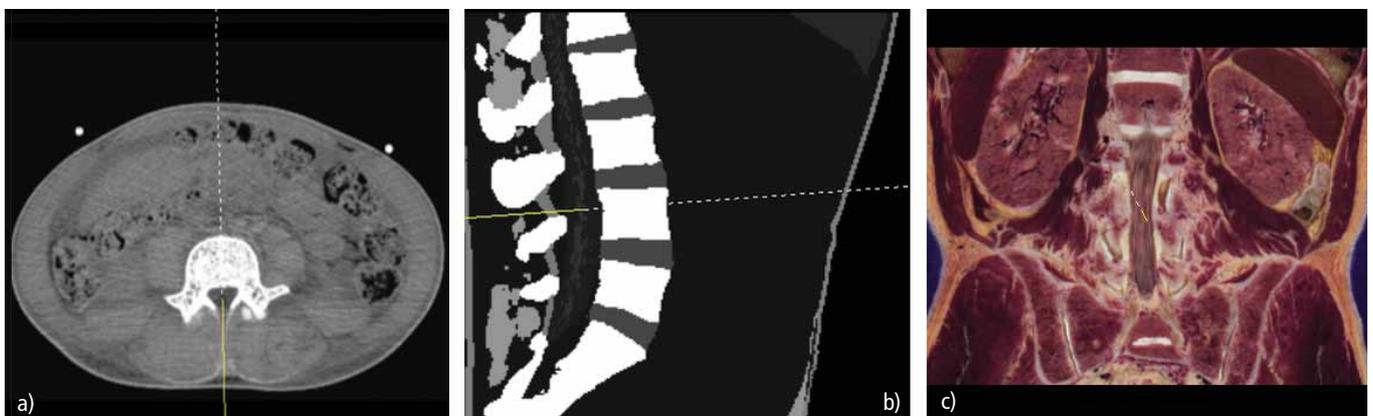


Fig. 4 2D visualization showing orthogonal slices and a projection of the virtual needle. a) CT data in a transversal slice. b) Label data in a sagittal slice. c) RGB data in a frontal slice

ment. Transversal motion and rotation of the needle is restricted using the multiproxy approach. The 14 needle shaft proxies are restricted to move on the straight line defined by \vec{p} and \vec{d} (► Fig. 3). The torque values that control the rotational axes of the 6DOF haptic device are calculated by integrating the lever action of each proxy on the needle's grip.

$$\vec{M} = \sum_{i=1}^{14} \vec{l}_i \times \vec{f}_i \quad (2)$$

Furthermore, a friction force that resists the needle's body from sliding through the tissue is computed based on the friction force of each needle body proxy.

2.2 Visual component

The visual component is made up of synchronized 2D and 3D visualizations that show the virtual body and the virtual needle and supporting annotations that inform the user about the human anatomy of the lumbar region. Three 2D views show orthogonal slices (transversal, sagittal, and frontal) of the image data (► Fig. 4). The slice viewer can either show the CT data $V_{CT}(\vec{x})$ or the label data $V_L(\vec{x})$. Other data like RGB cryotome anatomical image data $V_{RGB}(\vec{x})$ e.g. in case of the Visible Human [24] or the Visible Korean Human [25] can also be shown in the slice viewers if available. This data allows for a differentiation between soft tissues of the lumbar region and therefore can give a good anatomic impression (► Fig. 4c). The slice positions are selected in real-time according to the current position of the needle tip. The position of the needle is indicated by a projection of the needle direction vector \vec{d} onto the selected 2D plane.

The 3D scene shows a virtual representation of the needle and the surfaces of relevant medical structures (► Fig. 5). The organ surfaces are generated by the marching cubes algorithm [26] using the label data $V_L(\vec{x})$ mentioned in 2.1.5. Surface rendering using different colors and opacities for each organ can be used to give an impression of the anatomical coherences. The whole scene can be rotated, panned and zoomed using the mouse. Stereo view can be generated with shutter or anaglyph glasses to improve the impression of depth in the virtual body.

A text overlay in the lower left corner of the 3D view shows information about the structures that are being pierced by the virtual needle (Fig. 5). Depending on the number of structures that have been segmented and integrated into the label data $V_L(\vec{x})$ detailed anatomic knowledge can therefore enhance the LP trainer. The positions of important anatomic landmarks like dorsal processes or iliac crests are usually identified by palpation during a real LP. They can be visualized to give the user the possibility to recognize the correct insertion position for the virtual needle (Fig. 5).

