was assessed

and generate simulated mammography images,

6

Conclusion and Perspectives

were was as software was used

The main aim of this work ~~is~~ to develop a simulation framework capable of assessing ~~the quality of~~ breast compression ~~in~~ function of ~~the~~ paddle design, compression force ~~intensity~~ or breast positioning. ~~The~~ Image quality, ~~and the~~ average glandular dose as well as ~~the~~ patient comfort ~~have to be~~ considered when comparing different compression strategies. A Monte-Carlo based simulation ~~able~~ to compute the X-ray propagation through matter ~~are well known and largely accepted on the field. Such software was used to mimic a mammography exam and thus to assess~~ The image quality depending on the compressed breast thickness. The average glandular dose was computed using the method proposed by Dance D. et al. [31]. ~~The method was built based on a very simplistic template and~~ requireing ~~requires~~ only the knowledge of ~~the~~ compressed breast thickness and breast glandularity.

To assess the tissues deformation depending on the paddle design or the applied force compression a new biomechanical breast model was developed. ~~The latter allows to estimate~~ the outer ~~breast~~ shape ~~after~~ compression ~~but~~ also the associated ~~physical~~ patient comfort associated to assumed to be ~~to the~~ internal strain/stress intensity and distribution.

In this chapter, the main results and conclusions on the implemented applications are recalled. The possible improvements for a large prospect of applications are discussed.

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This model ~~enables to predicting~~ was used to predict the

6.1 Biomechanical breast model

an interesting the extraction of

Before modeling the mammography breast compression, the model fidelity to the real tissues deformation had to be assessed. In this scope, data sets describing in-vivo breast mechanics were needed. The MRI is ~~the sole~~ imaging modality allowing ~~to extract~~ the whole 3D breast geometry and the corresponding internal structures distribution. Therefore, MR images of two volunteers in three body positions (prone, supine and supine tilted) were acquired and used in this study. The two volunteers were chosen such that two different breast sizes were represented, small volume (breast cup A) and large volume (breast cup F). The boundary conditions describing breast deformation under gravity loading are easy to reproduce in a simulation framework. Thus, the acquired data made possible the ~~biomechanical model~~ calibration and evaluation of the biomechanical model.

As a The development of the biomechanical breast model was performed using the small breast volume (first subject). ~~A~~ small breast volume undergoes smaller deformations under gravity loading, ~~therefore~~ the ~~respective~~ breast model was suspected to lead to less ~~conver-~~ the convergence difficulties. To this end, the ~~respective~~ corresponding MRI volume of ~~breast~~ in supine position was used to build the finite element mesh. Then, combined with the MRI breast volume in ~~the~~ prone body position, it was used to estimate the subject-specific constitutive parameters and the corresponding stress-free geometry.

this From ~~the~~ first simulation~~s~~, the importance of considering the sliding boundary conditions at the juncture surface between the pectoral muscle and the breast was pointed out. The displacements driven by tissues' elasticity only were not enough to reflect the geometrical changes between the supine and prone breast configurations. Therefore, the breast tissues were allowed to slide over the pectoral muscle surface. Additional boundary conditions were considered by modeling the breast suspensory ligaments and fascial system. Including stiffer structures into the finite element model improved solution convergence capabilities. These new structures allowed ~~to estimate the~~ the estimation of breast deformations for a larger range of constitutive parameters ~~of~~ soft tissues. Consequently, the results obtained by model optimization process were improved.

According to the literature, a well defined breast model has to consider in-vivo measured constitutive parameters. To this end, the tissues Young's ~~modulus~~ moduli giving the best fit between the simulated and measured breast configurations of the first volunteer were computed. The optimal estimates, assuming Neo-Hookean material~~s~~ models, were ~~given~~ found to be ~~by~~ $\lambda^{r}_{breast} = 0.3\ kPa$, $\lambda^{l}_{breast} = 0.2\ kPa$, $\lambda_{skin} = 4\ kPa$, $\lambda_{fascia} = 120\ kPa$. The obtained mechanical properties are comparables ~~with~~ to the ones proposed in the literature when considering only ~~the~~ breast models with similar simulation frameworks [118, 52, 62]. ~~These~~ This result~~s~~ allowed to compute the breast geometry in supine and prone configurations ~~within~~ with a precision ~~an error~~ of 1.70 mm and 2.17 mm respectively. The model fidelity to the global breast deformation was evaluated using the breast geometry in supine tilted position. The Hausdorff distance between the breast skin surface extracted from the MRI volume and the simulated skin surface was equal to 6.14 mm. The larger error ($\sim 26.03\ mm$) was obtained on the left breast where the ~~tissues~~ lateral displacements of the tissues were overestimated, due to...(?)

to and

[Ajouter la cause de cette sur-estimation]

These results may be improved by developing a more complex breast support matrix or considering a region dependent stiffness for the skin or the fascial system. Adding stiffer materials in the strategically localized areas on the contact surface may limit the fascia deformations under a large stress range. Therefore, the sliding of breast tissues in supine tilted configuration may be reduced.

