DO HUMANS SENSE FINGER DEFORMATION OR DISTRIBUTED PRESSURE TO DETECT LUMPS IN SOFT TISSUE?

William J. Peine and Robert D. Howe

Harvard University
Division of Engineering and Applied Sciences
Pierce Hall, 29 Oxford Street
Cambridge, Massachusetts 02138 U.S.A.

TEL (617) 496-9098 FAX (617) 495-9837
EMAIL: peine@hrl.harvard.edu

ABSTRACT:

Detecting and localizing hard lumps in soft tissues is an important medical procedure. A psychophysics experiment measured minimum indentation forces required to detect a hard ball embedded in a soft rubber model. Ball size and finger indentation speed were varied. Threshold detection forces increased with ball size and decreased with indentation speed. The shape of the finger and contact pressure distribution on the finger were measured at the threshold force. The relative deformation of the finger induced by the ball was determined by comparing the shape of the finger indenting models with and without a ball at the same indentation force. The maximum relative deformation was nearly constant for the different ball sizes and increased significantly as indentation speed decreased. The measured pressure distributions show a considerable change across different ball sizes and indentation speeds. This suggests subjects sensed deformation of the fingerpad induced by the ball and not changes in the pressure distribution.

1. MOTIVATION

Palpation is a widely used and effective tool in many medical procedures. General practitioners, for example, use their sense of touch to determine muscle tone, assess the size of the liver and spleen, and detect lumps in the breast. Surgeons use palpation to quickly determine the thickness of an artery wall, and localize hidden tumors in the lung. Despite the frequency of use and importance, palpation has been little studied. By learning more about the palpation process, current procedures and training may be improved. An in-depth understanding would also enable the development of devices that measure, record, and recreate tactile information [Howe et al., 1995].

Palpation is a complex process from both mechanical and neurophysiological perspectives. Understanding the mechanical stimulus to the fingers requires analysis of contact mechanics, nonlinear time-dependent material behavior, and large deformation solid mechanics. The human sensory process, combined with neuro-muscular control, adds many complex factors. There has been some work to understand the relationship between mechanical stimulus to the finger, neural signals, and perception. Many of these studies, however, have looked at rigid surfaces in contact with the fingerpad [Phillips and Johnson, 1981; Johansson and Vallbo, 1983; Srinivasan and Lamotte, 1987]. In palpation, the finger is often in contact with surfaces of similar or greater compliance. This changes the stimulus to the finger as both the finger and tissue deform. One study involving soft materials investigated the ability to determine material stiffness through touch, but the stimulus to the finger was not analyzed [Srinivasan and Lamotte, 1995]. Pennypacker and Iwata [1990] have conducted experiments to quantify the ability to locate lumps in soft rubber models. This study examined perceptual abilities, but did not investigate the mechanics of detection during palpation.

One common palpation task is detecting and localizing a hard lump in soft tissue. This is the main objective of breast and prostate exams and an important part of several types of cancer surgery. The goal of this study is to determine the relationship between physical stimulus and detection of a hard ball embedded in a soft rubber material. We vary important parameters in the experiment (ball size and indentation speed) while measuring the mechanical stimulus to the finger (skin deformation and pressure distribution). The study consists of three parts. The first is a psychophysics experiment to determine the minimum indentation force needed for subjects to just detect the presence of the balls in the rubber models. The next step involves measuring the shape of the subject’s finger at the threshold force by photographing the finger through the side of the rubber model. Finally, the pressure distribution on the finger due to the contact with the model is measured using a localized pressure sensing technique. These three parts provide a detailed description of the mechanical stimulus to the finger when the ball is just noticeable.

2. EXPERIMENTAL METHODS

Studying palpation in a medical setting is difficult due to the complexity of the stimulus and interaction. To simplify our experiment, we designed models for subjects to palpate that simulated biological tissues and used a mechanical device to press the models against the subject's finger. The models were made of a clear, soft silicone rubber (General Electric Co., GE6166, Young's Modulus ≅ 4 kPa). Hard plastic balls were embedded in the rubber to stimulate tumors (Figure 1). Four models were produces with ball diameters of 6.4, 12.7, 19.1 and 25.4 mm. An additional model contained no ball. The models were constructed in boxes (100 x 100 mm base and 50 mm height) with glass sides. The distance between the top of the rubber surface and the top of the ball was 12.7 mm in all cases. As the subject's finger indented into the model, the ball and finger were visible through the sides of the model. A thin layer of oil was used to lubricate the rubber surface and minimize the friction between the subject's finger and model.