The view can be overlaid with up to three multiplanar reconstructions of the volumetric dataset that are perpendicular to each other. The orientation and position of the slices is defined by the orientation and posi-

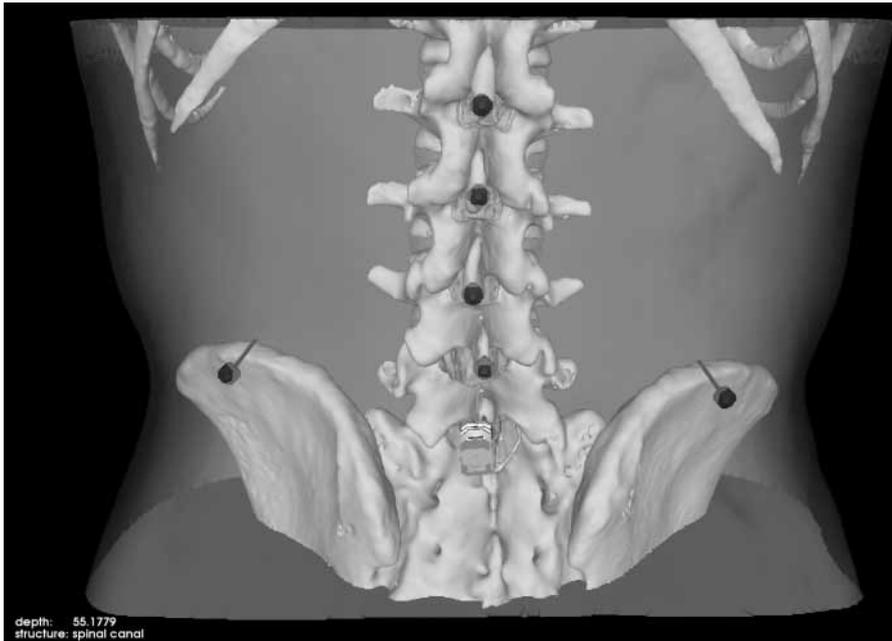


Fig. 5 3D visualization showing the virtual patient, the virtual needle and markers for spinal processes and iliac crests and annotations that indicate the needle's position (lower left corner)

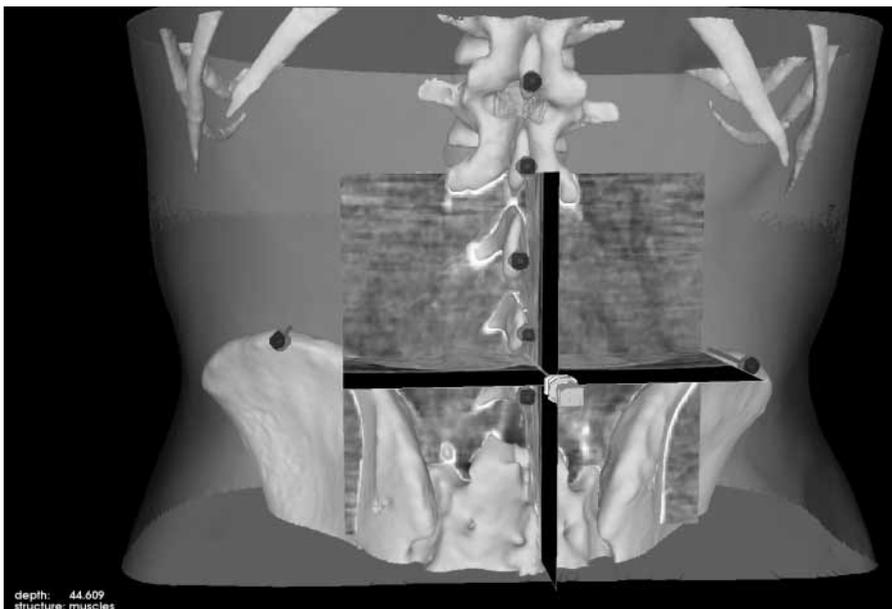


Fig. 6 3D view overlaid by multiplanar reconstructions of the volumetric CT dataset. The reconstructions are oriented according to the orientation of the needle.

tion of the virtual needle (► Fig. 6). This way the correspondences between surfaces and image data can be analyzed in real-time and the user has a better possibility to trace the target region of the needle in the two-dimensional image planes.

Additionally a needle cam can be used to give an impression of the human anatomy (► Fig. 7). This view is generated by a cam that shows the virtual scene from the perspective of the user-steered virtual needle.