The developed breast biomechanical model was then built up for the larger breast volume (second volunteer). However, because of a lack of time, the model optimization process was not performed for the latter volunteer. In future work, it would be interesting to perform the model optimization and evaluation on at least two more subjects with different breast morphologies and mechanical properties. The model calibration on a larger population ~~will~~ should improve its flexibility for further studies on breast compression techniques.

Despite providing good results in the multi-loading gravity framework, the developed breast model ~~turns~~ turned out to be less efficient in simulating the breast compression. ~~The~~ With this model, the maximal force needed to simulate the breast flattening was estimated relatively ~~small~~ low when compared to the mean recommended force ~~for a~~ of a typical mammography exam ($10N$ ~~vs~~ to $120N$). These low values of the compression force ~~is caused by~~ were due to tissue's abnormal softening under large stress rates. Tissue relaxation from a given stress threshold is a well known phenomenon when using Neo-Hookean materials. ~~This issue was~~ overcome by replacing the Neo-Hookean model by a Gent model for all involved hyperelastic tissues.

~~The advantage of using the Gent strain energy function is its similarity with the Neo-Hookean function.~~ The stress-strain relation remains the same for both models below a strain threshold defined by the J_m parameter. Beyond ~~the respective~~ this threshold, the Gent materials model is stiffening exponentially resulting in an asymptotic behavior. These properties allow to change the tissues mechanical response only for large strain rates, as ~~during the~~ it is the case during breast compression. On the other hand, they also allow to preserve the same mechanical response for relatively small strains, as induced by gravity loading ~~simulations~~ the ones.

The breast compression simulations were performed using both breast volumes. As the tissues constitutive parameters of the second volunteer were not estimated, the values proposed by others similar works were used. Therefore, the second breast model ~~dose~~ does not describes the subject-specific mechanical behavior. However, it provides a new realistic model ~~which~~ that may be used to assess the compression quality ~~as function of~~ of different compression types. The Gent material model improved the tissues mechanical response when ~~compressed~~ the breast is compressed between the paddle and the image receiver. A compression force of 22 N for the first volunteer and 95 N for the second volunteer was obtained. The results fit well the corresponding clinical data, 21.9 N and 94.8 N respectively.

Based on the same constitutive parameters, as estimated during breast compression, the Gent tissues model ~~were~~ was used to estimate the breast deformation under gravity loading. ~~It was~~ We found that, with such model, tissues displacements were over-constrained ~~for~~ in both supine and prone configurations. However, ~~it was~~ we proved that the Gent model may also improve the biomechanical model fidelity to the real deformations under gravity loading. ~~Yet~~ Therefore, we suggested to use two different values of the J_m parameter ~~have to be used~~ in order to obtain the best estimates in the two ~~cases of~~ use cases, multi-loading gravity simulations and breast compression simulations. ~~Therefore, A~~ A more detailed study has ~~to~~ then be considered in order to estimate ~~an~~ a such / and also / should

unique tissues contitutive model. To this end, more data describing the compression breast process, as paddle position with respect to paddle, is needed. The impact of using different constitutive parameters within tissues types ~~has to~~ be studied. However, increasing the number of model parameters might also increase the complexity of the optimization problem, ~~thus increase~~ the computation time and the size of the data set describing the subject breast mechanics.

the / es / a

In this work, we have assumed that breast mechanics do not depend on the glandular tissues distribution. This assumption is valid only if ~~the~~ global breast deformation is ~~needed~~, such as the skin surface deformation. However, when one wants to estimate the breast internal tissues displacements under compression or gravity loading, a more subtle definition of tissues materials is needed. In such case, the differentiation of the glandular and adipose tissues ~~will~~ be more relevant.

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During the modeling process, it has been observed that the breast tissues undergo extremely large deformations. This involves large convergence difficulties ~~because of~~ a bad element formulation during deformation. To improve the solution convergence capabilities, an hexahedral adaptive mesh ~~has to be~~ considered.

must be

In conclusion, the proposed biomechanical model was able to provide a good estimation of the breast deformation under different boundary conditions. The models based on breast geometries of two subjects were used to perform comparative studies between different compression methods.

