A Study on Reconstruction of Breast Medical Images to Serve as Training for Biopsy Procedures Guided by Ultrasound

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Abstract. *This article aims at reviewing some works that present important aspects for the construction of a virtual reality simulator for ultrasound (US) guided breast biopsy. The main focus is the reconstruction of the breast from the patient's actual images. This reconstruction will generate a 3D model that will be used in the simulation and will also contribute to the construction of a 2D US synthetic image (based on real US exams) to completely simulate the real exam. Other steps in the construction of the system are also under consideration, since the reconstruction of the images represents only the first step of a large simulation system. Working on the reproduction of medical movements and modeling forces are also the scope of this review in order to discuss the existent solutions and propose future steps.*

1. Introduction

Breast cancer is the second most frequent cancer in the world, most common on women, representing 22% of new cases each year (INCA, 2017; SBM, 2017). The earlier cancer diagnosis is given, the bigger are chances of avoiding its progression and improving cure chances. The correct medical expertise in the procedures can contribute to reduce the evolution of cancer as they contribute on diagnosis.

The biopsy procedure is the method used when a cancer is suspected. Unfortunately, training in real patients is rather common in many hospitals mainly in public ones, this is stressful for radiologists in training and for patients that are in a procedure with an under-training professional. Training professionals in biopsy in real patients is not an ideal approach mainly because the lack of experience of the trainee in this activity could potentially hurt patients.

Using phantoms like described in (Vieira, 2005) or using a 3D printer to print a single 3D model like (Waran et al., 2014) are ways to simulate real cases and avoid undesirable training directly on patients. Problems of using these approaches are its high cost and lack of representation, as it will represent only a case of a single patient for each phantom generated. Another problem with phantoms are that with their extensive use, they become less representative because of the physical characteristics of the materials used.

In an ultrasound-guided breast biopsy procedure, also known as core needle biopsy, a radiologist or surgeon uses a thin, hollow needle to remove tissue samples from the breast mass using ultrasound guidance (Mayo Clinic, 2016). The use of virtual reality environments using haptics to simulate the forces applied both on the needle and on the ultrasound (US) as well as the visualization of the 3D models based on real patients has the advantage of correctly reproducing the real tactile experience while permitting the existence of multiple real cases. These representations of real patients are based on medical images of real patient's exams like Magnetic Resonance (MR) or Computerized Tomography (CT). This kind of system could even inform problems of execution during the training and work as evaluation of the learning curve of the users.

The aim of this work is to diminish the gap between the training and the real life of radiologists on breast biopsy procedures guided by US as they are done today. The first step of the construction of this system is to correctly reconstruct the 3D model of the breast based on images of exams. This paper reviews some of these techniques pointed out by authors in the literature. Another step here proposed is the generation of synthetic US images based on real cases. We then discuss others steps related to the construction of the total simulation system for US-guided breast biopsy such as approaches used to reproduce medical movements on exams as well as force modeling involved on needle insertion.

The remainder of the text is structured as follows. Section 2 explains the problem of ultrasound guided breast biopsy and the necessity of a simulator to train professionals. Section 3 presents a review of many works concerning the important aspects to solve the problem in hand. Section 4 discusses the advantages and drawbacks of each method. Section 5 details our proposed method to reconstruct the images. Section 6 presents conclusions and future works.

2. Problem

When a cancer is suspected, biopsies are collected in the breast tumor, most often based on ultrasound (US) guidance, for further analysis. In US-guided breast biopsy, US imaging (2D image) is used to guide the radiologist's instruments to the site of the abnormal growth. The radiologist or surgeon has to manage the needle and the US probe at the same time (Oncoguia, 2014). So, the physician interacts with a 3D subject and with a screen showing a 2D image of US at the same time. There are some restrictions of movements to ensure the correct visibility of the needle, which has to be placed at the correct spot before taking the number of samples of the lesion needed to ensure the exam. Figure 1 represents the procedure.

Professional training for medical procedures in real environments is costly and risky both for the student and the patient. A way to reduce costs and risks of training is by the use of a virtual simulator. The first step on constructing a simulator for this is to reconstruct a 3D model of the breast. The 3D reconstruction of breast from medical images is a hard task because of the amount of deformation breast tissue undergoes (Mertzanidou et al., 2017).