2.3 Skill Level-dependent Graphical User Interface

► Figure 8 shows the graphical user interface (GUI). The GUI is dominated by the three-dimensional view of the virtual scene. Orthogonal slice views are shown on the right hand side. The parameters can be adjusted using menu items. Depending on the level of experience the users can choose between beginner, advanced and professional mode. These activate respectively deactivate specific viewing modes that guide the user during the virtual LP.

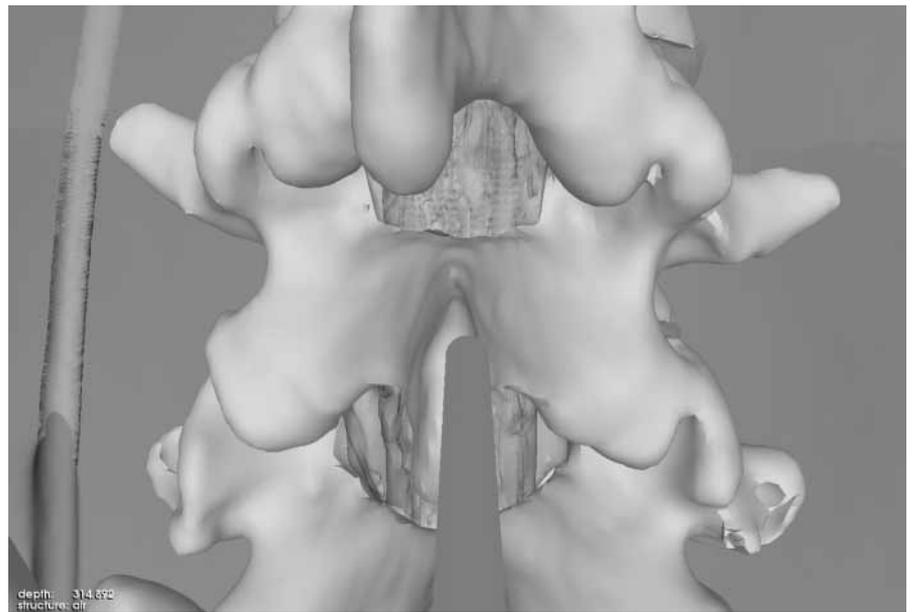


Fig. 7 Needle cam showing the 3D scene from the needle's perspective

2.4 Input Data

An XML file is used to provide the application with the label data $V_L(\vec{x})$, the CT image data

$V_{CT}(\vec{x})$, the optional anatomical RGB cryotome data $V_{RGB}(\vec{x})$, surface data of all relevant structures and landmarks, a three-dimensional representation of the needle, and an-