Subjects touched the models with the index finger of their right hand. Voluntary movements of the finger were precluded by gluing the fingernail and securing the forearm to a rigid support fixed to the table. The index finger was held at approximately 45 degrees by the constraint. Needles for image registration were also attached to the constraint.

A linear actuator raised the models against the finger. Although this is a deviation from typical palpation motions, a passive experiment allows accurate control over important parameters such as indentation speed and contact location. The mechanism consisted of a translation stage with 30 cm of travel that moved a cantilevered beam and platform that held the model. A force sensor under the platform measured indentation force (RMS noise 0.005 N, range 10 N) and an optical encoder (resolution 0.013 mm) measured displacement. The motion of the model was position controlled using a PD controller. The RMS position tracking error was less than 0.2 mm, and the force plateaus were accurate to within 3% with a repeatability of 0.02 N RMS. A kinematic coupling between the platform and model ensured that the location of the model (and thus the ball) was consistent from trial to trial relative to the subject's fixed finger. The balls in the models were aligned directly under the lowest point of the finger.

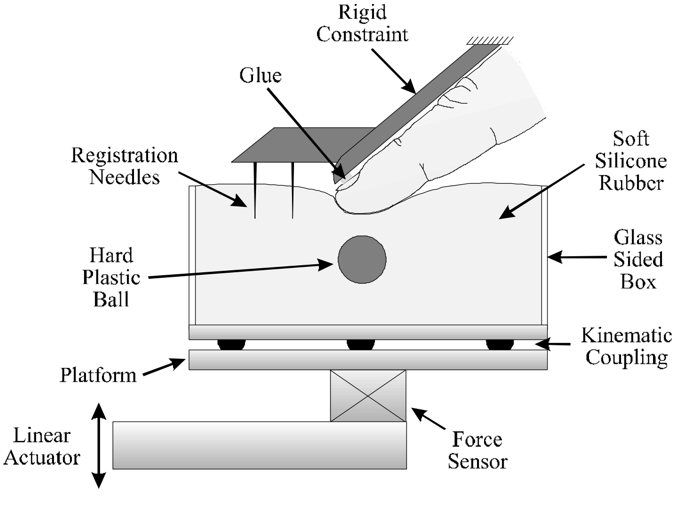
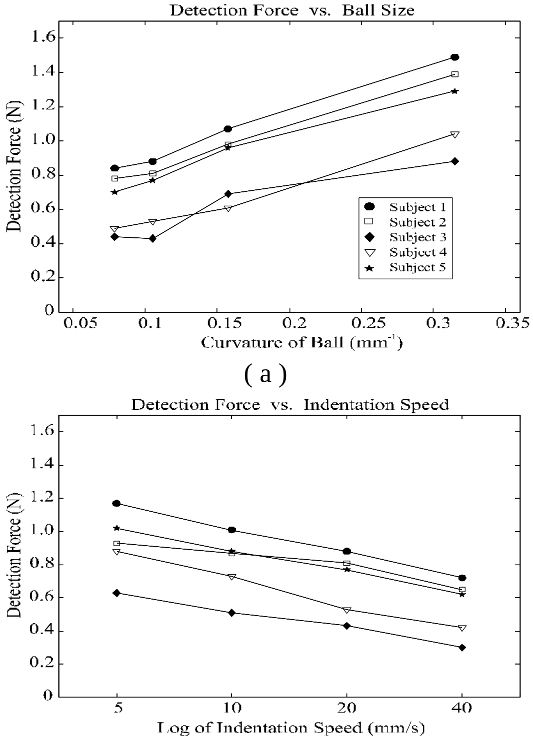


Figure 1. *Apparatus for Detection Experiment.* The linear actuator raises the rubber model against the subject's fixed finger to a specific contact force. The shape of the finger and location of the ball is visible through the side of the model.

