Mechanical Properties of the Haptic Signals Indicative of a Breast Cancer Tumor

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Abstract— **A clinical breast exam (CBE), in which a nurse or doctor palpates a patient's breast tissue searching for hard lumps, is a recommended annual breast cancer diagnostic for women over 40. Recent advances in training technology have suggested that the sensitivity of this exam can be improved and that clinicians are interested in improving training approaches. Currently researchers have an incomplete understanding of which features of the force pattern an observer must perceive in order to recognize the presence of a tumor. This limitation in our knowledge limits our ability to build more effective simulators that emphasize the specific characteristics of the signal that clinicians must perceive. Three experiments were performed using tissue analogs made from silicone rubber embedded with hard spheres. The size of the balls, their depth and the stiffness of the silicone were varied. The force exerted on a probe indented at regular intervals along the samples revealed the general force profile that a clinician may experience on his or her finger pad when searching for a tumor. Several measures of the force profiles were compared to the salience of the ball within the silicone: the ratio of the response force directly above the sphere to the force response far from the sphere, the rate of change of the force response near the sphere, and difference between the force above and to the side divided by the force to the side. These measures correlated with salience when the ball size and ball depth was varied, but not when the silicone stiffness varied. The results suggest that the relationship between the force profile and the salience of the stimulus is more complex that expected. Once this relationship is more fully understood, new training tools and procedures can be developed to trains clinicians and improve the sensitivity of clinical breast exams.**

I. Introduction

The American Cancer Society estimates that there will be 180,510 new cases of and 40,910 deaths from breast cancer in the United States in 2007[1]. One symptom of breast cancer is the development of tumors, which are perceived as lumps in the breast tissue. If these tumors are treated early, before reaching 2.0 cm in maximum diameter, the five-year survival rate is 92%, for tumors 2.1-5.0 cm, the 5-year survival rate drops to just 77%, and 65% for larger tumors [2]. To detect disease onset early, the American Cancer Society recommends that women over 40 receive a clinical breast exam and mammogram each year. A clinical breast exam, abbreviated CBE, involves the systematic palpation of the breast tissue by a trained clinician; whom searches the tissue for signs of hard, irregular nodules in the tissue. An estimated 70-90% of breast tumors are located by the patient, meaning that a vast majority of these tumors are palpable [3].

Unfortunately, clinical breast exams have a low sensitivity, in the range of 39-59% [3]. This lack of sensitivity may be related to a lack of training. Many physicians express a low confidence in their clinical breast examination (CBE) skills [4-6]. Many residents, nurses and physicians express a desire to increase their CBE competence [6-7].

Clinical breast exam training has proceeded as far as it can without a more detailed understanding of how clinicians perceive or detect a tumor. The most prominent research in the field was conducted in the 1980's and 1990's [13-15] by a team of researchers who first emphasized the development of the haptic perception of tumors [16] and later emphasized performance proficiency [17]. The training procedure, developed through these and similar research projects, generally relies on a series of prepared stimuli for the trainee to experience, including a silicone breast model embedded with small objects meant to represent tumors in their size and surface texture. Sometimes live models or actresses are also used, although, because of logistical issues, these simulated patients typically do not have breast tumors.

Several studies have pointed to the inadequacy of the current techniques and have called for the development of new training approaches [18-22]. Recently, Gerling *et al.2003* introduced a new technology for simulating breast tumors that involves inflating balloons inside a silicon model [23]. This approach allows trainees to practice the perceptual skill with a single model, which is not possible with a static model.

The purpose of the study described here is not to improve training procedures, *per se*, but to understand more precisely what skill needs to be trained. The first step in creating an effective training system is to define what specifically needs to be trained. For the purpose of this paper, the term 'haptic signal' will be used to define the aspect of touch that allows for a clinician to perceive a tumor. Currently, the inability to precisely define the details of a haptic signal limits our ability to design training simulators that specifically target the difference between normal and abnormal tissue, maximizing learning and performance. Breast tissue properties can vary widely from individual to individual. For example, some breasts contain cysts that cause tissue to feel lumpy while others feel [5]. These factors impact the sensation the clinician perceives during the clinical breast exam.