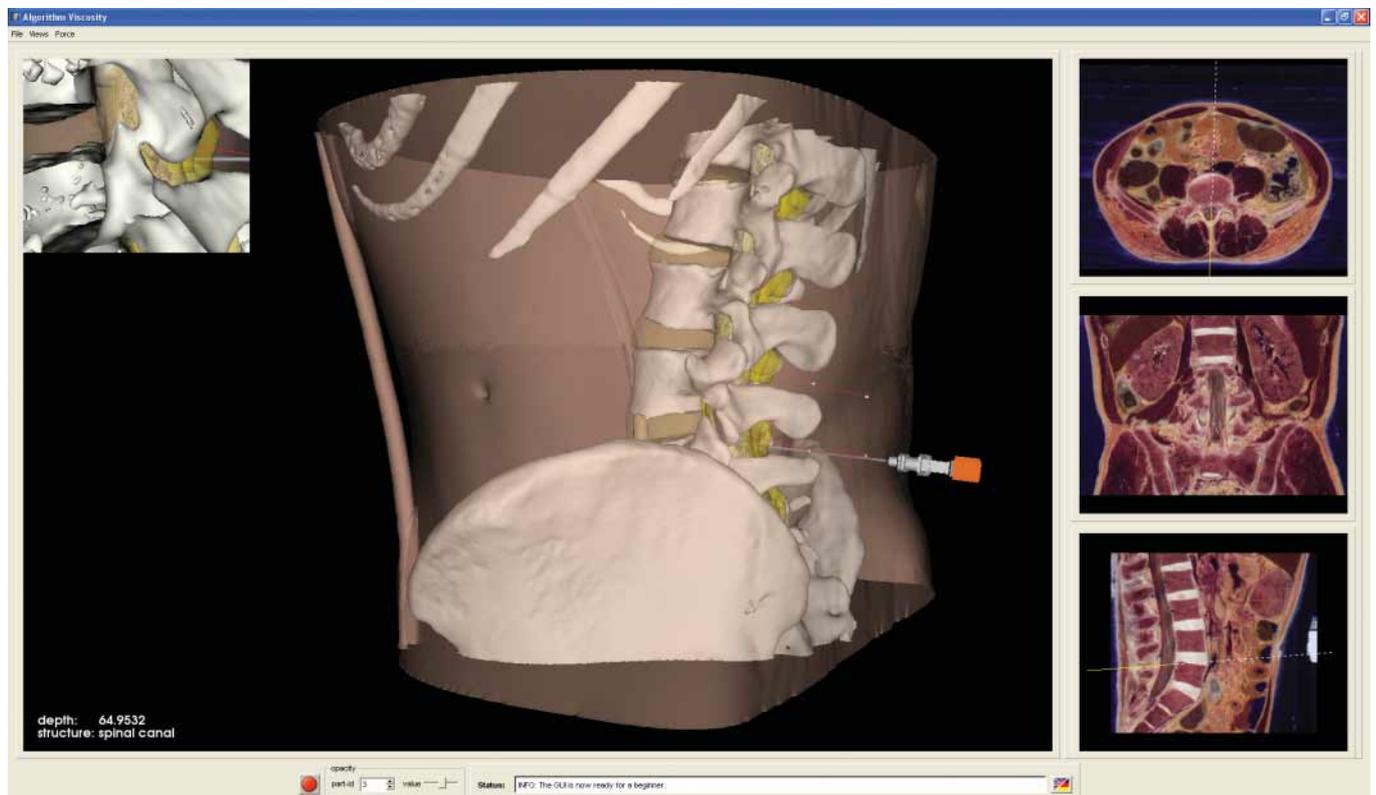


Fig. 8 Graphical user interface of the lumbar puncture trainer showing a (slightly rotated) 3D visualization of the virtual scene enhanced by a detailed needle cam view (upper left corner). Furthermore, orthogonal slices of the RGB data are shown on the right-hand side.



Fig. 9 One of the co-authors using the virtual lumbar puncture trainer wearing shutter glasses to enable stereographic visualization.

Table 1 Evaluation protocol: The user groups completed a similar training protocol except for the first training session in which the control group trained the ascites puncture instead of the LP.

Timeline and Mentoring	Training group (21 users)	Control group (21 users)
Preliminary Independent	Didactic LP material for self studies	Didactic LP material for self studies
Day one Mentored by medical student Approx. 25 min.	Theoretical LP introduction Synthetic needle game Other puncture (ascites) on two different virtual patients	Theoretical LP introduction Synthetic needle game Virtual LP training on two patients (P1 and P2)
Day two Mentored by medical student Approx. 25 min.	Virtual LP on two patients (P2 and P3)	Virtual LP on two patients (P2 and P3)
Afterwards Independent	Questionnaire	Questionnaire

No.	Statement	Mean	SD
1	I would have dared to do an LP before I completed the VR-based training.	3.5	1.6
2	I felt different forces at different virtual tissues	1.5	0.7
3	The needle control with the haptic device was intuitive.	2.2	1.1
4	The stereoscopic (3D) view eases the training.	2.5	1.3
5	The display of the virtual patients seemed realistic	2.0	1.1
6	The different visualization techniques helped to understand the anatomy of the lumbar region.	1.6	0.7
7	After the training I feel more confident to perform a real LP than before	1.9	1.1
8	I consider the training with such a simulator as useful.	1.5	0.7

Table 2 Evaluation questionnaire: The users were asked to decide how they agree or disagree to some statements about the training system. The scale of possible answers ranged from 1 (= strongly agree) to 6 (= strongly disagree).

notation strings. Furthermore, the visualization parameters like surface colors and opacities for each surface and the initial viewing position are defined. Friction, viscosity and penetrability parameters are defined for each structure to enable a realistic haptic impression.

2.5 Evaluation Component

An evaluation component has been developed to rate the success of the needle insertion and give feedback to the user. For this purpose the movement of the needle is recorded during the insertion. This user path is compared to an optimal path defined by experienced physicians. Furthermore the piercing of structures at risk like bones or nerves and the puncture time is evaluated. An overall score ranging from 0 to 100 is calculated to compare the success of different users. Besides the measurement for a successful outcome of the procedure (liquor could be extracted) it inherits scores to reflect the discomfort and pain of the virtual patient (time, hurting of structures at risk). Furthermore a feedback dialog analyzes the performance and gives hints how to improve the virtual LP (e.g. “The insertion point was too far left, move the needle to the right before inserting it”).

