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Simulation-based Ultrasound Training Supported by Annotations, Haptics and Linked Multimodal Views

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Abstract

When learning ultrasound (US) imaging, trainees must learn how to recognize structures, interpret textures and shapes, and simultaneously register the 2D ultrasound images to their 3D anatomical mental models. Alleviating the cognitive load imposed by these tasks should free the cognitive resources and thereby improve the learning process. We argue that the amount of cognitive load that is required to mentally rotate the models to match the images to them is too large and therefore negatively impacts the learning process. We present a 3D visualization tool that allows the user to naturally move a 2D slice and navigate around a 3D anatomical model. The slice is displayed in-place to facilitate the registration of the 2D slice in its 3D context. Two duplicates are also shown externally to the model; the first is a simple rendered image showing the outlines of the structures and the second is a simulated ultrasound image. Haptic cues are also provided to the users to help them maneuver around the 3D model in the virtual space. With the additional display of annotations and information of the most important structures, the tool is expected to complement the available didactic material used in the training of ultrasound procedures.

1. Introduction

Many Ultrasound (US) training simulators concentrate on specific tasks of US guided procedures, such as needle insertion and guidance. However, few simulators focus on the US techniques themselves, assuming knowledge of the trainees on the appearance of structures in ultrasound images (sonoanatomy). While it is true that current training curricula already include material to allow learning basic techniques, there is still place for improvement. For example, trainees still heavily rely on textbooks and static images as a source to study. However, US imaging is dynamic, and learning to manipulate the US probe is an essential part of the training process, too. Furthermore, access to US machines to train is still very limited, and even when available, the number of different scenarios is reduced, and learning to recognize certain pathologies, for example, is never trained.

In some areas of engineering, medicine and science, users must abstract 3D information and relationships from 2D representations of objects [OA92]. They must also understand these relationships to make sense of the data [Tor03]. This is also true in the specific case of medical students that are learning US techniques. During hands-on training sessions, it is rarely possible to have simultaneous access to visualizations of the scanned anatomy, while also looking at the 2D ultrasonic images. For this reason, students must mentally rotate and adapt their mental models of the anatomy to match the images they see. The complexity of the task increases even more if we consider that mental models might be built from Computer Tomography (CT) or Magnetic Resonance Imaging (MRI) data sets or experience with cadavers, which all look quite different from the images provided by US visualization. Furthermore, CT and MRI slices are normally presented in orthographic projections parallel to the XY, XZ or YZ planes, while US slices are almost always at oblique angles, since it is performed free-hand. By alleviating this cognitive load, trainees should be able to use their mental resources more effectively during the learning process.

Our aim is to complement current ultrasound learning curricula by providing an interactive learning tool that allows trainees to freely explore 3D anatomical models with a vir-

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tual ultrasound transducer that generates simulated images from these models. The tool allows to simultaneously view the interior of the anatomical models, a simulated US image that corresponds to the virtual probe and a 2D slice that corresponds to the cross-section of the structures visualized in the simulation. The views are complemented with contextual annotations that appear when related structures have become visible in the cross-section image. They indicate the names of the structures visible in the anatomical model as well as the US and cross-section images. To make interaction intuitive and natural, we employ a haptic simulation. Here, the user controls the probe using a 6DoF haptic device and receives 3DoF haptics feedback that help the users build a better mental model of the anatomy and its position and orientation in the virtual space and trains hand-eye coordination. To validate the usefulness of the tool for learning ultrasound techniques, we have conducted a user study and present the results.

The rest of the document is structured as follows. An overview of the related work is given in Section 2. This is followed by the description of materials and methods in Section 3, where we present the developed tool and discuss the most important technologies and algorithms used. The study design and its results are presented in Section 4, followed by the Discussion and Future Work, in Section 5. We give our final comments in Section 6.

2. Related Work

In medical visualization, annotations are frequently used to provide additional information about the visualized data sets. This often happens with the goal to facilitate the learning process of novices, e.g., to aid the memorization of anatomical structures. Preim et al. [PRS97] allow users to interactively explore a 3D anatomical model that is tightly linked with textual labels. Users can access additional information in a details-on-demand manner by clicking on annotations or anatomical parts. In [SCS04], Sonnet et al. describe a technique that facilitates labeling hidden parts of anatomical models by using an interactive explosion probe. Hartmann et al. [HGAS05] present a series of metrics for aesthetic annotation layouts, which they extracted from a large corpus of manually labeled medical text book images. These metrics are to be used as guidelines during the design of label placement algorithms. In [MP09], Mühler and Preim describe an algorithm that automatically places labels to annotate medial 3D models or 2D slices. Mogalle et al. [MTSP12] present a similar placement algorithm specialized on 2D slice data. Finally, Pick and Kuhlen [PK15] describe an annotation system that, among others, has been used for automated annotation placement in immersive medical visualization.