A psychophysics experiment used the method of limits to determine the minimum force required for subjects to just detect the presence of the ball in the rubber. This involved raising the models at a constant velocity against the finger to a specific force, maintaining that force level for one second, retracting the model away from the finger, and then asking the subject if they could feel the ball in the rubber during this process. By varying the force "plateau" levels, the detection force could be determined. In this protocol the detection force is the average of two different types of trials. The first starts with the force plateaus at a level well below the detection point. The force plateau level is slowly increased in repeated indentations. As the force level crosses the detection point, the subject indicates they felt the ball. In the second type of trial, the force plateaus start well above the detection point and are slowly lowered. In this case the subjects indicate when they can no longer feel the ball in the rubber.

There are a large number of parameters that can be varied in this experiment. Through pilot studies, we found a significant variation in detection force due to changes in ball size and indentation speed. Additional parameters of interest we did not investigate include ball depth, stiffness, and shape; rubber stiffness; and inhomogeneous rubber models (e.g. models with a thin, stiffer skin). Our experiment consisted of seven cases: four with a fixed indentation speed of 20 mm/s with ball diameters of 6.4, 12.7 19.1, and 25.4 mm, and three additional cases with the 19.1 mm ball at indentation speeds of 5, 10 and 40 mm/s. This provided four data points with variation in ball size and four with variation in indentation speed. Each subject completed 16 trials for each case: 8 with increasing forces and 8 with decreasing forces. The trials were broken into sets of 14 with rests between sets. All the cases in one set were of the same type (increasing or decreasing force). The order of presentation of ball size and indentation velocity in a set, as well as order of set type, was randomized. Periodically the model without a ball was presented to ensure the subjects were actually sensing the ball. Subjects never incorrectly detected a ball when it was absent. The data was taken over two days. A total of five unpaid subjects participated (mean age 22 years, 4 male and 1 female).

Once detection levels for each combination of ball size and indentation speed were determined, the shape of the finger at the detection force for each case was measured using photographs taken through the side of the rubber models. The camera was fixed to the apparatus and had a field of view of 40 x 60 mm. A flash located on the opposite side of the model back lit the finger and ball. This created an image with high contrast allowing the profile of the finger and ball to be easily extracted. The flash was electronically synchronized to fire at the beginning of the force plateau. Photographs were taken of the finger indenting into models with and without a ball at the detection forces measured for each case. By registering these images, a comparison between the shape of the finger with and without the ball at the same force was determined. Thus, the shape change of the finger induced by the presence of the ball could then be measured. This technique only works if the finger remains convex. No concavity was observed for any of the subjects at threshold.



(a)

(b)

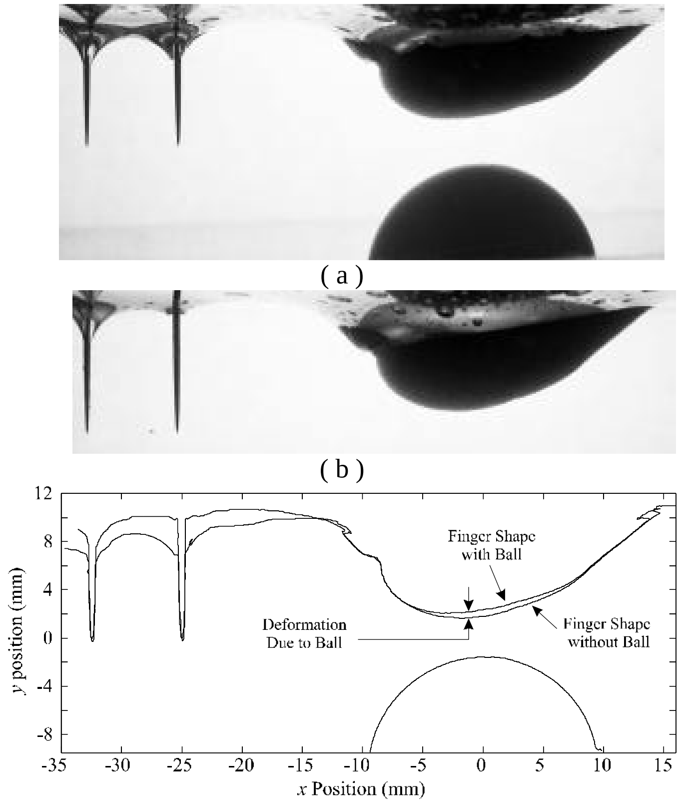
Figure 2. *Indentation Force Required for Detection.* Indentation force required by all subjects for variations in (a) ball size and (b) indentation speed.

