6

Conclusion and Perspectives

The main aim of this PhD work was to develop a simulation framework capable of assessing breast compression as a function of paddle design, compression force or breast positioning. Image quality, average glandular dose as well as patient comfort were considered when comparing different compression strategies.

A Monte-Carlo based simulation software was used to compute the X-ray propagation through matter ~~are~~ and to generate simulated mammography images. The image quality was depending on the compressed breast thickness. The average glandular dose was computed using the method proposed by Dance D. et al. [31] requiring only the knowledge of compressed breast thickness and breast glandularity.

To assess the breast deformations depending on the paddle design or the applied compression force a new biomechanical breast model was developed. This model was used to predict the outer shape of the breast under compression ~~and also~~ as well as the patient comfort assumed to be associated to internal strain/stress intensity and distribution.

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

After beeing evaluated with comparisons with real data collected through MR images,

6.1 Biomechanical breast model

Before modeling the mammography breast compression, the model fidelity to ~~the~~ real tissues deformations had to be assessed. In this scope, data sets describing in-vivo breast mechanics were ~~needed~~ collected. ~~The~~ MRI is an interesting imaging modality allowing the extraction of the whole 3D breast geometry ~~and the corresponding~~ with the distribution of each internal structure~~s~~ ~~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 calibration and the evaluation of the biomechanical model.

Oui ! De mémoire tu n'avais pas aussi clairement parlé des tailles + lorsque tu avais introduit les volontaires dans le chap.3

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

From this first simulation, the importance of considering the sliding boundary conditions at the juncture surface between the pectoral muscle and the breast was pointed out. Indeed, The displacements driven by only tissues' elasticity 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 breast deformations for a larger range of soft tissues constitutive parameters. ~~Consequently, the results obtained by model optimization process were improved.~~ pas clair

According to the literature, a well defined breast model has to consider in-vivo measured constitutive parameters. To this end, the tissues Young's 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 models, were found to be $\lambda^r_{breast} = 0.3\ kPa$, $\lambda^l_{breast} = 0.2\ kPa$, $\lambda_{skin} = 4\ kPa$ and $\lambda_{fascia} = 120\ kPa$. The obtained mechanical properties are comparable~~s~~ to the ones proposed in the literature when considering only the breast models with similar simulation frameworks [118, 52, 62]. This result allowed to compute the breast geometry in supine and prone configurations with a precision 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 lateral displacements of the tissues were overestimated due to large strains

Attention, je réalise que c'est sans doute "accuracy" qu'il faudrait utiliser dans ta thèse et non "precision".

observed over the fascia and skin surfaces.

These results may be improved by developing a more complex breast support matrix or considering region dependent stiffness for the skin or the fascia system. Adding stiffer materials in the strategically localized areas on the contact surface may limit the fascia deformations under a large strain 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~~ this volunteer. In future work, it would be interesting to perform ~~the~~ such model optimization and evaluation on at least two more subjects with different breast morphologies and mechanical properties. The model calibration on a larger population 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 turned out to be less efficient in simulating ~~the~~ breast compression. With this model, the maximal force needed to simulate ~~the~~ breast flattening was estimated to be relatively low when compared to the mean recommended force of a typical mammography exam ($10N$ vs $120N$). These low values of the compression force 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. We therefore suggested to overcome this issue by replacing the Neo-Hookean model by a Gent model for all involved hyperelastic tissues.

The stress-strain relation remains almost the same for both models below a strain threshold defined by the J_m parameter. Beyond this ~~respective~~ 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~~ 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 breast compression simulations were performed using both breast volumes. As the tissues constitutive parameters of the second volunteer were not ~~estimated~~ optimized, the values proposed by others similar works were used. Therefore, the second breast model does not describes the subject-specific mechanical behavior. However, it provides a new realistic model that may be used to assess the compression quality of different compression types. The Gent material model improved the tissues mechanical response when 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~~ which fits well the measured ~~corresponding~~ clinical data (21.9 N and 94.8 N respectively).