2.6 Virtual Patients

Input data for the LP simulator has been generated based on the Visible Human male data set [24], the Visible Korean Human data set [25] and CT data from three patients of the University Medical Center Hamburg-Eppendorf. We used the CT data and the segmentations (label data) of skin, bone, muscles, ligaments, fat and target area. Most of the segmentation information of the Visible Human and Visible Korean Human has been available to us. Some structures like ligaments and target area have been manually or semi-automatically segmented by medical students. The patient CT data has also been segmented by medical students using volume-growing and manual interaction in approx. one week. Surface models have been generated based on the label data to enable the 3D visualization. Parameters for haptic and visual components

and the definition of the input data are provided to the framework using the XML file. The force parameters have been adjusted so that the forces to pierce the different tissue layers reflect the forces measured during real interventions and porcine studies [27, 28]. However since the forces that can be felt during an LP strongly depend on the constitution of the patient (e.g. age, calcification), the force parameters have been manually adjusted in cooperation with medical experts so that the puncture process seemed realistic to them.

2.7 Evaluation of the Training System

The training system has been evaluated in a questionnaire-based pilot user study. The participants have been divided into a training and a control group. Each of which completed a predefined study protocol given in ►Table 1. All participants were given some didactic material for self-studies on the LP preliminary to the first training session. In the first training session all participants started with an additional theoretical LP introduction and a synthetic needle game that asked the users to hit some targets inside a virtual cube with tubes in it. This way all participants got familiar with the haptic device and the VR setup. The control group users then trained a puncture task different to the LP: The ascites puncture that is done by inserting a needle into the abdomen of the patient. Two virtual patients that are different from the virtual LP patients have been used for this training. The other group trained the LP on two virtual patients (P1 and P2). In the next training session at least 24 hours later all users had to complete virtual LPs, six on patient P2 and six on patient P3. During this session the puncturing attempts were automatically monitored by the evaluation component (Section 2.5). The total score of each attempt together with the information if the user was successful in reaching the spinal canal were stored in a file. All training sessions were mentored by medical students. No system developer influenced the participating users. After the training all users were asked to fill out an anonymous web-based questionnaire (►Table 2) by rating statements about the training system. A Likert scale ranging from 1 (= strongly agree)

Table 3 Automatically achieved scoring results: mean score and success rate in puncturing the virtual patients P2 and P3 for training (n = 21) and control group (n = 21). Each participant accomplished six trials on each virtual patient.

Scoring results	P2		P3	
	Mean score	Success rate	Mean score	Success rate
Training group	54.0 %	53.3 %	35.9 %	25.4 %
Control group	49.7 %	46.7 %	31.1 %	13.0 %

to 6 (= strongly disagree) was used to record their opinions. Furthermore the users could write free text comments and suggestions via the web interface.

3. Results

3.1 System Requirements

The puncture simulator runs on a dual Xeon 3GHz windows system with 2 GB Ram and NVIDIA Quadro FX 4400 graphics card without haptic simulation performance problems (e.g. vibration effects).

3.2 User Study

Forty-two participants (equally split into control and training group) completed the evaluation protocol and 40 completed the questionnaire. Users were medical students and five users already performed a few (1–5) LPs during a clinical fellowship. None of the users stated to be stereo blind allowing all participants to use the stereoscopic visualization of the system.

3.2.1 Scoring Results

The mean scores and the percentage of successful puncturing attempts (the needle reached the spinal canal) are shown in ►Table 3. The group of participants that were trained on virtual LPs achieved better results and a higher success rate compared to the control group that trained the virtual ascites puncture.

3.2.2 Questionnaire Results

The mean rating and standard deviation of each statement is shown in Table 2. No sig-

nificant differences in the questionnaire results were found between control and training group. Many of the users contributed comments in the free text fields to highlight characteristics of the simulator and to express suggestions. Many of the comments focused on the intuitiveness of the system. Some users stated that it was difficult to place the needle with the haptic device. A few users suggested improving or adjusting the haptic feedback for bones and the ligamentum flavum. Many users pointed out that the visualizations from different perspectives were very impressive and gave new insights into the human anatomy.