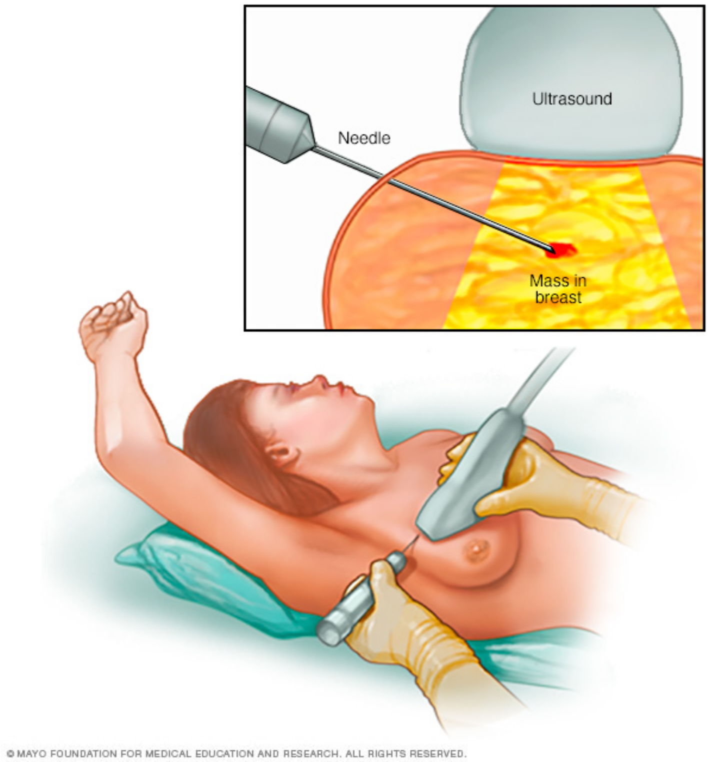

Figure 1. US-guided breast biopsy scheme using Core needle, obtained from (Mayo Clinic, 2016)**.**

3. Related works

The importance of using deformable models in concert with low-level image processing techniques (such as region growing, edge detection, and mathematical morphology operations) like segmentation and matching/registration as previous steps in the reconstruction of medical images are described in (McInerney & Terzopoulos, 1996).

An extensive review of registration techniques is presented in (Sotiras et al., 2013). Authors presents three main components for image registration algorithm: 1) A deformation model subdivided in geometric transformation derived from physical models, geometric transformation derived from interpolation theory and knowledge-based geometric transformations; 2) An objective function subdivided in Geometric methods (inferred by the correspondences and/or by the spatial transformation), Iconic methods (Intensity-based, Attribute based and multimodal registration) and Hybrid methods; 3) An optimization method separated into three categories, two based on the nature of the variables that they try to infer: continuous, and discrete and the third one called miscellaneous to join heuristic and metaheuristic approaches.

First thing before starting a 3D reconstruction is to define the best inputs in order to obtain the desirable outcome related with the problem in hand. The next section separates the inputs chosen in each paper studied.

3.1. Images used as input

There are many studies with different approaches for reconstruction considering the training of biopsy as the final goal. Some construct the 3D objects based on mammograms (Oliveira et al., 2008). Other reconstruct patients' breast by means of bidimensional thermographic images (Araujo et al., 2012). There are even works that make the reconstruction over x-ray images of slices of breasts obtained on a mastectomy (Mertzanidou et al., 2017) while other reconstruct the prostate over slices obtained in prostatectomies (Bauer et al., 1999; Egevad et al., 1999).

Many approaches reconstruct a 3D model only using MR (Arathi & Parameswaran, 2014; Cline et al., 1987; Waran et al., 2014) and CT images (Arathi & Parameswaran, 2014; Jalalian et al., 2015; Mastmeyer et al., 2016; Vidal et al., 2008).

An approach known as multi-modality fusion, where information acquired by different imaging devices or protocols is fused was made by (Ni et al., 2008, Ni et al., 2011), which uses US images combined with CT ones to introduce more realism in ultrasound-guided needle insertion to make the biopsy on livers.

Another approach used by (Sclaverano et al., 2009) is to use many US images previously captured in many positions to construct a 3D volume considering the positions where the images were taken.

Once input images are defined, it is important to deal with the methods used to reconstruct the images needed to the simulation.

3.2. Reconstructing the organ

This section describes the important steps in reconstruction adopted in the works studied. Those steps include segmentation and registration of medical images as well as the generation of synthetic images using medical images as input.

