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Psychophysical Detection of Inclusions with the Bare Finger amidst Softness Differentials

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Abstract

Softness discrimination and the detection of inclusions are important in surgery and other medical tasks. To better understand how the characteristics of an inclusion (size, depth, hardness) and substrate (stiffness) affect their tactile detection and discrimination with the bare finger, we conducted a psychophysics experiment with eighteen participants. The results indicate that within a more pliant substrate (21 kPa), inclusions of 4 mm diameter (20 mm³ volume) and greater were consistently detectable (above 75% of the time) but only at a depth of 5 mm. Inclusions embedded in stiffer substrates (82 kPa) had to be twice that volume (5 mm diameter, 40 mm³ volume) to be detectable at the same rate. To analyze which tactile cues most impact stimulus detectability, we utilized logistic regression and generalized estimating equations. The results indicate that substrate stiffness most contributes to inclusion detectability, while the size, depth, and hardness of the stimulus follow in individual importance, respectively. The results seek to aid in the development of clinical tools and information displays and more accurate virtual haptic environments in discrimination of soft tissue.

Keywords

Softness discrimination; inclusion detection; psychophysics; tactile perception; medical simulation

1 Introduction

Inclusion detection, or the detection of one body (a stimulus) within another, is important in many environments, particularly clinical surgery (e.g., cauterization during surgery, the removal of cysts using surgical scissors) and palpation exams (e.g. breast and prostate cancer screenings). It is necessary to understand how the characteristics of the substrate in which the stimulus is embedded and dimensions of the stimulus itself affect tactile perception. This knowledge can inform the development of appropriate clinical tools and information displays [1–2].

With the advent of minimally invasive surgery, teleoperation, and virtual-environment applications, there is a growing interest in how to present human operators with natural tactile and haptic experiences, particularly those experienced through a sheath or other form of constraint [3–6]. Many of these devices involve the interaction of a rigid body (probe or indenter) with an elastic body (tissue). In these cases, such as during laparoscopic surgery, the operator feels the shaft of the instrument and therefore uses cues such as its angle, the force at its tip, and any vibrations in the shaft. For this class of interaction, psychophysical

research has focused on texture perception or discrimination of absolute stiffness [7] in order to determine how to build simulated environments or appropriate virtual feedback devices.

Another class of interactions involves the bare finger and another elastic body (tissue). In fact, some robotic devices are now being developed to incorporate tactile sensors that mimic human perception [8]. However, there has been less focus on the underlying psychophysical experiments, modeling, and simulation that surround bare finger interaction with soft objects. Most research in this area has focused on the discrimination of softness [9–10], roughness [11], and objects through a glove [12]. Other analysis of perception with the bare finger surrounds the modeling of neural responses (both single-units and populations of mechanoreceptors in fingertip skin) [13–14].

The objective of the work presented here is to conduct a psychophysical experiment to characterize the factors that surround inclusion detection. The overall goal is to understand how varying the characteristics of the substrate and inclusion affect tactile perception in a constrained environment.

2 Methods

We conducted an experiment using a modified method of constant stimuli with 18 participants and inclusions that varied in size, depth, and hardness that were placed within substrates of two stiffness levels. The participants' task was to palpate the substrate and indicate if the stimulus is present. The objectives of the study were to determine a) the size of inclusions consistently detected at three discrete depths, b) how substrate stiffness impacts detectability, c) how inclusion hardness impacts detectability, and d) how each of the variables differentially impact inclusion detection.

2.1 Apparatus

An apparatus was built specifically for this study. The main components were a hole to constrain the finger, a thin sheath, and twenty-three cylindrical substrates (30 mm diameter and 20 mm tall) mounted onto a round platform. The substrates were made of silicone-elastomers of two stiffness levels (21 and 82 kPa) that simulate the feel of interior human prostate tissue and other internal organs. The platform was housed within a structure that restricted viewing of the substrates and included the finger hole angled at approximately 110 degrees from the participant. A sheath made of silicone-elastomer (2 mm thick, 180 kPa) was attached to the hole. This constrained the finger at the knuckle and extended beyond the length of the finger. The platform of substrates could be rotated so that only the substrate under test was located beneath the sheath.

Each cylindrical substrate included a single polyethylene balloon embedded at one of three depths: 5, 10, and 15 mm. Balloons of seven volumes were used: 20, 40, 80, 200, 470, 1060, and 1770 mm³ that correspond to diameters of 4.0, 5.0, 7.5, 10.0, 15.0, 17.0, and 20.0 mm, respectively. The balloons were filled with water, thereby controlling hardness of the stimulus. Balloons could be inflated to be hard, like a rock, but were not detectable when deflated. In this study, three hardness levels were used: 23, 27, and 31 durometers, type Shore A.