4. Discussion and Future Work

4.1 Discussion

The scoring results (Table 3) show that a virtual LP training improves the performance of the LP on the simulator. The fact that scoring and success rate for the virtual patient P2 are better than for P3 is caused by the different levels of difficulty of the virtual patients. P2, the Visible Korean Human, is very slim and young and therefore very easy to puncture. P3 (a CT-based dataset) is very corpulent and shows some ossification of the lumbar region. Furthermore this patient suffers from lumbar spinal canal stenosis. Therefore the spinal canal of this patient is hard to reach with the needle.

The questionnaire results (Table 2) show that the training system is well accepted by the medical students (statement 8). Especially the manifold of visualization techniques enables the users to learn more about the anatomy of the lumbar region (statements 5 and 6). The force sensation has been verified by comparing the force curves in existing literature. Nevertheless it is important that the users feel

different forces on different structures during the needle insertion. The participants of this study experienced these differences (statement 2) and many users stated the system to be intuitive (statement 3). However this aspect could be improved as described in Section 4.2. The acceptance of stereoscopic visualization (statement 4) is slightly worse than the other quality aspects. One explanation for this could be that the visual refresh rate decreased when stereoscopic visualization was enabled which could have been observed by the users. Nevertheless the stereoscopic visualization still eased the training for many users. Comparing statements 1 and 7 one can say that the VR-based LP training helps to improve the self-confidence of the users performing an LP.

4.2 Limitations

The results of the pilot study and the aspects illustrated in Section 4.1 are quite motivating to further investigate the development of a VR-based LP training system. However some limitations and still existing drawbacks of such a simulator should be kept in mind.

The haptic device described in Section 2.1.1 limits the translational force output to a maximum of 8.5 Newton which can only be rendered as a peak force. In case a user presses onto the bone continuously (2–3 seconds) the device will give way to prevent the motors from overheating. Latest experiments with a high force version of this device which is able to render forces of up to 37.5 Newton as peak and 6.2 Newton continuously show that it is possible to overcome this limitation by using such a device.

The hardware acquisition costs of more than US\$ 50,000 restrain the intention to commercialize this training system in the near future. However it is expected that hardware costs will further decrease while VR hardware properties will increase so that the acquisition of VR hardware that runs different surgical training simulators might be worthwhile in the future.

The intuitiveness of the system is limited by the interface that is presented to the users. In our case it is only the handle of the haptic device and the screen of a CRT monitor instead of the back of a real patient and a real LP needle. This difference leads to limited im-

mersion into the virtual world. We tried to balance this lack of intuitiveness by using a synthetic needle game to improve the user's ability to steer the virtual needle. However the interface of the system could be improved by e.g. attaching a real needle to the haptic device in the future.

Some aspects of an LP like palpation, complications or reactions and feelings of a real patient are not simulated or can not be simulated. Therefore, the use of a virtual training system cannot replace the direct training on the patient. It should rather be considered as a first training method that supports the users preparing their first real LP.

4.3 Future Work

Soft tissue deformations have not been implemented in our approach since only small deformations arise during the lumbar puncture and a realistic simulation of deformations would strongly increase the computational complexity. Nevertheless, the definition of haptic properties like stiffness or friction for each segmented structure enables the user to identify tissues like skin or muscles as soft and structures like bones or ligaments as more solid. If other puncture interventions are considered to be simulated one has to think about simulating soft tissue deformations during needle insertion. DiMaio et al. present an interesting approach in [29]. Furthermore, we are working on LP cases with different pathologies to achieve a greater variety of virtual patients.

4.4 Conclusion

A virtual reality simulator for lumbar punctures has been presented. In the training system a haptic device with six degrees of freedom is used to control a virtual needle and perform the virtual LP. During the insertion of the needle different tissues like muscles, fat, skin and bones can be felt by means of viscosity, resisting force and friction. The extended haptic volume-rendering technique facilitates force feedback from labeled as well as unsegmented structures. The restriction of transversal needle movement together with the rotation constraints enabled by the 6DOF device facilitates the perception of realistic

needle behavior. The synchronization of force feedback and miscellaneous visualization techniques provide a realistic impression of the anatomy. Evaluation results show a high user acceptance of visualization techniques, force feedback and suitability for the preparation of a first LP. The use of virtual reality techniques opens up new opportunities for supporting and improving LP training in medical education. The training method offers a new way of understanding human anatomy and gaining experiences in using a puncture needle.

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