A phantom of a human body was constructed through volumetric CT dataset after a manual segmentation on (Zhu et al. 2006, Zhu et al. 2007). The authors also proposed the generation of synthetic US images based on US image samples used to form a 3D texture bank of generated texture. The process of synthesis involves shadow simulation by ray-casting, artificial noise imposition and alpha blending based on the mapping between probe/needle positions informed by sensors.

The 3D object representing the breast constructed by (Oliveira et al., 2008) is based on measures extracted from mammograms. Although authors propose a virtual reality framework for medical training, the model lacks on realism on visual representation.

The system described in (Ni et al. 2008, Ni et al. 2011) first stitches together the US images with different scan angles to generate a panorama. It registers the resulting stitched volume with the CT volume to obtain a correlation. Authors used keypoint detection and the 3D scale-invariant feature transform (SIFT) descriptor that makes use of difference-of-Gaussians on first steps.

The 3D reconstruction technique for MR/CT 2D image stack proposed on (Arathi & Parameswaran, 2014) is based on Shapelets. Shapelets decompose an image on different elementary shapes. It is based on the linear decomposition of each object in the image into a series of localized basis functions of different shapes. The authors used a bank of five Gaussians as the basis function. So, the shapelet used is so called Gaussian shapelet. The steps to obtain the 3D view are, for each slice of the 2D MR/CT image: Generating the gradient values in the two directions; Obtaining the Slant and Tilt values; Finding the gradient correlation (basically a convolution between the gradient values and the shapelet basis function); Getting the tilt correlation; Obtaining the overall correlation between the surface and the shapelet (gradient and tilt correlation measures are multiplied); These steps are executed on different scales of the shapelets (for all the bank of Gaussians) and the correlation measures thus obtained for each case is then summed up to get the final reconstruction of this slice. After all the slices are processed the summed-up correlations (for each slice) is finally stored together to build a volume.

The segmentation technique that is implemented in (Jalalian et al., 2015) is Fuzzy C-means clustering. The authors use seven clusters for image partitioning according to the color spectrum in computed tomography laser mammography images.

A region growing algorithm combined with anatomical information is used to segment breast images on (Montero et al., 2016). It represents one knowledge-based geometric transformation.

In (Mastmeyer et al., 2016), the authors opted for modeling US wave propagation and interaction with the human tissues (by reflection and absorption) based on CT data, as this is very computationally costly, they use GPU computing (CUDA programming on NVIDIA Quadro 4000). Is important to point out that the US image is a 2D image, and here it is constructed over 3D data from CT.

The modeling of US images was also the choice by (Vidal et al., 2008), who uses fluoroscopy. As first step a 2D multiplanar reconstruction (MPR) image, that is, an oblique image computed from the original set of parallel CT slices. The MPR image was directly computed by 'reformatting' the input CT data. This method, as well as Mastmeyer's, needs hardware support for updating images in real-time with a good resolution. So, they also managed to use GPU programming.

The 3D models used on (Brazil et al., 2016; Brazil et al., 2017) were generated by Fuse software™ and makes use of the Unity3D engine. Authors cite that the visual interface facilitates 3D models import and placement on simulation scenes. Unity has a dedicated developer's online community, and permits many programming languages to incorporate functionalities.

The algorithm proposed by (Mertzanidou et al., 2017) combines neighborhood slice information with free-form deformations (FFD), which enables a flexible, nonlinear deformation to be computed subject to the constraint that a coherent 3D volume is obtained. In a pre-processing step, intensities are normalized to a reference slice using histogram matching. The slice in the middle of the stack is used as a reference image and remains unchanged. As we move toward the two ends of the stack, the remaining slices are registered to their single neighboring slice using a rigid block-matching transformation. Additionally, a second registration task is performed where each slice is transformed using FFD, considering the similarity to both of its neighboring slices to enforce structural coherence across slices.

With the 2D and 3D reconstructed images in hand, it is important to know the methods used so far to simulate the biopsy procedure itself.

3.3. Reproducing the medical movements

Recently most of the works on simulating medical procedures makes the use of haptic devices, as it can simulate tools used in surgery. With the advance of technology, haptic devices are becoming more flexible in a way that they could represent movements in more degrees of freedom (DOF).

