A Computational Modeling Approach for Studying Tissue–Cutter Interaction in Breast Biopsy Procedure[1]

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1 Background

Vacuum-assisted biopsy (VAB) technology is designed to provide large-core breast tissue samples that improve the accuracy of breast cancer diagnosis. Using a more sophisticated cutting method (i.e., rotational cutting) than traditional tools, this technology is capable of removing tougher tissue, such as calcifications. However, this technology still has shortcomings and limitations. Tiny tissue samples and unsuccessful sampling have been reported in Ref. [1]. In some of the reported cases, the biopsy cutting mechanism was not strong enough to traverse through dense tissue. In other instances, tiny tissue samples were obtained when sampling very soft tissue, such as adipose tissue. Occasionally, a "dry tap" occurred, which indicates that the tissue sample is not fully separated from the breast. As a result, zero tissue volume is retrieved in the sampling sequence. In the event of any of these issues, the patient must undergo a rebiopsy. Understanding the device–tissue interaction during the VAB cutting process is important to improving the current design of VAB tools. The majority of VAB tools utilize the rotational cutting method that drives a hollow cylindrical cutting needle to rotate and translate simultaneously to cut the tissue. The tissue applied forces in both normal and tangential directions. In comparison to the traditional biopsy sampling method, i.e., core needle biopsy, the introduction of the tangential force is the key to improve the tissue sampling performance. The "slice–push ratio," defined as the ratio of the tangential component of the cutting speed to the normal component of the cutting speed, has been identified as a main factor that affects the tissue-cutting force [2]. Currently, this factor has only been investigated in limited cutting conditions, i.e., cutting linear elastic phantom tissue using a low needle insertion speed. In reality, higher cutting speeds and more sophisticated tissue properties are involved in the VAB cutting process.

In this paper, we present a computational approach to study the tissue-cutting process of a VAB procedure. A finite element analysis model is developed to simulate a VAB needle to cut three main types of breast tissue: adipose, fibroglandular, and tumor. The model is able to predict the tissue-cutting force when the tissue is undergone large deformation and progressive damage.

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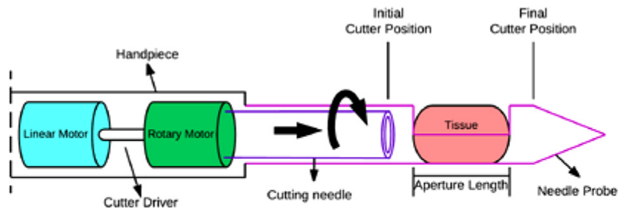

Fig. 1 The setup of VAB tissue cutting

2 Methods

A diagram describing the VAB cutting process is shown in Fig. 1, where the cutting needle is at its initial position. To begin, the cutting needle accelerates to desired rotational and translational speeds before coming into contact with the tissue. After first contact, the cutting needle continues to traverse through the tissue with constant cutting speeds. In a successful scenario, the tissue will be deformed and progressively ruptured until a tissue sample is fully separated from the main tissue.

An explicit dynamic model is developed using ABAQUS EXPLICIT. The needle probe is a 7G needle with an outer diameter of 4.57 mm and an inner diameter of 3.81 mm. The cutting needle is a hollow cylinder with an outer diameter of 4.19, an inner diameter of 3.43 mm, and a sharpened top surface. We assumed that a portion of tissue is drawn into the aperture of the needle probe to conform to the inner surface of the aperture.

The needle probe and the cutting needle are assumed to be rigid as their deformation is negligible and not of concern. During the cutting process, the needle probe is fully fixed by the surrounding breast tissue so it is assigned zero motion. The cutting needle is specified with a motion that describes the translational and rotational cutting speeds. The total simulation time is the travel time for the cutting needle to go from the initial position to the final position.

Hyperelastic models for adipose, fibroglandular breast tissue are collected from the literature. We found that the variation of the tissue stiffness among these models is significant. In order to include the extreme cases, the softest adipose tissue model and the toughest fibroglandular tissue model are selected. We also select a model with a medium stiffness of 3 kPa as the base model for studies of different cutting speeds. For the tumor tissue, the only available model for ductal carcinoma in situ is selected, which is a linear elastic model with a Young's modulus of 2162 kPa. The fracture behavior of the breast tissue is not available in the literature. Maximum tensile and shear strains ($\varepsilon_v, \varepsilon_t$) are set for each tissue type. These values are used as the fracture criteria in the simulation. Once either of the maximum strains is reached, the particular element at the cutting surface is removed and new device–tissue contact surfaces are created. A summary of the breast tissue properties is provided in Table 1.

3 Results

The cutting force was solved under various combinations of rotational and translational cutting speeds. Five slice–push ratios: $R = [0, 0.5, 1.0, 5.0, 10]$ and three translational cutting speeds: $v_a = [100$ (high), 50 (medium), 10 (low)$]$ mm/s were investigated. The predicted cutting forces are shown in Fig. 2. The cutting force reduced by an average of 5.38% when the slice–push ratio increased from 0 to 1, while bigger reductions were found to be 24.10% and 19.05% when the slice–push ratio increased from 1 to 5

Table 1 Breast tissue models used in this study [3–5]

Tissue type	Model type	$\varepsilon_v, \varepsilon_t$	Tissue stiffness (kPa)
Adipose (base)	Neo-Hookean	0.6, 0.3	$C_1 = 3$
Adipose	Neo-Hookean	0.6, 0.3	$C_1 = 0.08$
Fibroglandular	Neo-Hookean	0.3, 0.15	$C_1 = 105$
Tumor	Linear elastic	0.3, 0.15	$E = 2162$