By obtaining more information about the signals clinicians seek to perceive and discriminate among, training programs can be created to rehearse the distinction between the critical signal and commonly confused signals. Such a simulator may not be designed for realism. It may, for example, begin

Manuscript received March 19, 2007

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by presenting an exaggerated version of the signal, a caricature signal, and also exaggerate the properties of the types of contrasting signals. A similar training approach is sometimes used in the study of anatomy; students study simplified, stylized sketches of anatomical features before being exposed to the complexity and variability observed in a cadavers.

For haptics, however, it is not clear what features should be exaggerated. Presumably the clinician is interpreting a pattern of stimulation across his or her fingertip. At a basic level, when performing a palpation exam, the skin on the finger tip is deformed, creating stresses within the skin's microstructures, producing a neural signal. However, the sense of touch is far more complicated and involves many different systems working together. As it is currently understood, Merkel cells and Parisian corpuscles are both capable of sensing and responding to applied force and fingertip skin deflection [12]. While the slowly adapting Type I mechanoreceptors in the fingertip skin are sensitive to stimulus edges and curvature [8-9]. These skin receptors respond to the stresses and strains applied to the skin; and encode this information by a series of neural signals, that are interpreted by the brain [12].

However, the details of this perceptual system are only now being fully appreciated through careful studies of primates and finite element models [10-11]. It is not clear what physical properties cause these cells to send a neural signal. Presumably, the force interaction between the expert's fingers and the breast tissue results in a characteristic pattern of force across the fingertip. However, the deformation and compression experienced at the fingertip co-varies, resulting in compression forces that will be dependent on the material properties of the breast amongst other properties. In either case, the specific attribute of the signal that triggers recognition is also not well understood.

For the purposes of this research, a haptic signal stimulates the Merkel cells [12] in the expert's fingertip. These signals are then transmitted to the brain where they are interpreted, although the details of these processes are not fully understood.

In an attempt to determine what a clinician is searching for while palpating, the physical properties corresponding to the applied forces can be analyzed. It may be that the observer is most sensitive to the difference in force directly above and to the side of the nodule, which we refer to as the height of the signal. Alternatively, the observer may be most sensitive to the sudden change in the force, from the background to the peak, which we call the slope of the signal. These will be different if, for example, the effect of a large inclusion is felt further away than a small inclusion, even if the signal height is similar.

Although we do not know exactly what aspect of the haptic signal the clinician interprets to be the presence or absence of a tumor, we know that some tumors are more difficult to find than others. Deep and small tumors are more difficult to perceive than shallow and large tumors [17]. We presume that deep and small tumors present a more subtle haptic signal than shallow and large tumors. Whatever the property of the perceived signal is, it should be large for easy-to-detect tumors and small for hard-to-detect tumors. Further, tumors embedded within a tissue with a very low hardness are more easily detected compared to denser or harder tissue, and thus harder tissue presents a more subtle signal than softer tissue.

Based on these observations, we chose to explore the following hypotheses:

1) The signal is the ratio of the peak response force above the tumor to the response force to the tissue near the tumor;
2) The signal is the slope of the response for curve moving from the tissue next to the tumor to the top of the tumor.
3) The width of the signal will raise the magnitude of the haptic signal;
4) Deep tumors have a smaller signal than shallow tumors;
5) Small tumors have a smaller signal than large tumors;
6) Stiff tissue provides a smaller signal than soft tissue;

Three experiments performed were designed to test the six hypotheses stated, with the main goal to determine what physical property makes up the haptic signal used by clinicians to locate tumors.

II. Experimental Methods

Three simple experiments were performed where a metal probe was used to measure the reaction force obtained from pressing the probe into various silicone molds containing tumor analogs. Each experiment tested three rectangular silicone samples, approximately 14 cm long, 4 cm wide, and 3 cm deep, with a polystyrene ball embedded within it. The three experiments were run using the same procedures. The first experiment explored how the size of the nodule affects the reaction force. The second looked at how the hardness of the tissue altered the reaction force. Finally, the third experiment tested how the location of the nodule, in terms of depth, affected the reaction force.

Each experiment was performed identically, and consisted of pressing a finger sized probe into each silicone sample, and measuring the resulting mass difference using the strain gage from an electron scale. This measurement was recorded and the approximate resulting force placed on the metal probe was calculated.