The use of virtual and augmented reality to develop simulators to train ultrasound guided procedures is not new. Most of the existing simulators focus on needle insertion procedures because of the difficulties to obtain enough training, such as lack of patients and use of unrealistic phantoms. Magee et al. [MZR*07] proposed an augmented reality simulator with a mannequin, probe and needle. Computer Tomography (CT) scans were registered to the mannequin and the ultrasound simulation was generated from 3D textures obtained from real ultrasound images and mapped to the corresponding tissue types. Vidal et al. [VHGJ08] presented a simulator with patient specific data with an ultrasound simulation based on CT images, post-processed to add effects such as shadowing. In [NCQ*11], Nie et al. present a biopsy simulator. The ultrasound simulation presented was an interpolative approach, where several US images where *stitched* together to create a volume, which was sampled to generate the final image. In [CQCH12], Chan et al. observed the lack of mechanisms to motivate the learner in most of the training simulators, and proposed to include seriuos-game elements to improve learning. Their US simulation approach generates ultrasound images from example textures, obtained from real US images.

To enhance the training of manual skills and hand-eye coordination haptics, have been included into various medical simulators. The applications range from fundamental techniques like palpation [UMK12] and needle insertion [PND*11, NCQ*11] to complex surgeries like Laparoscopy [BZH*06] and Endovascular procedures [RAFB05]. Also simulators for ultrasound-guided needle puncture employing haptic feedback have been implemented [FCV*07, VHGJ08]. A detailed overview on the research in this field can be found in [CMJ11].

Most of these works provide, in one or the other way, improvements to training of needle insertion and guiding techniques, but focus mainly on eye-hand coordination tasks, assuming that trainees already have knowledge of ultrasound imaging and can locate the structures involved in the procedure being trained. Furthermore, the simulators lack the didactic aspect and cannot be used for independent learning, since most of the feedback is received from a supervising expert. On the commercial side, products such as ScanTrainer from Medaphor and UltraSim from MedSim, offer complete didactic experiences using interpolative approaches for the ultrasound simulation. However, although the ultrasound images are registered to 3D anatomical models, these do not match exactly, and the content in the image does not always reflect the 3D models.

Here, we propose an ultrasound simulator and didactic system, that can be used independently by trainees to learn about the basics of ultrasound and sonoanatomy at their own pace. To this end, the system combines realistic ultrasound simulation, visualization on 3D anatomical models, haptic feedback and a dynamic annotation system in an easy-to-use desktop application, that can be used to complement current curricula. We make emphasis on a simultaneous visualization of simulated ultrasound images, the cross-sectional 2D images and the exact corresponding anatomical model, supported by the use of an real-time generative simulation approach.

3. Materials and Methods

This section describes the proposed application and its main features, as well as the algorithms and techniques used.

3.1. Interface

The designed prototype application has a simple user interface. As seen in Figure 1, the main screen is divided into two parts: the foreground and the background. Also in Figure 1 we can observe that the anatomical model and the virtual probe (**VP**) are displayed in the foreground (A), while in the background two images are displayed: a simulated ultrasound image (**ImS**) of the scanned anatomy (B) and a corresponding cross-sectional 2D slice (**ImC**) (C) . The US image (**ImS**) is annotated (D) to show where the structures appear in the image. These are linked to **ImC**, the anatomical model and other additional information by the use of colors. At the bottom left (E) a tabbed panel shows information about different structures and how to identify them through their appearance in ultrasound images or their position relative to other more prominent structures. Users can interact with the model by scanning it with a virtual ultrasound probe **VP** which in time is controlled via a haptic device. A virtual slice (as shown in Figure 2) is attached to the end of the probe, so that users can better appreciate its position within the model and see which structures are currently being scanned and rendered in the image. Additionally, a physics-based haptic simulation is used to aid the users to more easily align the virtual probe with the model. The haptic cues can also help the users to build a clearer mental model of the spatial position of the anotomical model.

Other Features

To reduce visual cluttering and facilitate viewing internal structures, such as the arteries and nerves, that are otherwise covered, some structures such as muscles and skin, considered as secondary in this context, can be displayed with a fixed transparency, or they can be turned off completely. Still, the structures will continue to be used for the ultrasound simulation as well as to render the 2D slice, as can be seen in Figure 2. To facilitate the identification of the different anatomical structures, these are also color-coded in the slice.

3.2. Ultrasound Simulation

A realistic and interactive simulation of ultrasound images is needed for training and learning applications. The simulation should also be able to reproduce as many US effects and artifacts as possible, since these are, in many cases important visual cues that help physicians to recognize specific structures.