The photographs of the finger were digitally scanned, with a resulting image pixel size of approximately 13 μm. A contour detection algorithm located the edge of the finger and ball. The edges were spatially filtered using a forth-order low-pass filter with a cutoff frequency of 1.6 cycles/mm to remove high frequency noise. Using the outline of the needles penetrating into the rubber, the finger edges from all the images were aligned and registered. Fifth order polynomials were then fit to the finger shapes. The relative deformation induced by the ball could then be determined by subtracting the shape of the finger measured when the ball was present from the finger shape when the ball was absent. Due to the complexity of the signal processing, only one set of finger pictures was analyzed for each case. To estimate the repeatability of the measurement, relative deformation curves were measured for one case seven times from seven independent indentations into the model with the ball, and seven indentations into the model without a ball. The RMS error between the seven relative deformation curves was less than 0.025 mm across the entire finger length.

The final step of the experiment was to measure the approximate pressure distribution on the fingerpad at the detection force levels for each of the seven cases. An apparatus was constructed to measure the local contact pressure at any point on the finger. Wax replicas of a subject's index finger were made from a plaster of paris mold. A tube running the length of the wax finger was inserted into the mold during the construction process. To measure the pressure at a specific point on the finger, a 0.75 mm hole was drilled normal to the local surface through the wax finger into the central tube, which connected to a compressed air supply. After the wax finger was indented into the rubber to the appropriate detection force level (using the same apparatus mentioned above), the air pressure was slowly increased. When the air pressure inside the hole in the finger equaled the contact pressure at the surface of the rubber around the hole, air would escape. Using an electronic pressure sensor (RMS noise 0.01 kPa; range 20 kPa), the transient in the pressure created by the air escaping around the finger determined the contact pressure at the location of the hole. By drilling holes in different locations on the wax finger, the pressure distribution along the midline of the finger was measured. Standard deviations of repeated measurements at the same hole location and indentation force were less than 0.07 kPa.

3. RESULTS

Figure 2 shows the detection forces required for each of the five subjects for variations in ball size (2a) and indentation velocity (2b). The same trends were observed for all subjects: detection required more force as the ball size decreased or the curvature increased. We found an approximately linear relation between detection force and curvature of the ball. We also found a linear relation between the log of the indentation speed and the required force for detection: the slower the indentation, the higher the detection force.



(a)

(b)

(c)

Figure 3. *Measurement of Finger Shape at Detection.* (a) Subject 4 at threshold force for the model with 19.1 mm ball, (b) same indentation force for model without a ball, (c) extracted and registered edges from images. Relative deformation of the finger caused by the ball is determined by subtracting the two finger shapes.

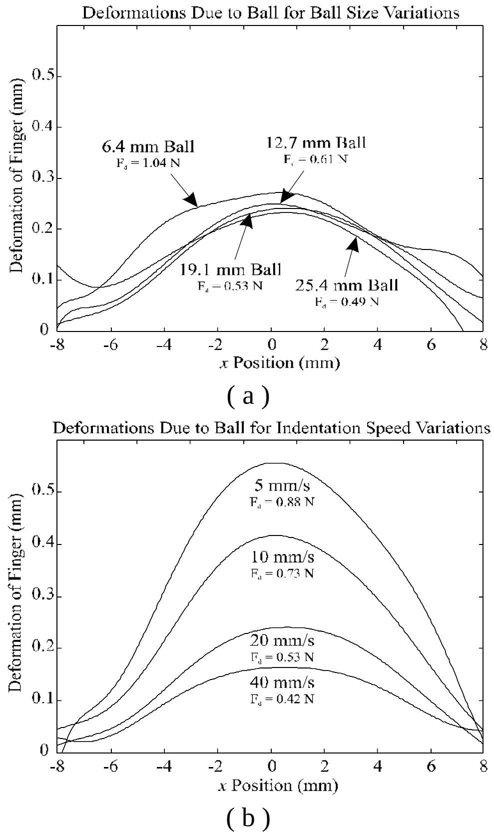


Figure 4. *Deformation of Finger Created by Ball.* Relative deformations at threshold from Subject 4 for variation in (a) ball size and (b) indentation speed.