Based on the same constitutive parameters, as estimated during breast compression, for the first volunteer the Gent tissues model was used to estimate ~~the~~ breast deformation under gravity loading. We found that, with such a model, tissues displacements were over-constrained in both supine and prone configurations. However, we proved that the Gent model may also improve the biomechanical model fidelity to the real deformations under gravity loading. Therefore we suggested to use two different values of the J_m parameter in order to obtain the best estimates i~~n the two use cases,~~ for multi-loading gravity ~~simulations~~ and breast compression simulations. A more detailed study has then to be considered in order to estimate a unique tissues contitutive model. To this end, more data describing the compression breast process, such as ~~paddle~~ breast position with respect to paddle, is needed. The impact of using different constitutive parameters within tissues types should also be studied. However, increasing the number of model parameters might ~~also~~ increase the complexity of the optimization problem, ~~and also~~ as well as the computation time and the size of the data set describing the subject breast mechanics.

In this work, we have assumed that the breast mechanics does not depend on the glandular tissues distribution. This assumption is only valid if a global breast deformation is assessed, such as the breast 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 a case, the differentiation of the glandular and adipose tissues should be more relevant.

During the modeling process, it ~~has been~~ observed that the breast tissues undergo extremely large deformations (up to 150%). This involves large convergence difficulties due to ~~a~~ bad element formulations during simulations. To improve the solution convergence capabilities an hexahedral adaptive mesh ~~must be~~ might be considered.

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~~ various compression methods.

6.2 Breast compression and patient comfort

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 when using standard rigid or flex paddles. To compute ~~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 even improved compared to the image quality obtained with a rigid compression paddle. ~~The~~ Such a better image quality obtained when using the flex paddle could be explained by a better overall breast compression. The paddle tilt allows a better compression of the tissues close~~r~~ to the nipple, relaxing the tissues ~~closest to~~ located in the chest wall region. Our simulations tend to confirm that the paddle tilt may displace breast tissues towards the chest wall. The tissues accumulation on the retromammary space may hide clinical relevant information and thus increase the false negatives rates.

A second study was performed to assess the impact of breast positioning on breast compression mechanics. This time, the paddle deflection due to ~~the~~ its material elastic properties was considered to enable solution convergence when the compression paddle is close to the chest wall. Three breast compression simulations were performed with various distances between the paddle and the chest wall. In this context, only the larger breast volume was used, the smaller volume being not adapted to such a simulation. The results showed that patient comfort can be improved by positioning the paddles farther from the pectoral muscle. For an equivalent breast thickness under compression, the compression force decreased from 158 N to 59 N for a difference of 15 mm in the distance from chest wall to paddle. On the other hand, clinical guidelines request to place the paddle as close as possible to the chest wall. Therefore, one may have to find a compromise between the exam quality and the patient comfort. our simulations show that

These two preliminary studies have shown that the clinical compression quality can be assessed using such simulation frameworks. The tools designed during this PhD thesis may be used to perform wider studies on existing breast compression systems 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~~ less relevant paddle models.

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~~ laws of 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 a data set of breast MR images in three different body positions of the same volunteer. Therefore, our biomechanical breast model was first calibrated using prone and supine configurations. Then, its mechanical response was evaluated on a third breast configuration (supine tilted). Because of a lack of reliable data, none of the 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 breast compression in terms of image quality, average glandular dose and patient comfort. Due to its modularity, this framework supports ~~different~~ various paddle designs and different breast geometries and compositions.

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

- The differences of the compression qualities in terms of patient comfort, image quality and average glandular dose between ~~a~~ standard rigid and flex paddles ~~was~~ were quantified. We have showed that, for the small breast, there was no difference in patient experience or image quality between the two paddles. However, using the flex paddle to compress the larger breasts may ~~improve~~ reduce the patient's ~~experience~~ discomfort without affecting the image quality or the average glandular dose.

- The impact of breast positioning on the compression mechanics and patient's comfort was analyzed. The obtained results have proved that the breast positioning ~~have~~ has a significant impact on patient comfort. Indeed, the surface pressure in the juxtathoracic area increased when the paddle was positioned closer to the chest wall.

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