In the first experiment the size of the embedded nodule, was varied while keeping the hardness of the silicone and nodule placement relatively constant. The experiment used three silicone samples with similar hardness, but containing balls of different sizes: 10 mm, 5 mm, and 2.5 mm. The silicone hardness used was considered to be the medium hardness value for these experiments, although a quantitative measurement was not taken. Also, the nodule's location within the sample was controlled, placing them at the approximate geometric center of the samples, which is referred to as the medium or average level for these experiments.

For the second experiment, the hardness of the silicone was varied while nodule size and placement were held constant. The experiment used three silicone samples that differed in their hardness, identified by hard, medium and soft. However, no quantitative measurements were recorded to determine the relative hardness of each sample; the samples were checked to ensure there was a difference between the three samples. Further the location of the nodule was placed at the medium

level as explained above. The same procedure was used to measure the reaction force on the indented probe.

Finally, the third experiment varied the location of the nodule in terms of height from the surface. For this experiment the silicone hardness and nodule size were kept constant. The 5 mm nodule was located 7.5 mm, 17.5 mm and 37.5 mm from the upper surface. Again the same procedure was used for calculating the reaction force on the probe.

III. Experimental Results

Figures 1, 2 and 3 illustrate the force response to the probe for each experimental condition at each probe position. Tables I, II, and III summarize these data. The force without the nodule column presents the average probe response in the flat regions of the curve to the left and right of the central peak. The force with the nodule is the response to the probe when it was positioned directly above the ball. The ratio is the force with a nodule divided by the force without a nodule. The Normalized Ratio column presents the difference between the force with and without the nodule dividing by the force without the nodule. The signal width represents the distance between the two base points of the upward spike. This represents the linear distance between where the nodule first affects the reaction force and where it discontinues affecting the reaction force on. The slope column presents the approximate linear slope of one side of the peak. It is calculated in Newtons per centimeter, and helps compares the rate at which the nodule affects the surrounding tissue properties.

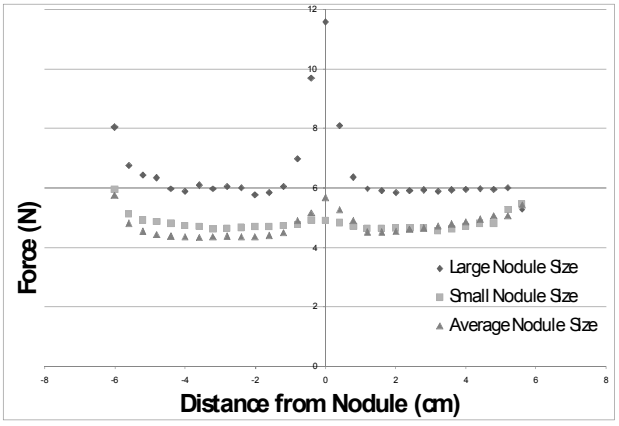

Figure 1: Experiment 1: Probe Force for Silicon with Simulated Tumors of Different Sizes

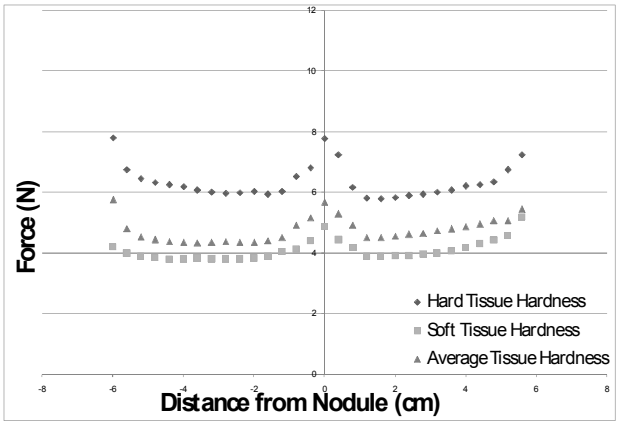

Figure 2: Experiment 2: Probe Force for Silicone Samples with Different Elasticity and Simulated Tumors

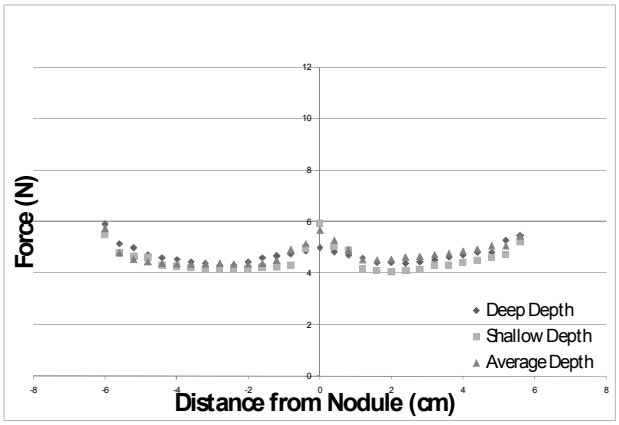

Figure 3: Experiment 3: Probe Force for Silicone with Simulated Tumors at Different Depths.