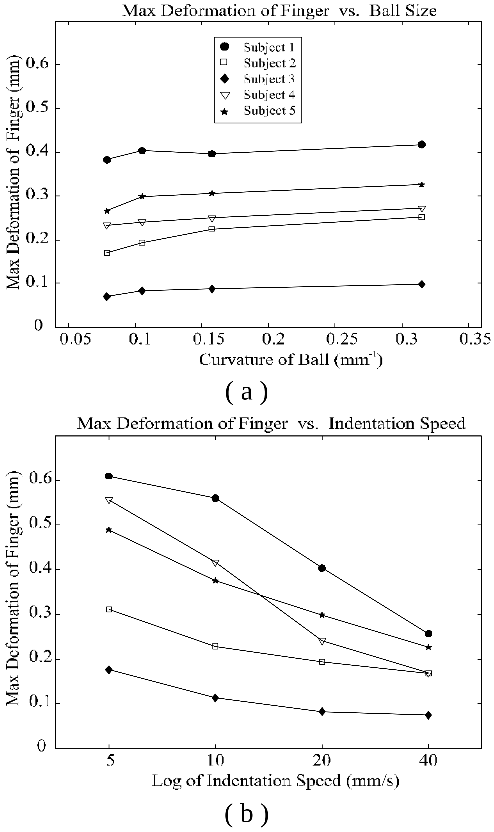


Figure 5. *Maximum Relative Deformation of Finger Caused by Ball.* Maximum deformations at threshold for all subjects for variation in (a) ball size and (b) indentation speed.

The deformation induced by the ball was measured for all cases. Figure 3a shows a photograph of a typical subject at the detection force for the 19.1 mm ball using a 5 mm/s indentation speed. Figure 3b shows the same subject at the same indentation force contacting the model without a ball. The extracted and registered profile shapes of the finger, ball, and needles in these photos are shown in Figure 3c. The relative deformation of the finger induced by the ball was found by subtracting the finger shapes shown. Figure 4 shows the relative deformation curves measured for the same subject for the different ball sizes (4a) and indentation speeds (4b). The shape of the relative deformation curves was approximately the same for all cases. This shape could be described many ways (e.g. curvature). We chose to use maximum deformation because it was most straight forward to measure. Figure 5 shows the maximum deformation induced by the ball versus ball size (5a) and indentation speed (5b) for all subjects. As with the detection force, all subjects showed the same trends. The maximum deformations induced by the ball were relatively constant for the different ball sizes, but they significantly increased as the indentation speed decreased.

The local pressure measurements taken with the wax finger indentor show the distributed pressure on the finger when contacting the models with a ball is different from the pressure distribution created when contacting the model without a ball. Figure 6a and 6b shows the pressure distribution along the centerline of the finger for the 6.4 and 25.4 mm ball cases, respectively. The solid squares show the measurements taken using the model with the ball and the open circles show the pressures measured using the model without a ball. Figure 6c shows the locations of the pressure measurements on the finger. Because the same indentation forces were used when taking measurements using the models with and without a ball, the integral of the pressures is the same. The difference in the pressure distributions caused by the ball was calculated by subtracting the two curves. Figure 6d shows the measured pressure difference for each of the two ball sizes. The 6.4 mm ball causes a high, narrow pressure concentration above the ball, while the 25.4 mm ball causes a lower, wider pressure concentration.

A similar trend was observed for the other ball sizes and indentation speeds. Figure 7 shows the pressures measured on the finger directly above the ball for each of the ball sizes (7a) and indentation speeds (7b) using the appropriate detection forces contacting models with and without a ball. As with the cases shown in Figure 6, the pressures above the ball are higher when the ball is present in the model. As ball size and indentation speed decreased, the pressure concentration caused by the ball increases in magnitude. It should be noted that the change in pressure for the variation in indentation velocity is due to the change in indentation force and is not a result of viscous properties of the rubber. Since the integral of the pressure distributions must be the same for the case with and without a ball, the width of the pressure concentration narrows as the magnitude of the difference increases.