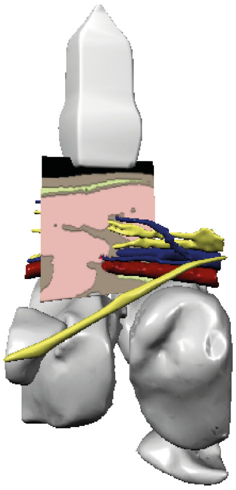
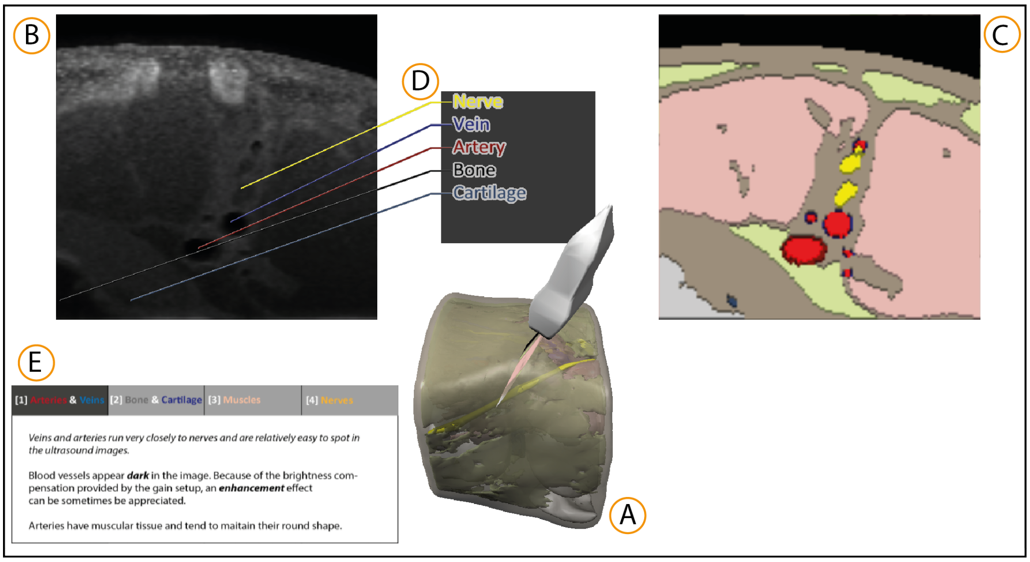


Figure 2: *Virtual probe and slice showing scanned structures with color codes.*

The simulation approach used for the ultrasound images is based on the work presented in [LUKK11], which employs geometrical acoustics [Vor08] to model the ultrasound wave as rays and their interactions with the media they traverse. Using this methodology it is possible to model effects such as reflections, reverberation and shadowing, based on the difference in acoustic impedance of the materials. An example can be seen in Figure 3 (A), where a bone is visible with strong reflections and shadowing. Additionally, since the actual image formation process is emulated, effects such as enhancement, which causes structures to appear brighter than they should, can be modeled by taking into consideration the absorption values of the materials, as seen in Figure 3 (B). Another important feature, is that the ultrasound probe and its beam pattern are also modeled allowing the use of virtual transducers with different properties, such as frequency, geometry and focus point for different learning scenarios. Furthermore, the beam model is three-dimensional and therefore, the simulation also includes the effects of lateral, axial and elevational resolution. The effects of this property can be appreciated in Figure 3 (C).

Since different types of material present different speckle patterns in Ultrasound images, 3D textures were generated using various backscattering models, as in [LTJK14]. These textures are sampled by the simulation algorithm to generate the different material types that can be seen in the simulated images. For example, for the darker cartilage structures around the bone, we modeled a texture with less scatterers as the texture used for the brighter muscle tissue. An example of this can be appreciated in Figure 3 (A), which shows the bone surrounded by a cartilage layer. It is also important to mention that a large part of the realism we achieved with the ultrasound simulation was obtained with a high level of detail of the underlying models. In this case, we segmented a



Veins and arteries run very closely to nerves and are relatively easy to spot in the ultrasound images.

Blood vessels appear ***dark*** in the image. Because of the brightness compensation provided by the gain setup, an ***enhancement*** effect can be sometimes be appreciated.

Arteries have muscular tissue and tend to maitain their round shape.

Figure 1: *Screenshot of the Application. A) Anatomical model. B) Simulated ultrasound image. C) Cross-sectional 2D slice of the model. D) Annotations. E) Information pane.*

CT volume, focusing on maintaining most of the irregularities in the structures; avoiding to smooth them out, as is done frequently for 3D visualization tools.

Additionally, we extended the framework to include the option to render the 2D Slice (**ImC**) that corresponds to the structures visualized in the US simulated image and which is used by the annotation framework to select the anchor points.