2.2 Participants

Ten male and eight female participants (mean age = 20.4 years, SD = 1.4) were enrolled in the human-subjects study, approved by the IRB at the University of Virginia. A demographic questionnaire indicated that no participant had any remarkable prior experience working with his or her hands.

2.3 Procedure

Using a modified version of the psychophysical method of constant stimuli [15], participants palpated the substrates to determine the detectability of stimuli. Typically the method of constant stimuli employs stimulus and noise only trials presented in a randomized fashion where all stimulus combinations are presented an equal number of times. However, here we made three modifications to reduce the number of trials and thereby participant fatigue. First, only 31 of the possible 42 combinations of independent variable levels (stimulus size, depth, hardness and substrate stiffness) was presented to participants (Table 1) as pilot testing identified combinations that were always or never detectable and therefore were removed from this study. Second, the number of times that each stimulus combination was presented varied depending on the difficulty of detecting the stimulus in the pilot study. The most difficult to detect were presented four times, while the easiest to detect were presented twice and the rest were presented three times (Table 1). Third, to address potential trial order issues, participants were presented with stimuli and noise trials in one of six random orders.

Every participant completed two, 90-min experimental sessions, held on separate days. Before the first experimental trial, participants had a hands-on practice session with feedback concerning whether or not the substrate contained an inclusion. They were instructed to achieve a consistent search technique: move one's finger across the substrate surface in lines parallel with and then perpendicular to the participant's seated position. When traversing these line paths, participants were instructed to use small, dime-sized circular motions. During training and the experimental trials, the proctor monitored the pressure exerted on the substrates to ensure that finger pressure remained within 4 and 6 N and that the quadrants were palpated in the specified order. When participants deviated from the specified pressure or palpation order, they were reminded of the appropriate technique.

During the experimental trials, participants palpated 192 substrates, half of which contained a stimulus (the balloons were not inflated for the others). Participants were given 20-sec to examine a single substrate. After each trial, participants informed the proctor (via "yes" or "no") as to whether a stimulus was present and the proctor noted the response. Participants were given a 10-sec break between subsequent trials, a 60-sec break after every 10–17 trials and a 5-minute break after every 32–42 trials.

2.4 Data Analysis

In seeking to identify general relationships between the independent variables (stimulus size, depth, hardness and substrate stiffness) and inclusion detectability, graphical analysis was used to address objectives a–c. Logistic regression was used to address objective d. For the logistic regression, we used generalized estimating equations or GEE, [16]. Substrate stiffness was considered both a fixed and random effect and stimulus size, depth, and hardness as quantitative and continuous variables. Size was coded as 1–7 (4 mm – 20 mm); depth was coded as 1 (15 mm), 4 (10 mm), and 7 (5 mm); hardness was coded as 1 (23 durometers), 4 (27 durometers), and 7 (31 durometers); and substrate stiffness was coded as 1 (82 kPa) and 2 (21 kPa).

For logistic regression, one response per participant for each combination of independent variables was needed. Therefore, if participants detected at least half of the stimuli for a specific combination of variables, the response was considered a "yes" (coded as 1) and if less than half of the stimuli were detected, the response was considered a "no" (coded as 0).

Statistical analyses were conducted using R. For the logistic regression results, the *geeglm* function for GEE from the *geepack* package was used.

3 Results

In general, deeper and smaller stimuli were more difficult to detect at both substrate stiffness levels and stimuli were more likely to be detected in the 21 kPa substrate compared to the 82 kPa substrate. To help illustrate the impact of size and depth on the percent detected, Figure 1 depicts the relationship between detection percentage and stimulus size at each of the three depths for the 82kPa stiffness (top) and the 21kPa stiffness (bottom).

The detection rate for larger inclusions in stiffer substrates is similar to smaller inclusions in more pliant substrates, given equal depth (Figure 1). For example, at a depth of 15 mm, 17 mm inclusions in the 82 kPa substrate were detected at approximately the same percentage as 10 mm inclusions in the 21 kPa substrate (80% and 75% respectively).

The impact of hardness can be more readily seen for particular size-depth combinations. Figure 2 illustrates the result of varying the hardness of a 10 mm diameter stimulus at a 10 mm depth, for both the 21 and 82 kPa substrates. At the lowest hardness (23 durometers, type Shore A) the percent detected in the stiffer substrate (82 kPa) drops to 75% from 100%. In contrast, the percent detected in the more pliant substrate (21 kPa) was not affected by changes to stimulus hardness. Similarly, in the other two cases where hardness was varied, the percent detected was impacted more in the 82 kPa substrate compared to the stimulus in the 21 kPa substrate (Figures 3 and 4).