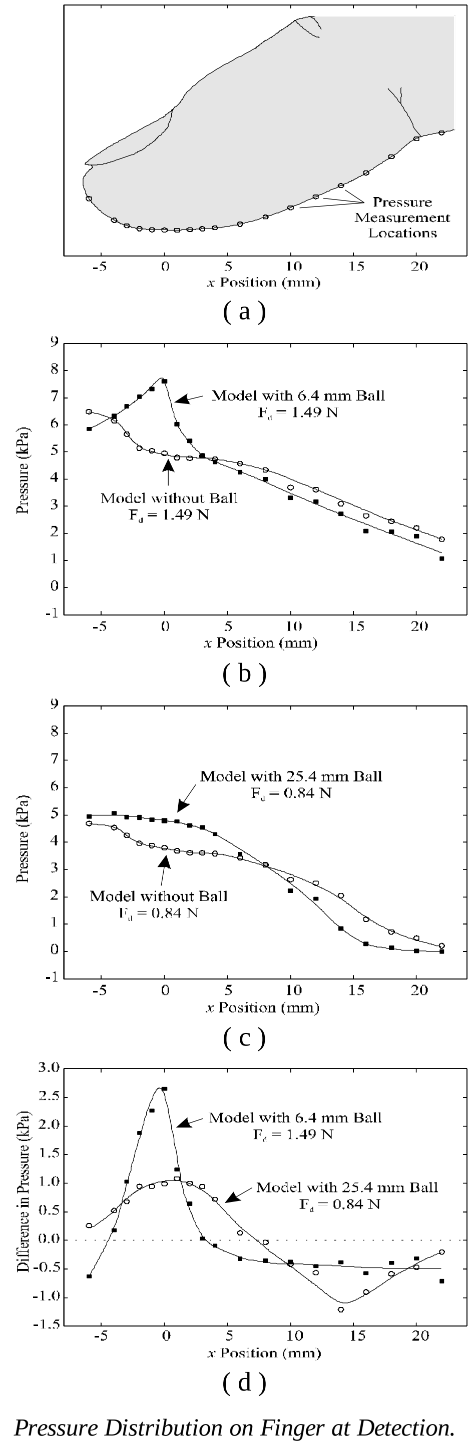


Figure 6. *Pressure Distribution on Finger at Detection.* (a) The locations of the pressure measurements on the wax finger. The solid squares indicated local pressure measurements taken using models with (b) 6.4 mm ball and (c) 25.4 mm ball, and the open circles show pressures using the model without a ball at the same respective detection force levels. (d) The difference in the pressure distribution caused by the presence of the ball. The solid squares shows pressure differences due to 6.4 mm ball, and open circles show pressure differences due to 25.4 mm ball.

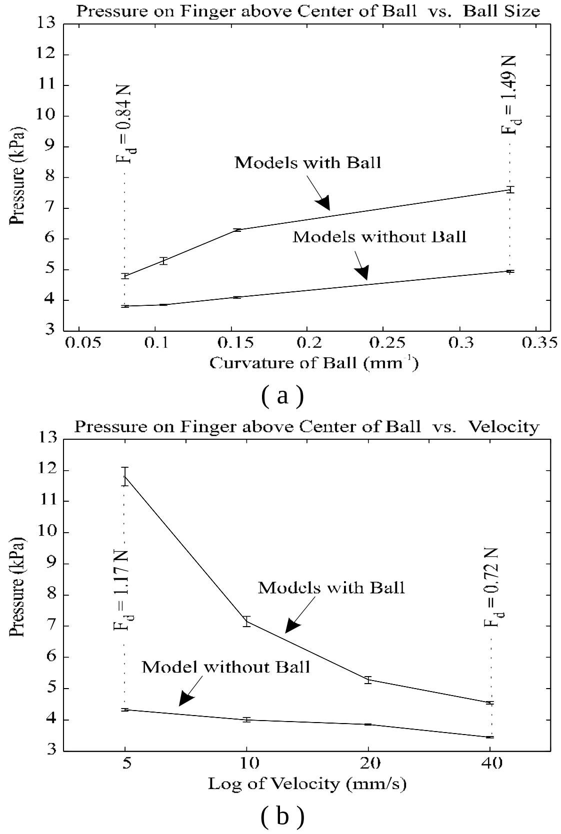


Figure 7. *Pressure on Finger above Center of Ball.* Pressure measurements for variation in (a) ball size and (b) indentation speed. Error bars show standard deviation of five trials for each case.