6.2 Breast compression and patient comfort

compare / or / when

The developed biomechanical breast model together with the image simulation framework were used to assess the clinical compression quality whithin different compression strategies.

A first study was performed to compare the breast compression quality ~~then~~ using standard rigid ~~and~~ flex paddles. To ~~estimate~~ the breast compressions, the proposed biomechanical model was calibrated for two different breast volumes (small and large) with various mechanical properties (soft and firm). The results showed that, using the flex paddle may improve the patient comfort without affecting the image quality and the delivered average glandular dose. Moreover, despite a breast thickness varying linearly from chest wall to nipple, the image quality seems to be preserved or improved compared to the image quality obtained with a rigid compression paddle. The ~~improved~~ image quality ~~for~~ the flex paddle could be explained by a better overall breast compression. The paddle tilt allows a better compression of the tissues closer to the nipple, relaxing the tissues closest to the chest wall. In the same time, the paddle tilt is suspected to facilitate the tissues displacement toward the chest wall. The tissues accumulation on the retromammary space may hide clinical relevant information and thus increase the false negatives rates.

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A second study was performed to assess the impact of breast positioning on breast compression mechanics. This time, the paddle deflection due to the material elastic properties was considered ~~for a better estimation of the patient comfort~~. Three breast compression simulations were performed with various distances between the paddle and the chest wall.

to enable finite element convergence in extreme deformations, when the compression paddle is in contact with the chest wall.

Est-ce quelque chose que tu as observé grâce à tes simulations ? Qu'est-ce que tu en conclues ?

under compression

the being

In this context, only the larger breast volume was used, ~~The~~ smaller volume ~~was~~ not adapted to such a ~~set of~~ simulations. The results showed that, ~~the~~ patient comfort can be improved by positioning the paddles farther from the pectoral muscle. For an equivalent breast thickness, the compression force decreased from 158 N to 59 N for a difference of 15 mm in the distance from chest wall to ~~the~~ paddle. On the other hand, clinical guidelines request to place the paddle as close as possible to the chest wall. Therefore, ~~the technologist~~ one ~~has~~ to find a compromise between the exam quality and the patient comfort.

italique

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~~may have~~

The two preliminary studies have shown that the clinical compression quality can be assessed using such simulation frameworks. The tools designed during this thesis, may be used to perform wider studies on existing breast compression, But also to provide a first estimation of the performance of a new, not yet implemented, paddle design. Simulation based studies are less expensive in time and materials than the usual clinical studies, therefore they may be used to discharge the more irrelevant paddle designs.

systems

Key contributions

The key contributions concerning the finite element breast modeling are the following:

- We introduced new boundary conditions which reflect the motion of the breast over the thoracic cage. They included sliding contact surface based on Coulombs friction law combined with stiff support structures. To our knowledge, the breast support matrix was considered for the first time into the finite element model. The generic model includes suspensory ligaments together with the fascial system, and was built based on their anatomical description.

- The iterative algorithms allowing to estimate the breast stress-free geometry are generally using only one breast configuration (supine or prone breast configuration). In this work we proposed an optimization algorithm which estimate the breast stress-free geometry starting from supine configuration and then iteratively correct it based on the prone configuration.

- We disposed of ~~an exceptional~~ a data set of breast MR images in three different body positions. Therefore, ~~the~~ our biomechanical breast model was first calibrated using prone and supine configurations. Then, its mechanical response was evaluated on the third breast configuration (supine tilted). Because of a lack of reliable data, none of ~~previous~~ previously published biomechanical breast models was evaluated in such wide panel of deformations.

- We evaluated the capability of the proposed biomechanical breast model to reproduce the breast compression mechanics as described by several clinical studies. This analysis allowed us to point out the limitations of the Neo-Hookean strain energy function when modeling such large deformations. Accordingly, a new material constitutive model defined by the Gent strain energy function was proposed.

- We developed a simulation framework allowing to quantify ~~the~~ breast compression ~~quality~~ in terms of image quality, average glandular dose and patient comfort. Due to its modularity, ~~the~~ this framework supports different paddle designs and different breast geometries and compositions.

Using previously described tools, two studies assessing the breast compression quality were performed, demonstrating :

- The difference of the compression quality in terms of patient comfort, image quality and average glandular dose between a standard rigid and flex paddles was quantified.
- The impact of breast positioning on the compression mechanics and patient comfort was analyzed.

A list of publications resuming the results of this work is provided below.

Je préférerais voir ce que tu as démontré (les résultats obtenus) plutôt que la description de ce que tu as cherché à évaluer.