3.3. Annotations

Using the framework from [PK15], annotations that provided the names of all anatomical structures currently visible in the US and the cross-sectional slices were added. In general, we followed an approach similar to the one described in [PRS97] and placed annotations in a designated area, a so-called layout column. This layout column was placed right between the 2D US and cross-sectional slices, as can be seen in Figure 1 (D). For every anatomical feature that is currently visible in one of the two 2D slices, the column accommodates a short textual label showing the feature's name. The association of each label to its anatomical feature was established using a leading line that was connected to the respective feature in the US slice. For association of labels to their features' location in the cross-sectional slice and the 3D model, a consistent color coding similar to that of [MP09] was used. In our design, we applied the color of each feature to its label and leading line. An additional white halo around label and leading line ensured a good contrast and thus a good legibility.

To determine the feature-side endpoint of each label's leading line—its so-called anchor point—, we employed a simple segmentation approach. Whenever the 2D slices were updated, the cross-sectional slice and its color coding were used to perform the segmentation. For this, each pixel was classified based on its color and fused with other 4-connected pixels into connected components using a straight-forward region growing algorithm. Each leading line's anchor point was finally determined to be the central pixel of the largest connected component's axis-aligned bounding box for the associated feature. In case this point did not belong to the feature—e.g., if the feature had a pronounced concave shape—we used a random pixel from the largest connected component instead. To minimize the motion of anchor points between updates, the system first checked if a previous anchor point still belonged to the correct feature and reused it if it did.

To further improve the clarity of the annotation layout, we ordered individual text labels such that their leading lines did not intersect. However, to avoid undesirable visual discontinuities that arise from reordering annotations (see [HGAS05]), we used animations for positional changes. Animations were also used to fade annotations in or out if the corresponding feature became visible or invisible.

3.4. Haptics

The haptic simulation should support the user in controlling the virtual US probe. It should be easily possible to bring the probe in a steady resting position on the surface of the anatomical model or to smoothly move upon it. To make

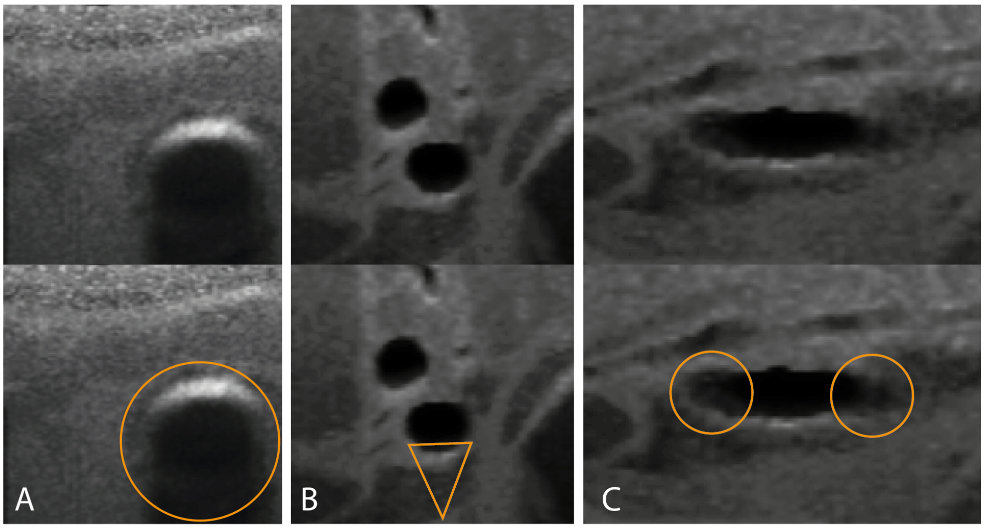


Figure 3: *Simulated Ultrasound Images. A) Bone with strong reflections and shadows. B) Blood vessels with some enhancement at the bottom edge. C) Blood vessel at an oblique angle, part of the walls walls can be seen due to the thickness of the beam.*

the interaction intuitive a natural behavior of the probe is pursued and a physics-based haptic simulation is employed.

To this end, the common virtual coupling approach [AH99] is applied due to technical stability reasons. Here, the virtual probe is controlled by the simulation and then coupled to the input of the haptic device via a spring-damper system. As a result, the behavior of the probe is determined by the simulation and respects the employed laws of physics while following the input of the user. The mechanics of the probe and the anatomical model are modeled as rigid-bodies and are simulated with a fixed time step employing an implicit scheme for the temporal integration of the governing differential equations. A detailed description of the according equations including their derivations can be found in [ESHD05].