Table I

Experiment 1 Results: Testing Affect with Varying the Nodule Size

Model	Force Without Nodule (N)	Force With Nodule (N)	Ratio	Normalized Ratio	Signal Width (cm)	Rate (N/cm)
Small	4.675	4.905	1.049	0.049	2.000	-0.167
Medium	4.535	5.670	1.250	0.250	2.400	-0.770
Large	5.934	11.576	1.951	0.951	2.400	-3.365

Table II

Experiment 2 Results: Testing Affect with Varying the Tissue Hardness

Model	Force Without Nodule (N)	Force With Nodule (N)	Ratio	Normalized Ratio	Signal Width (cm)	Rate (N/cm)
Soft	3.920	4.866	1.241	0.241	2.800	-0.486
Intermediate	4.535	5.670	1.250	0.250	2.400	-0.770
Hard	6.020	7.770	1.291	0.291	2.000	-1.349

Table III

Experiment 3 Results: Testing Affect with Varying the Depth of the Nodule

Model	Force Without Nodule (N)	Force With Nodule (N)	Ratio	Normalized Ratio	Signal Width (cm)	Rate (N/cm)
Shallow	4.216	5.945	1.410	0.410	3.200	-0.878
Medium	4.535	5.670	1.250	0.250	2.400	-0.770
Deep	4.494	4.983	1.109	0.109	3.600	-0.343

IV. Discussion

At the conclusion of the experiment, the data presented some conflicting results. From Experiment 1, the data provides some evidence that the size of the nodule affects the haptic signal, and leads to possible definitions for what makes up a haptic signal. Both the Force Ratios and Slope measures start to define a pattern, which is: both measurements are high for the large nodule, low for the small nodule and at an intermediate level for the medium-sized nodule. If you assume that these measurements correspond to the value of the haptic signal, then this result follows the expected pattern that it is more difficult to detect smaller nodules than larger nodules [1]. However, when looking at the nodules' signal width, they are very similar, which suggests that signal width is not a critical factor in the haptic signal for detecting embedded tumors.

These conclusions were reversed when analyzing the data from Experiment 2. Our hypothesis stated that the soft tissue would provide a more prominent haptic signal than the hard tissue. However, both of the candidate signals, the ratio and the slope, are higher for the hard tissue than the soft tissue. This contradicts the results from Experiment 1, which implies that the ratio and slope properties may not affect the haptic signal strength. It is also possible that the ratio and slope do play a role, but that there is a secondary property which impacts the signal for various tissue stiffnesses. In either case the results are not conclusive and require more testing to bring to light any confounding variables.

Further, when analyzing the result from Experiment 3, the conclusions from Experiment 1 are supported. Both proposed measures of the haptic signal have higher values for shallow tumors than the deep tumor.

Thinking that the salience of the signal might be relative to the background force, we calculated the force equivalent of the contrast measure used in vision (the Weber fraction), by taking the difference between the signal and background force divided by the background force, which we have called the normalized force in the tables above. However, since this is equal to the ratio minus 1, there was no difference in the ordinal ranking, suggesting that the haptic signal is not an obvious analog to visual contrast.

All together the three experimental results only partially support the six hypotheses. Hypothesis 3 was not supported because the width of the signal was effectively constant for all the trials. However, hypotheses 1 and 2 were partially confirmed, but the results from Experiment 2 imply that there may be some confounding variables that are affecting the results. Hypotheses 4, 5, and 6 were neither confirmed nor rejected, because we could not pinpoint the true components of the haptic signal. However, these three hypotheses are more intuitive and are used to help define the components of the haptic signal.