In (Srinivasan et al., 2004), authors talk about a necessity of using haptic devices about six to seven DOF but they do not detail the two haptic devices used in their laparoscopic training system.

The authors of (Zhu et al., 2006, Zhu et al.,2007) use real equipment with sensors attached, in the needle and in the ultrasound probe to interact with a full scale penetrable model made of latex plastic and foam that simulates the patient.

There are some papers that do not make use of haptic devices and do not describe the way of interaction like (Bauer et al., 1999; Oliveira et al., 2008), which seems to use traditional I/O devices like mouse and keyboard to reproduce the movement of the needle through the 3D model.

The system for US-guided needle puncture of (Vidal et al., 2008) uses two haptic devices, each one with 6-DOF device offering 3-force DOF. Authors talk that more DOF would be better but the feedback of the radiologists about using the system were that the sensations was close to real.

Many US images were captured with different positions during real US-guided prostate biopsy sessions in (Sclaverano et al., 2009) and when the position required during the simulation does not correspond with any data on database, an interpolation is made to construct the image.

The US-guided liver biopsy proposed on (Ni et al., 2008, 2011) used for the US transducer a haptic device with 6-DOF device offering 3-force DOF and for the needle a more flexible one with 6-force DOF. In addition, the system generates a US synthetic image that approximates the image viewed in a real exam. Figure 2 shows the interaction of with the system.

A simulator using three haptic devices and two-camera images called PalpSim has been developed, allowing trainees to feel a virtual patient using their own hands (Coles et al., 2011). Two haptic devices, with 3-DOF assembled together to form a 5-force DOF force feedback device, were used for palpation and the other for needle insertion (6-DOF device offering 3-force DOF). Camera images were used to capture the movement of trainees' hands and insert them into the 3D scene.

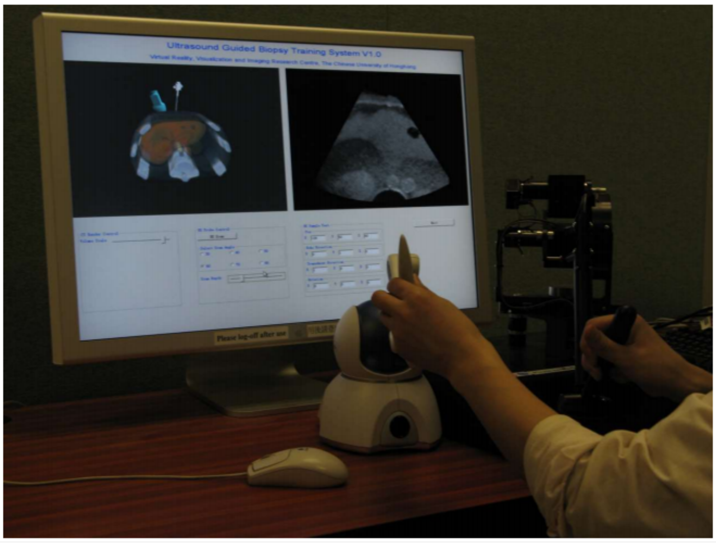

Figure 2. Interaction of the system proposed by Ni et al with the use of two haptic devices. Ni et al., 2008, 2011). On screen left the 3D model and on right the US synthetic image generated.

A 6-force DOF haptic was also used on (Mastmeyer et al., 2016) but only to represent the needle on US-guided needle insertion procedures in liver surgery.

A haptic device with a 6-DOF positional sensing offering 3-force DOF to represent the needle was used for simulate breast exams in (Brazil et al., 2017) and for epidural anesthesia in (Brazil et al., 2016).

3.4. Modeling the forces

A summary of the important aspects of a realistic organ-force models is well described on (Srinivasan et al., 2004), where authors say that a good organ-force model must reflect stable forces to a user, display smooth deformations, handle various boundary conditions and constraints, and show physics-based realistic behavior in real time.

A review of many works in the field were done by (Abolhassani et al., 2007) considering needle insertion forces, modeling tissue deformation and needle deflection during insertion. The authors identified also that less force is required to puncture and penetrate tissue using robotic insertion than using manual insertion. Pointing to a fully automated solution in a near future can lead to safer and more accurate needle insertions.