The haptic interaction between the probe and the model should also reflect frictional effects. This yields not only a more realistic behavior but also enables the user to bring the probe into a stable resting position and obtain a steady US image. To integrate the simulation of frictional contacts a so-called constraint-based approach is applied for collision response, which is well-suited to model this kind of physical effects. Thereby, contacts are modeled based on Signorini's law [DMD*06] to prevent inter-object penetrations and the approximate Coulomb friction model described in [OTSG09].

The resulting mechanical equation system forms a linear complementarity problem which is solved using a projected Gauss-Seidel (GS) approach known to be fast enough for the required simulation in real-time. The applied algorithm uses a blocked handling of the equations originating from each contact as in [KK14] to speed up the solving process. To increase the robustness of the simulation, the algorithm is augmented by an additional constraint correction technique based on [Bau72] to resolve constraint violations resulting from numerical errors and the linearization of the governing equations. Furthermore, an approach described in [ESHD05] called constraint force mixing is applied to stabilize the solving process.

The complete haptic simulation is performed with a time step of 1ms and is executed on the commonly used haptic update rate of 1kHz. This includes also a collision detection step which is carried out with the Bullet Physics Library.

4. User Study

A preliminary user study was performed to evaluate and validate the developed application described above as a viable option to learn basic ultrasound imaging, anatomy and sonoanatomy. The study was designed to focus on aspects of the quality of the users' experience and the software's usability.

One of the subjects that concerns the investigation is the ability of the trainees to recognize landmark structures in ultrasound images after using the proposed learning tool. Structures are recognized first by their general appearance. Some ultrasound textures, effects and artifacts are very characteristic of certain tissue types, for example, the anechoic (dark) tubular structures with enhancements effects are most probably blood vessels. Another way to recognize structures is by their position relative to other structures. This, however, assumes knowledge of the scanned anatomy. In fact, ultrasound experts rely so much on this, that without contextual information of the scanned anatomy, they have difficulties recognizing structures. Therefore, a learning tool and the corresponding knowledge-measurement instruments must be attached to a specific anatomy. In this case, we used a model of a knee obtained from manual segmentation of a CT scan; this was done using 3D Slicer [FBKC*12]. The segmentation was converted to a surface representation for the simulation and visualization.

The measurement of *Learning* was done two-fold. First, we are interested in quantifying the knowledge the participants possess on ultrasound and anatomy before and after using the learning application. The second dimension we are interested in, is the users' perspective on their learning experience with the software, mainly, if they feel they are able to learn by using the application.

This last aspect is closely related to usability, for which we also apply measuring instruments, namely usability questionnaires to gain insight about the interaction techniques and selected features, and if they contribute to the learning process. How and in which measure each feature contributes is a more difficult question to answer without first answering the first one, and will therefore be postponed to another iteration of the study. Nonetheless, we are interested in two main features proposed for the learning tool: the Annotation System and the use of haptic interaction, and accordingly investigate them through the questionnaire.

According to the mentioned research questions and measurements mentioned above, we formulate the following hypothesis to be proved by the study:

H1 The proposed tool can be used to successfully learn basic ultrasound imaging.

- **H1a** Users will perform better in a test after using the tool.
- **H1b** Users will feel they have learned.

H2 The tool will be considered useful by the users.

H3 The proposed features will be perceived as a support for the learning process.

- **H3a** The annotations system will be perceived as helpful by the users.
- **H3b** The haptic feedback will be perceived as helpful by the users.

4.1. Participants

Seventeen people (2 female and 15 male, ages M = 28.35, SD = 5.55) participated voluntarily in the study. Since evaluating usability and user experience was a priority, all participants were required to have prior experience with Immersive Virtual Environments and 3D visualization. None of the test subjects for this preliminary study had medical background or previous knowledge of anatomy or ultrasound imaging. This situation was however not considered an issue since the application is designed for beginners and additionally guaranteed a common knowledge baseline among participants. All of the participants had normal or corrected-to-normal vision and normal motor skills. Only one participant reported a slight difficulty for spatial perception.

4.2. Design

The study is based on a $2x1$ within-subjects design with a pre- and post-test methodology to observe two dependent variables: (a) the participants' ability to identify structures in simulated images and (b) their ability to identify structures in real ultrasound images. A test was applied to every participant at the beginning of the study. They were given as much time as required, but every participant took around ten minutes to solve the test. The exercises in this test were designed based on exercises found in US textbooks and on input from experts in the area who evaluated the difficulty and viability of the exercises. Three types of exercises were used with simulated and real images, and consisted on identifying structures in them. These were formulated as follows:

E1 The following image shows 4 marked structures labeled from A to D. Identify these structures and fill the table below. Choose your answers from the following words: Bone, Nerve, Artery, Vein, Connective Tissue, and Muscle. The answers are not repeated.

E2 In the following image, identify and label the following structures: (A) Artery, (B) Bone and (C) Nerve.