4. DISCUSSION

The primary purpose of this experiment was to determine what physical parameters humans are sensing when they just begin to detect the presence of a hard lump in a soft material. This cannot be answered with absolute certainty, but a good hypothesis can be presented. Our results show the deformation of the fingerpad induced by the presence of the ball was nearly constant for the different ball sizes when the indentation speed was held fixed. This was true even though the indentation forces and pressure distributions were different. This suggests that subjects could detect the ball when the relative deformation of their finger crossed a certain threshold.

Another detection mechanism that explains these results is sensing skin curvature. Subjects could detect a change in the curvature of the skin from the “baseline” level of the finger contacting homogeneous rubber. The shape of the finger (and thus curvature) did not significantly change as indentation force increased when touching the model without a ball. Because the relative deformation of the finger from this state was similar for the different ball sizes, the shape and curvature of the finger was also similar for these cases. Thus, the ball is felt when the change in skin curvature reaches a threshold level. There has been significant work showing a strong relation between changes in skin curvature and mechanoreceptor response [Phillips and Johnson 1981; LaMotte and Srinivasan 1987]. Goodwin and Wheat [1991] performed a psychophysics experiment to measure the ability to discriminate changes in curvature of rigid indentors pressed against the fingerpad. Although the mechanical stimulus to the finger when contacting soft materials is significantly different, we observed detectable curvature changes of a similar magnitude ($\cong 0.03\ \mathrm{mm}^{-1}$).

Recent monkey neurographic experiments are consistent with our results [Vega-Bermudez and Johnson, 1998]. These experiments show the firing rate of type I mechanoreceptors in the skin in response to indentation by a raised feature was independent of a "baseline" force offset applied by a flat surface to the fingerpad. This suggests the neural responses from these mechanoreceptors encode a change in local shape or curvature from an offset level rather than the absolute force or pressure distributions. In our experiment, the pressure distribution induced by the homogeneous rubber acts as an offset force. Subjects detected a change in shape or curvature of the finger with respect to this offset stimulus.

The changes in detection force due to variations in indentation speed can be attributed to the time-dependent response of the mechanoreceptors. Type I mechanoreceptors in the skin are believed to resolve spatially distributed information. The firing rates of these mechanoreceptors are highly dependent on the temporal frequency of the applied stimulus. Higher temporal frequencies induce higher firing rates [Johansson and Vallbo, 1983]. As the indentation speed in our experiment increased, the frequency content of the stimulus of the ball increased. Subjects became more sensitive to changes as this frequency of stimulation increased. This is evident in the decreasing maximum relative deformation as the indentation speed increased. This also explains why subjects prefer to quickly move their fingers in small circular motions when searching for a lump using natural palpation motions [Peine, Foucher and Howe, 1998]. Moving in quick circles provides a high frequency, repeated stimulus.

These results are also helpful for determining design requirements for tactile feedback systems that measure and recreate tactile information. We are developing a surgical instrument that allows surgeons to palpate internal tissues using minimally invasive techniques [Howe et al., 1995]. Our device consists of a rigid sensor probe the measures distributed pressure as it contacts internal tissues, and a tactile shape display that recreates the appropriate localized shape directly on the surgeon's finger. With this instrument, lumps can be located just as they are in traditional surgery while minimizing damage to healthy tissue. Ideally, tactile feedback would provide realistic sensations such that the surgeon feels as if she or he is touching the tissue directly. This requires, at minimum, matching the system's sensitivity to that of the human sense of touch. It is also important to display and control the tactile sensations surgeons are using for detection. From our data (Figures 4 and 6), the pressure sensitivity for the distributed pressure sensor should be less than 0.5 kPa. The shape display should control the shape output to a high level of accuracy, less than 0.05 mm.

The logical next step to advance our understanding of what humans are sensing during palpation involves microneurography studies. This will provide insight to what the mechanoreceptors are sensing and how firing rate changes with input stimulus.

This in no way is a complete analysis of the palpation process of lump detection in soft materials. There are many other parameters we did not vary in our experiment. It would be interesting to compare our results to the relative deformations created when these parameters are changed. For example, does the maximum deformation change when the surrounding rubber is made stiffer? It would also be of value to determine detection abilities when using natural, active palpation motions compared to the passive case studied here. When determining the shape and size of the ball through palpation, shape and curvature changes of the finger may become very important. Further experiments are needed to understand this part of palpation.

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