Because the experiments did not provide clear answers, a post test was performed to help enhance the understanding of the previous results. We considered the post hoc premise that the signal might have been distorted by the unusually high values of the force. We repeated experiment 2, but with an indentation depth of 10 mm, which produces a force level more similar to those of the other experiments. In this case, the ratio indicated that the soft tissue would produce a more salient signal than the hard tissue. However, the signal width varied, and the rate measure was inconclusive.

Table IV

Experiment 4 Results: Testing Affect with Varying the Tissue Hardness by Inserting Probe by 10 mm

Model	Force Without Nodule (N)	Force With Nodule (N)	Ratio	Normalized Ratio	Signal Width (cm)	Rate (N/cm)
Soft	2.575	2.904	1.128	0.128	2.800	-0.132
Intermediate	2.709	3.002	1.108	0.108	2.400	-0.162
Hard	2.872	3.061	1.066	0.066	2.000	-0.059

Ultimately these experiments raise more questions than they answer; however; they provide a stepping stone for future research. Although the ratio, contrast and slope measures were all consistent with our expectations under some conditions, they were not reliable across all conditions, suggesting that the approach is incomplete. While it is reasonable to consider that the salience of the signal must be considered under similar exploration condition (i.e. similar force levels) the large reversal in haptic signal order is highly surprising and suggests that such a simple measure of salience may not be possible with touch as it is with vision.

These experiments do have some clear limitations. Some are related to the details of the investigation. The force curves presented in Figures 1-3 all have flares caused by the adhesion of the silicon to the edge of the sample container. Experiments 1 and 3 were supposed to have the same tissue hardness, and thus would expect the hardness of the tissues to be the same; however, because the samples were made from different mixtures of silicone, even with the same recipe, each sample's hardness was different. More samples and repeated trials would allow us to estimate the differences caused by manufacturing variations, and would provide a better base value for comparison. Other limitations were caused by the flaws some of the logic and assumptions made for the experiment. Silicone has slightly different mechanical properties than biological breast tissue. The silicone samples are homogeneous, whereas breast tissue is heterogeneous; this difference in homogeneity may alter the results slight, but should not significantly alter the definition of a haptic signal, and its application in a clinical setting. Another variable not considered is each material's elasticity. Silicone is effectively a linear elastic material, whereas fatty tissue is nonlinear. Although these limitations may limit the experiments validity in a clinical setting, the magnitude of the forces presented here should not affect the validity of the experiments with respect to understanding the perceptual qualities of a stimulus within a silicone bed.

V. Conclusion

Using the assumption that deep and small tumors are more difficult to perceive than large, shallow tumors, as other research implies, we set forth to determine what mechanical properties, the haptic signal, are involved in detecting a tumor, or simply what makes deep and small tumors harder to detect than large and shallow ones. After performing a series of experiments the results were inconclusive in determining what factors influence this haptic signal. We were unable to

find a consistent feature in the force pattern that correlated with the salience of the stimulus. The ratio of the force above the tumor to the background and the rate of change of the force moving from the open silicone to a position directly above the tumor were consistent with the salience in some conditions, but not all. In particular, these measures failed when the stiffness of the silicone varied. If the probe depth was changed, the ratio factor varied with salience, but the rate of change did not. This conclusion was also true for the slope of the force pattern, but changed when looking at the width of the signal, in this case the measurement did not vary with detection difficulty. Although the results are surprising, they did not provide enough evidence to determine which mechanical properties compose a haptic signal.

The next step for this line of research is to discover a haptic feature which correlates with the salience of the perception of the presence of an embedded tumor. This model could then be manipulated in a training simulator to improve the clinician's sensitivity to the particular haptic signal.

The long-term goal of this research is to improve the sensitivity of the clinical breast exam by improving the procedures for teaching the exam and provide a basis for future work dealing with detection using the human tactile system. This system is very sensitive and is used heavily in the medical community to help diagnosis and treat patients. By understanding how the system works, training for these procedures can be enhanced, increasing their effectiveness. However, the first step is to concentrate on Clinical Breast Examinations, because increasing the effectiveness of this low cost procedure has the potential to increase the life expectancy of women by early detection and treatment.

To accomplish these goals, and fully utilize the capabilities of touch, more effective training systems which focus on the critical attributes of this haptic signal. This will allow us to create training stimulators and training protocols towards that target specific properties producing the necessary stimuli and allowing clinician's to focus their attention on the critical aspects of this haptic signal.

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