Real-time prediction of breast lesions displacement during Ultrasound scanning using a position-based dynamics approach*

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INTRODUCTION

The non-invasiveness and real-time capabilities of ultrasound (US) imaging make this technique appealing for guiding the needle towards suspicious areas during breast biopsy procedures. However, the fact that certain malignant lesions are often challenging to be distinguished on US has raised interest in finding some ways to combine knowledge about lesions position obtained from pre-operative modalities with real-time information provided by intra-operative US. In order to correctly estimate lesions displacement, it is essential to account for the large deformations the breast undergoes due to the compression forces applied with the US probe by the physician, to guarantee proper probe-tissue coupling and obtain acceptable image quality. An additional challenge is posed by the fact that breast behavior varies a lot across the population, thus requiring patient-specific models [1].

Biomechanical models represent a valuable tool to account for anatomical deformations resulting from US probe interaction. Although the finite element method (FEM) has been extensively used in breast biomechanics, it was never employed to compensate for US probe-induced deformations, due to its incompatibility with real-time computation. In addition, the main bottleneck of FE simulations is the generation of 3D mesh of the anatomy, a process which has to be repeated for every subject in a patient-specific context [2]. A valuable alternative to FEM is represented by geometry-based approaches, like the position-based dynamics (PBD). The PBD approach models objects as an ensemble of particles whose positions are directly updated as a solution of a quasi-static problem subject to geometrical constraints, thus making the method stable, robust and able to achieve real-time performances [3]. An additional advantage of this approach is that it does not require the construction of a 3D mesh of patient anatomy, which simplifies its translation into the clinical workflow. The PBD scheme has been used by Camara et al. to create a patient-specific biomechanical model of the kidney for the real-time simulation of intra-operative US [4]. In their work, optimal PBD parameters are estimated as those describing the deformation of kidney phantom subject to different levels of probe-induced deformations.

In this work, we present a biomechanical model of the breast based on the PBD formulation available in NVIDIA FleX. To the best of our knowledge, this is the first model able to predict in real-time the displacement of internal lesions due to the interaction with US probe. In order to obtain a patient-specific description of the deformation, PBD parameters are fine-tuned on the anatomy of interest (in our case, a realistic breast phantom) by tracking the displacement of a US-visible landmark. In this way, we obtain a patient-specific model that can accurately predict in real-time the displacement of the other internal areas during US scanning.

MATERIALS AND METHODS

The experimental data are acquired from a Freehand Ultrasound System (FUS) based on a MicrUs US device (Telemed, Vilnius, Lithuania) equipped with a linear probe (model L12-5N40) and an optical tracking system MicronTracker Hx40 (Claron-Nav, Toronto, Canada) (Figure 1). The overall probe spatial calibration error achieved is below 1mm (±0.7147).

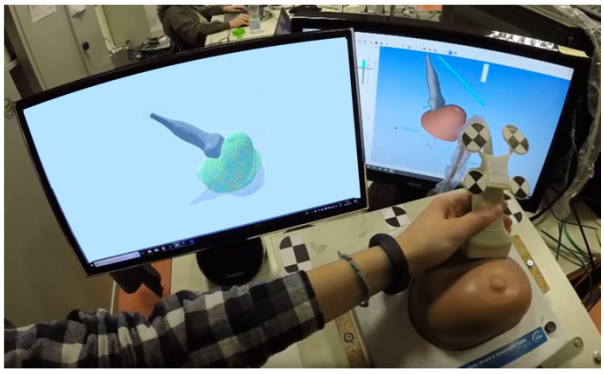

Fig 1. The FUS system allows to map the real positions of the CIRS breast phantom and the US probe to the 3D Slicer scene (right monitor). Information about probe spatial transformation is communicated to the simulated environment in Unity (left monitor).

A realistic multi-modality breast phantom (Model 073; CIRS, Norfolk, VA, USA), which has several dense and stiff internal masses of diameter 5-10mm, is used to evaluate the capability of the PBD model to provide correct estimates of biopsy targets. Before applying the model to predict lesions displacement, PBD parameters are tuned to account for the specificity of the anatomy of interest. In particular, we optimize the value of *cluster spacing, cluster radius* and *cluster stiffness* parameters, while we set other parameters in accordance to values reported in [4]. Considered parameters are controlling the deformable behavior of soft objects through the PBD constraint called "region-based shape matching". Optimal parameter values are estimated with a greedy strategy as those minimizing the average localization error on a US-visible landmark (in our case,