E3 From the following image, draw the shapes of the structures into the empty space provided below, then, label them with: Bone, Nerve, Artery, Vein, Connective Tissue, or Muscle. Draw and label as many structures as you can see.

After the pre-test was finished, participants had a 20 minute session to use the application. All the features of the tool, along a short description of the anatomic scene, were printed and handed out. The first five minutes of the session were used to explore these features. This was immediately followed by 10 minutes of free exploration. In the remaining 5 minutes, participants were asked to solve two tasks to make sure all of them had explored the complete anatomy at least once. These tasks were designed to imitate scanning tasks that are usually done in hands-on workshops. The first task consisted on locating the main artery and position the probe so that the artery was displayed at its short axis at the center of the US image. Participants had to rotate the probe to change to long axis visualization of the artery, of course, without losing sight of it. Task two consisted in finding the nerve and scanning it along its path, following also simultaneously any ramification when possible. The whole procedure was designed and implemented as comparable to a real learning process as possible.

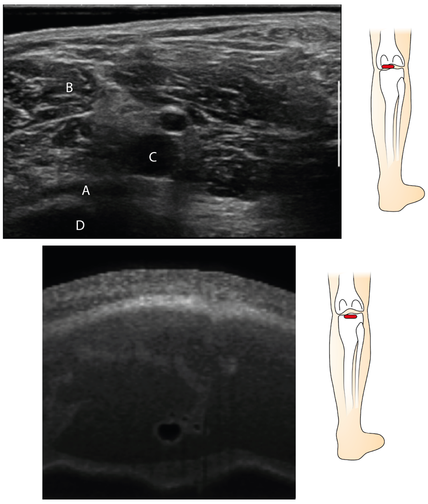


Figure 4: *Sample of images used with test exercises.* Top *shows a real ultrasound image used with **E1**.* Bottom *shows a simulated ultrasound image used with **E3**.*

Table 1: *Questions to collect participants' experience in learning.*

Q1	I quickly learned about the general anatomy of the knee.
Q2	I can easily remember the position of structures relative to each other.
Q3	I can easily recognize prominent structures such as arteries and bones, using the tool.
Q4	I can easily recognize prominent structures such as arteries and bones, in real ultrasound images.
Q5	I can easily describe specific structures in ultrasound images.
Q6	I would feel confident using a real ultrasound scanner.
Q7	Being able to see the internal anatomy was useful.
Q8	I often used the information on the 2D slice to the right to find structures that were hard to identify in the US slice to the left.
Q9	I understood the spatial relation between the 2D ultrasound slice and the 3D model.

Table 2: *Questions to collect participants' opinion about annotations and haptics.*

Q10	I found the information presented in the annotations useful.
Q11	The mapping of the annotations to the corresponding anatomy in the different views was helpful.
Q12	The haptic feedback helped better position the virtual probe where I wanted.
Q13	Scanning the model with the stylus but without haptic feedback would have been difficult.

After this session, the post-test, which contained the same questions as the pre-test, was applied. Both tests were completed on paper by the participants without using the application. To motivate the participants to learn and try to answer the questions correctly, prizes were offered, during the presentation of the study, to the three participants with the best results in this post-test.

Following the post-test, the participants were asked to fill the SUS questionnaire [Bro96] to evaluate the user experience and test **H2** regarding the system usability as a whole. Additionally, a modified USE Questionnaire [Lun01] was applied, especially to test the system's *ease of use*, *ease of learning* and the user's *satisfaction* using the system. Both questionnaires were also applied to evaluate the usability of the annotation system and the haptic interaction. To test **H1b**, specific items were designed to measure the participants' feelings towards their learning experience with the tool. These questions are listed in Table 1. To test **H3**, the questionnaire included specific questions to evaluate the participants' perception of the usefulness of the annotation system (**H3a**) and of the haptic feedback (**H3b**). These questions are listed in Table 2.

Completing these questionnaires took around 10 minutes. In total, including the short presentation and collecting demographic data at the beginning, the complete study took around 1 hour per participant.

4.3. Apparatus

The hardware setup, shown in Figure 5, consisted of three desktop computers with an NVIDIA GeForce GTX 780 Ti graphics processor unit (GPU). A Phantom Omni haptic device positioned at the right of each workstation (optionally to the left for left-handed users). The study was conducted with three participants at a time and in the same room, which was big enough to allow independent and quiet work.