Additionally, all the works commented in Section 3.3 have used force modeling to simulate the feedback from the surgeons/radiologists to the medical equipment's that the haptic devices are simulating. In (Vidal et al., 2008), authors make a series of measurements of forces applied in the needle using markers in real exam and managed to incorporate the force measurements that have been made on real tissue into their model.

4. Discussion

The objective of the reconstruction here proposed is to serve as a first step in a system to correctly simulate biopsy procedures were patients are placed lying on her back while doing the procedure. As we discussed in previous sections, many 3D reconstructions are made using images from MR or CT, which has a stack of 2D images. To obtain MR images that could be used for 3D reconstruction, the patients are positioned lying face down (RadiologyInfo, 2016) the gravity forces contributes with the deformation that has to be considered on the registration methods. On the case of CT scans the patient is lying on her back (RadiologyInfo, 2017). As the position of CT and the one of the biopsy procedure are the same, the degree of deformation is much smaller in comparison with MR.

To correct simulate procedures guided by ultrasound, it is important to reduce the differences between the reconstruction from images and the real procedure. Considering this, the use of a combination of CT images and US in order to simulate more realistic US images seems to be a very good approach. This approach has the advantage of presenting more realistic images and without the problem of huge computational effort that could make the solution very expensive in terms of hardware requirements. The drawback here is the necessity of more input data, in this case a great number of US images.

The use of existent 3D models, permitted with the use of Unity3D engine (Brazil et al., 2016, Brazil et al., 2017), is a way to accelerate the development of the whole simulation system for US-guided biopsy training, but it could lack on representation of external visualization of the model. Nevertheless, a combination of this with other techniques could be a good way to treat this matter.

The approach using SIFT descriptor (Ni et al., 2008, Ni et al., 2011) and the interpolation used in (Sclaverano et al., 2009) seems to work nice, but they rely on the information positions that US images were taken.

Synthetic US generations presented by (Mastmeyer et al., 2016; Vidal et al., 2008) are good approximations of the real image, but both depends on a huge hardware to allow real-time simulations.

Using of Fuzzy C-means (Jalalian et al., 2015) demonstrated good results to segment CT images as well as the use of depth information with Shapelets to reconstruct a 3D model from 2D slices (Arathi & Parameswaran, 2014). Shapelets are examples of geometric methods inferred by the correspondences and by the spatial transformation.

As we could notice on Section 3.3, the papers vary from ones that do not make use of haptic devices to others that use three haptic (two combined). The most common DOF haptic device used to simulate the variety of medical procedures studied was the one with 6-DOF positional sensing offering 3-force DOF. One motivation to this limitation is the high cost of more flexible equipment.

The parameterization of the forces dividing the force applied on the needle in cutting, friction and stiffness forces (Abolhassani et al., 2007) or a mechanical model for the action of forces (Brazil et al., 2016) are needed to simulate the correct amount of deformation in the tissues.

The use of real forces measured and incorporated to the systems (Vidal et al., 2008) could bring more realistic feelings to the physicians but rely on more dependency of input data. Besides, for more accurate models, patient-specific parameters (e.g., age, gender), vascular pressure, bleeding and temperature should be investigated in addition to the type of tissue into which the needle is inserted (Abolhassani et al., 2007). That brings a huge dependency on input data for constructing a real model through force measuring.

5. Proposal

Considering the discussion about the type of images used on 3D reconstruction of model based on real patient data and the US-guided breast biopsy, we decide to use CT images as basis to our reconstruction method for the internal 3D model.

The construction of the organ starts from the CT images. These images will be preprocessed using Fuzzy C Means to obtain the Region of Interest (ROI), in this case the whole region that belongs to the patient's breast. Once the ROIs are obtained, we will use shapelets to generate the 3D model. To manage and refine external aspects of the 3D model, we intend to use Unity 3D, a three-dimensional development engine. This process is presented in Figure 3.

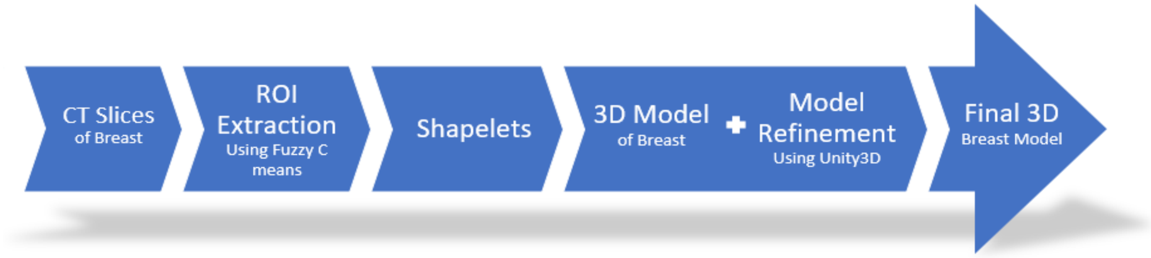

Figure 3. Steps of 3D reconstruction from breast CT images.