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one of the internal lesions), when applying four different input deformations with the probe (5, 10, 15, 20 mm). Localization error is computed as Euclidean distance between the model-predicted and the real displacement provided by the FUS of corresponding fiducial points. It's worth mentioning that any internal structure which is detectable on US can be used for this tuning process. The PBD model with updated optimal parameters is then used to infer the displacement of 9 segmented lesions under four deformations as done previously. To evaluate the performances of the proposed approach, we compare it with both a FE and a rigid model. The FE simulation is performed on a mesh of 26,220 linear tetrahedral elements, exploiting SOFA framework[1]. The breast is modelled as a homogeneous Neo-Hookean material, whose elastic properties are set in accordance with the work in [6].

RESULTS

Optimal values for the cluster spacing, cluster radius and cluster stiffness parameters obtained with the calibration procedure are 11.2, 8.5 and 0.46 respectively.

Figures 2 and 3 compare the performances of the proposed deformation model with a FE and a rigid model. Localization errors relative to both PBD and FEM are computed as difference between the model-predicted position and the real lesion position (extracted from US image), at each deformation level. On the other hand, in the rigid case, lesion position at rest always corresponds to the predicted position. The green, purple and orange lines in Figure 2 show the trend of the localization error at increasing deformation levels for the PBD, FEM and rigid model. It's immediately possible to notice that errors obtained with the PBD model are aligned with FE models, with no significant differences. Both PBD and FEM outperform the rigid case by at least halving the prediction error on all the tumors, as emerges from Figure 3.

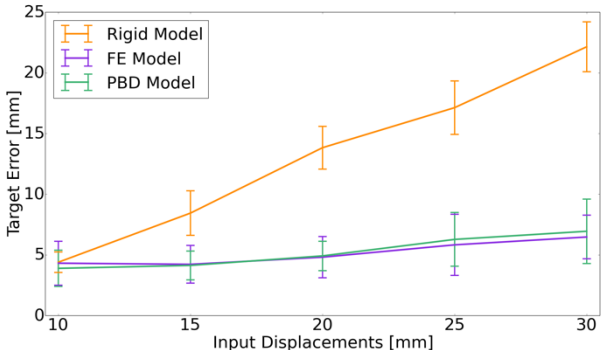

Fig 2. Average target error in mm at different levels of applied deformations for PBD (green), FEM (purple) and rigid (orange) models.

Considering computation times, the average time needed for the PBD model to predict anatomical deformations following the 4 input displacements is 6.99s (±0.36), which approximately corresponds to 1.75s for simulating each input deformation. On the other hand, the FE model takes 16.37s (±0.73) on average, which corresponds to nearly 4.09s for each input deformation. Therefore, FEM takes more than twice the time needed by the proposed PBD approach to perform the simulation, even without a significant improvement in prediction accuracy.

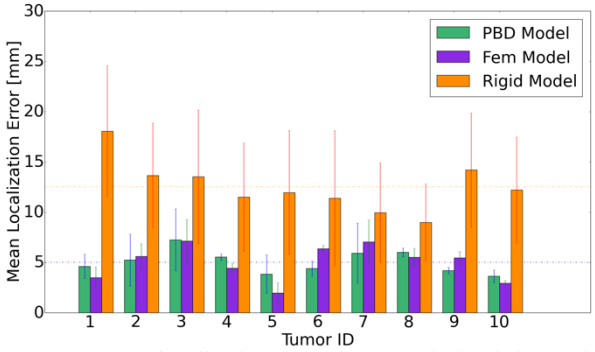

Fig 3. Average localization error in mm obtained for each tumor with the PBD (green), FEM (purple) and rigid (orange) model. Horizontal dashed lines represent the corresponding average error.

CONCLUSION AND DISCUSSION

Exploiting PBD formulation for modelling breast deformations has proved successful in predicting in real-time probe-induced displacement of internal lesions during US scanning. The proposed approach achieves comparable accuracy with FE models, but with faster computational performance and without even requiring tedious 3D mesh generation. Furthermore, it outperforms rigid models usually employed for lesion tracking in biopsy procedures. As future work, we will make the model able to describe heterogeneous structures of breast tissues. We expect this improvement to have a significant impact on simulation accuracy, especially when dealing with real clinical cases. Eventually, we will include the real-time PBD deformation model within a robotic framework able to perform an autonomous US-based guided percutaneous procedure, from the US scanning to the needle insertion.

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