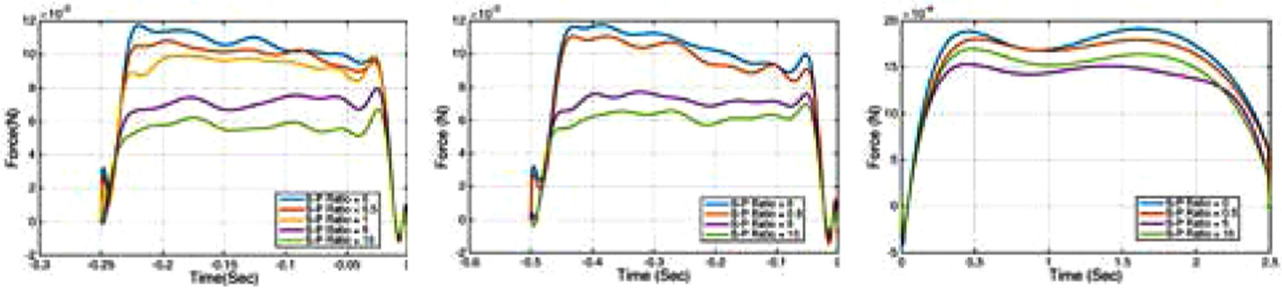

Fig. 2 Cutting forces in different slice–push ratios (using the base model). From left and right are high, medium, and low translational cutting speeds.

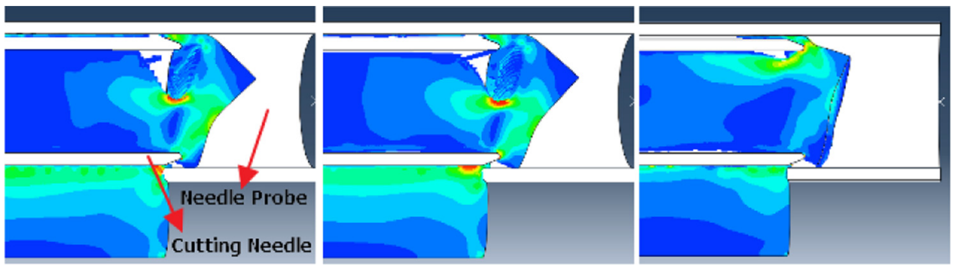

Fig. 3 The visualization of von Mises stress at the end of cutting process in different slice–push ratios. From left to right, $R = [0.1, 1, 10]$. When R is higher, the tissue fracture occurs more surrounding the tissue–cutter contact surface, which increases the volume of the tissue sample.

and from 5 to 10. The effect of increasing the slice–push ratio is also observed in the visualization of the cutting simulation (Fig. 3). The tissue sample quality gradually improves as slice–push ratio increases.

We used the cutting speed configuration: [$va =$ high, $R = 1$] to investigate how tissue stiffness affects the tissue-cutting force. All of the three tissue types were simulated. The mean cutting force of the tumor tissue is 23.62 times that of the fibroglandular tissue. This number is close to the ratio of their stiffness ($2162/105 = 20.59$). The mean cutting force of the tumor tissue is 10,639 times that of the adipose tissue. This number is much less than the ratio of their stiffness ($2162/0.08 = 27{,}025$). The result of these two comparisons, tumor versus adipose and tumor versus fibroglandular, is very different. In the former case, the tissue stiffness is the main variable that controls the magnitude of the tissue-cutting force. In the latter case, the tissue stiffness appears not to be the only factor. Higher maximum strain resistance that is assigned to the adipose is considered to make the influence.

4 Interpretation

In general, it is evident that increasing the slice–push ratio reduced the cutting force in the axial direction of the cutter. This tendency agreed with a recent experimental study [2]. However, the exact relation that we found between the tissue-cutting force and the slice–push ratio was a little different. We found that the reduction of the cutting force was much more significant when the slice–push ratio increased from 1 to 10, but was less when the slice–push ratio increased from 0 to 1. In the previous study, however, the reduction of the tissue-cutting force was much more significant when the slice–push ratio was between 0 and 1, but became trivial when the slice–push ratio was larger than 2. This conflict may be caused by two facts: (1) coaxial cutting needle (this study) versus single cutting tube (previous study); (2) much higher translational cutting speeds: [100, 50, 10] s mm/s (this study) versus as slow as the clinical needle insertion rate of 2 mm/s (previous study). This paper is the first to study the effect of cutting different types of breast tissue. We found that cutting the toughest tissue (tumor tissue) produced the largest cutting force, while the softest tissue (adipose tissue) resisted much less. Looking further into each of the cutting force, there are a few factors with different levels of influence. We concluded that the tissue stiffness is the main factor, while the maximum strain resistance was also influential.

The greatest uncertainty in this VAB tissue-cutting model relates to the tissue properties. Particularly, the information of the tissue fracture points was not directly from the breast tissue data as they are not currently available. We defined these values based on general soft tissue properties such as tendon, ligament, and muscle.

In summary, we proposed a feasible approach to predict dynamic tissue-cutting force during a VAB procedure. To develop more realistic tissue fracture properties, more tissue characteristics (e.g., viscoelasticity, anisotropy, and strain rate) should be considered. The boundary conditions of the tissue can also be refined by introducing the suction applied by vacuum. Using a local breast tissue portion and fully constraining its surface connecting to the global breast is a necessary simplification. If the condition at the local–global breast interface was of concern, the model would include the entire breast and simulate from a needle insertion process to a cutting process. However, this would require much more modeling effort and longer simulation time. To the best of our knowledge, the proposed model is the first to realistically simulate the VAB cutting. The results have the potential to provide important design insights for improving current VAB tools.

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