4.4. Results

The questions of the pre- and post-test are divided into two categories: simulated **(S)** and real **(R)** images and are compared separately. Figure 6 shows a summary of these results in absolute values. The maximum obtainable scores were 17 pts. and 12 pts. for **(S)** and **(R)** respectively. For the pre-test, the average points obtained were 3.58 (SD=1.64) for **(S)** and 3.29 (SD=1.87) for **(R)**. For the post-test, the average points obtained were 9.29 (SD=2.07) for **(S)** and 7.40 (SD=1.81) for **(R)**. A two-tailed paired t-test was applied for both categories, which resulted in a p-value of $< .001$ for **(S)** and **(R)**. Thus, for **(S)** and **(R)**, a highly significant difference

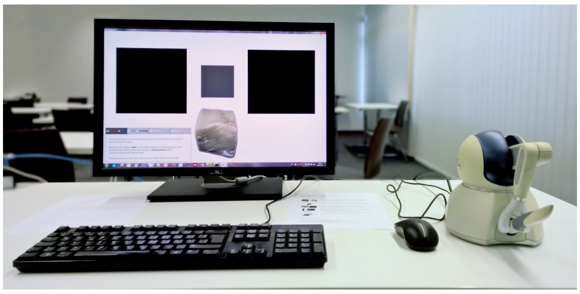


Figure 5: *Workstation setup for the user study; three stations were used.*

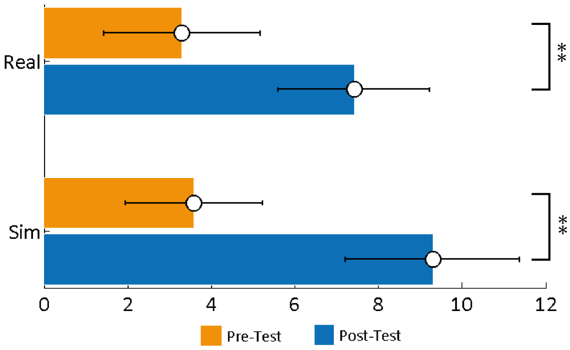


Figure 6: *Average results of the pre- and post-tests. Error bars denote standard deviations. Asterisks (**) denote highly significant difference (p-value > 0.001)*

was found, while the participants reached an increase of 5.71 points of 17 (0.33 normalized to 1) for **(S)** and of 4.11 of 12 (0.34 normalized to 1) for **(R)**.

Questions Q1 to Q9 from the applied questionnaire (see Table 1) collected the participants' opinion about their learning experience and were evaluated with a 5-point Likert scale. The results of each individual question are plotted in Figure 7. The questions with lower scores are Q4 (3.2), Q5 (3.12) and Q6 (2.47), which are related to the participants' confidence regarding real ultrasound images, which were not available for learning in the application. This contrasts with the score of Q3 (4.76), which states: "I can easily recognize structures using the tool". Regarding the features of the application, namely the annotation system and the haptic feedback, results to questions Q10 to Q13 are plotted in Figure 8.

For the applied usability tests, the results are as follows. The SUS questionnaire is normalized to a score of 0-100 and presented in Table 3. The results for the USE-based questionnaire were also normalized and are presented in Figure 9. In general, for almost all cases, a value greater than 70 was measured, which is the common threshold for these questionnaires. Only for the case of satisfaction with the Annotation System a value of 61.97 (SD=23.30) was observed.

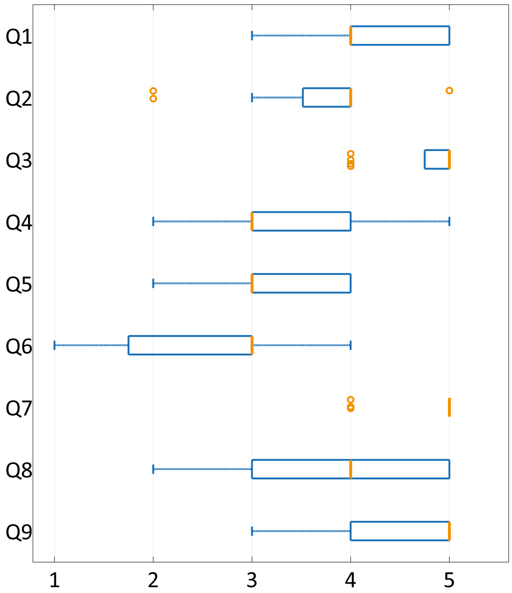


Figure 7: *Results for the 5-point Likert scale questionnaire regarding Learning Experience (Questions Q1-Q9).*

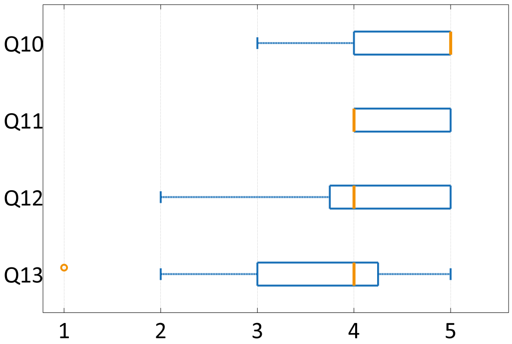


Figure 8: *Results for the 5-point Likert scale questionnaire regarding the Annotation System (Q10 and Q11) and Haptic Feedback (Q12 and Q13). Error bars denote standard deviations.*