We propose the use of real US images in order to generates the synthetic US images closer to real needed to simulate the procedure in real-time. The idea, presented in Figure 4, is to do geometric transformations derived from interpolation in the US used as input. The data searched in US images will be based on the elements presented in the 3D breast model generated by the CT reconstruction that lies below a US probe position (to be simulated in future by a haptic device). For that matter, we will use multi-modality fusion (Sotiras et al., 2013), that is, fusing information acquired by different imaging devices or protocols (US and CT images). All the images to be used as input of our proposal should be obtained at the Antonio Pedro University Hospital (HUAP), Federal Fluminense University, in Niteroi, RJ, Brazil.

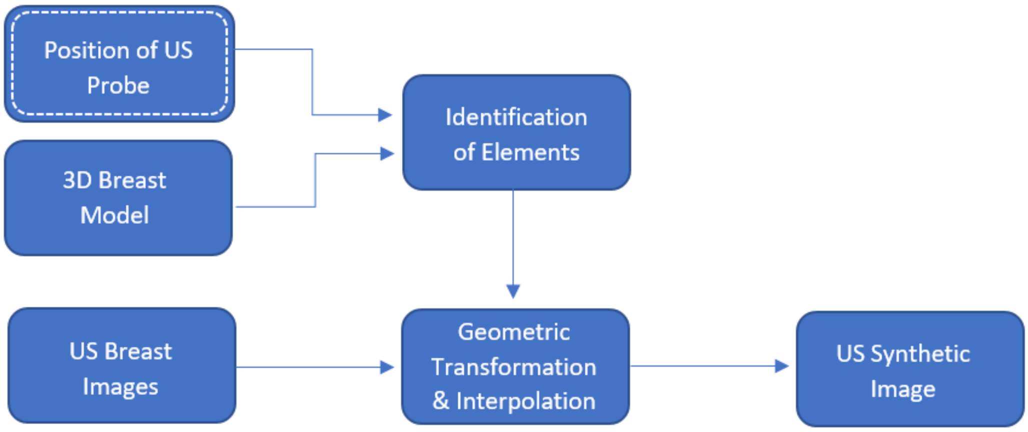

Figure 4. Demonstration of steps proposed in this work to generate US synthetic images

6. Conclusion and Future works

This work presents a theoretical proposal of a method to reconstruct a 3D model of breast as well as 2D synthetic US images. We plan to increase the image realism of the US synthetic images generating it by using real US images. This approach avoids the huge processing cost of generate these images using CT ones, the drawback is the necessity of more input data.

As future works, once constructed the 3D model, we intend to use haptic devices and model of forces of the needle insertion like (Abolhassani et al., 2007; Brazil et al., 2016, Brazil et al., 2017; Srinivasan et al., 2004) and considering the similarities of the problem, some simulations about the use of the US-Guided training as on (Ni et al., 2008, Ni et al., 2011; Srinivasan et al., 2004; Vidal et al., 2008; Zhu et al., 2006, Zhu et al., 2007). The idea is to use at least two haptic devices, one to represent the needle and the other to the US-probe.

In case of the force model, the idea is to construct a parameterized model with variables that could be calibrated to simulate the differences for each patient. Factors like age, gender and many other have influence in the forces that need to be made to the needle penetration in tissues as commented in (Abolhassani et al., 2007).

Introducing simulation of breathing movements (Mastmeyer et al., 2016) is also a good idea when we are looking to making the training simulation more realistic. The exams we intend to simulate are made on the breast, over the lung, in a in vivo patient, which determine the importance of considering breathing movements in our case.

We intend to improve the training including on the simulator some warnings to the trainees as they do wrong movements with the needle and US-probe. Another idea is to record the trainings in a database, so it could be used to help evaluating the learning curve of the users, indicating the ones who need more training.

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