5. Discussion and Future Work

As shown in the results from the pre- and post-tests (see Figure 6), participants were able to better recognize structures in simulated as well as in real ultrasound images; this supports **H1a**. Of course, the recognized structures are limited to the ones that were annotated in the system, namely arteries, veins, bone, cartilage and nerves. The results between **(S)** and **(R)** are not directly comparable, nevertheless,

Table 3: *Results of the SUS questionnaire for the application, the Annotation System and the Haptic Feedback.*

	Mean	SD
Application	83.23	10.56
Annotations	70.88	8.78
Haptics	77.35	6.93

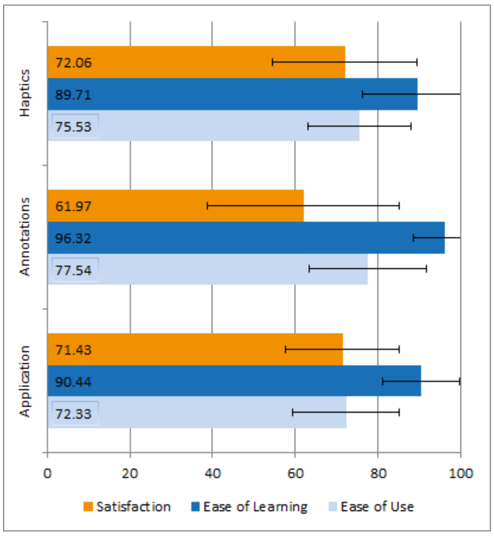


Figure 9: *Results of the USE Questionnaire. Error bars denote standard deviations.*

the increase of knowledge for real images is also highly significant, which further supports **H1a**. Using the application, participants only had a written description of how structures should look like and the corresponding simulation; real images with annotations were not used. This might have impacted negatively on the participants' confidence when solving the exercises involving real ultrasound images during the test, and this reflects in the lower scores for questions Q4-Q6. Despite this situation, we consider hypothesis **H1b** to be supported, since participants did felt they learned by using the application (Questions Q1-Q3).

Hypothesis **H2** is supported by the results of both the *SUS* and USE questionnaires, although it is clear that there still exists place for improvement. Furthermore, from questions Q7-Q9, we can infer that having simultaneous multiple views was considered useful by the participants.

These results also support **H3a** and **H3b**. Most of the negative comments for the haptic system were regarding the amount of time required to hold the stylus up, which is tiresome after a few minutes of use. However, participants did agree that the use of the haptic device and feedback helped them to better control and position the virtual probe to where they wanted (Q12 and Q13). Regarding the annotation system, improvement suggestions from the participants were mostly to request to add more features or change the way the annotations were shown. For example, one user suggested to allow annotations to be shown per structure, others would have liked to have every occurrence of the structure annotated. A design decision while developing was actually to remove this option since it caused too much visual cluttering; a compromise of course, is allowing the users to choose their preferred option.

Overall, the results of the study are positive regarding the tool as a learning system for ultrasound techniques as the presented study shows the feasibility of the tool to support learning of ultrasound, however, open questions can still be identified. Thus, the next step is to make improvements on some of the interaction techniques and features and add more information to the system regarding other structures. The annotation system will be extended to include some of the features suggested by the participants, such as being able to select a specific type of annotation to be displayed. A second study is being planned with medical students as participants to evaluate the tool in a realistic setting and to measure how effective is the training using the simulation, compared to conventional training without a simulator (or possibly with other simulators).

A more detailed model that includes more structures is also required to improve the simulation and make it look more similar to the real images to increase the confidence of users. To this end, the initial CT data scans should be made with the simulation requirements in mind, so that the relevant structures and regions of interest appear clearly in the volume with enough resolution. Physics-based deformations will be introduced to allow users to train movement related characteristics of the anatomy, for example, the fact that veins disappear when they are pressed down with the probe. The hardware setup should also be improved, especially regarding the use of the haptic device to minimize fatigue and allow longer training sessions.

6. Conclusions

We have presented a didactic application that combines ultrasound simulation, an annotation system, haptic feedback and multiple visualization and allow users to dynamically and freely explore a 3D anatomical model by *scanning* it with a virtual probe. The tool shows simultaneous views of a simulated ultrasound image, a 2D slices and a 3D model of the scanned anatomy. The views are registered, color-coded and annotated to alleviate the users cognitive load and aid them in their learning process. We have performed a user study with participants with no medical background and showed that they were able to learn to recognize structures in simulated and real images after a session with the application.

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