The following logistic regression model was used to determine how the independent variables impacted detection of the stimulus, where p is the percent of stimuli detected.

$$\log(p/(1 - p)) = \beta_0 + \beta_1(\text{stiffness}) + \beta_2(\text{size}) + \beta_3(\text{depth}) + \beta_4(\text{hardness}) \quad (1)$$

Table 2 depicts the output of the model using stiffness as a random effect. The output indicates that all variables significantly impacted detection of the inclusion. In addition, the values of the coefficients indicate that stiffness of the substrate most contributes to detectability, then size, then depth and finally stimulus hardness. The results are presented using $\alpha = 0.05$ for significance.

Tables 3–4 show the model outputs from a sub-group analysis with substrate stiffness considered as a fixed effect. From the subgroup model outputs, we can see that all stimulus variables significantly impacted detection of the stimulus in the 82 kPa substrate. However, in the more pliant substrate (21 kPa) stimulus, inclusion hardness was not a significant factor in detection. Further, we see in the 82 kPa model, the coefficients for size and depth are comparable, while in the 21 kPa model, size has a greater impact on detection.

An analysis of two factor interaction effects was completed in two steps. First interaction effects to consider were identified. Each two-way interaction was added one at a time to the main effects model. Using this method, the size-depth, depth-stiffness, and hardness-stiffness interactions effects were significant. However, when the statistical analysis was conducted with these three interaction effects along with the main effects, only the size-depth and stiffness-hardness interactions were significant (Table 5). The values of the coefficients indicate that stiffness of the substrate still most contributes to detectability, then size, then depth, then stimulus hardness, and then the size-depth and stiffness-hardness interactions.

4 Discussion And Conclusion

This study sought to understand the effects of substrate stiffness and inclusion characteristics on tactile perception in a constrained environment, representing a clinical setting. Through an elastic sheath, participants palpated 31 different combinations of substrate stiffness and stimulus size, depth, and hardness.

Within a more pliant substrate (21 kPa), inclusions of 4 mm diameter (20 mm³ volume) and greater were detected above 75% of the time, but only at a depth of 5 mm. Inclusions embedded in stiffer substrates (82 kPa) had to be twice that volume (5 mm diameter, 40 mm³ volume) to be detected at the same rate.

Substrate stiffness most impacted inclusion detection in all cases while the interaction of stiffness and hardness also played a role in detection, particularly in the less pliant substrates (82 kPa). However, compared to size and depth, stimulus hardness did not play as large a role in detection and was not a significant factor in the model of the more pliant substrates (21 kPa), similar to results found in [1]. This could be, in part, because the hardness of the stimuli was not varied over a large enough range (only 23 to 31 durometers, Shore A). To give some perspective on the hardness of various objects in durometers, Shore A, a rubber band is 40, a rubber shoe heel is 70, and a shopping cart wheel is 100. It might be appropriate to go up to 60 durometers, Shore A in further studies in addition to including more substrate stiffness levels.

The results of this study may aid in the development of clinical tools and information displays and more accurate virtual haptic environments in discrimination of soft tissue.

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Figure 1. Detection percentage as a function of stimulus size and depth at two stiffness levels – 82 kPa (top) and 21 kPa (bottom). Standard error bars are shown around data points.

Figure 2. Detection percentage as a function of stimulus hardness for a 10 mm diameter, 10 mm deep stimulus for both substrate stiffness levels. Standard error bars are shown around data points.

Figure 3. Detection percentage as a function of stimulus hardness for a 15 mm diameter, 15 mm deep stimulus in the 82 kPa substrate. Standard error bars are shown around data points.

Figure 4. Detection percentage as a function of stimulus hardness for a 10 mm diameter, 15 mm deep stimulus in the 21 kPa substrate. Standard error bars are shown around data points.

Table 1

Stimulus trials per participant.

Stimulus dimensions			Number of trials at 82 kPa stiffness	Number of trials at 21 kPa stiffness
Size (dia mm)	Depth (mm)	Hardness (durometers, Shore A)		
4	5	31	4	2
4	10	31	2	4
5	5	31	3	2
5	10	31	3	3
7.5	5	31	3	-
7.5	10	31	3	2
7.5	15	31	-	4
10	5	31	2	-
10	10	23, 27, 31	4, 4, 4	4, 4, 2
10	15	23, 27, 31	-, -, 2	4, 4, 3
15	10	31	3	-
15	15	23, 27, 31	4, 4, 4	-, -, 2
17	10	31	2	-
17	15	31	3	-
20	15	31	2	-

Table 2

First order coefficients for the main effects model.

	Coefficient	SE	Wald St.	Pr(> W)
Intercept	-10.41	1.51	47.33	5.99e-12
Stiffness	2.16	0.41	28.33	1.02e-07
Size	1.29	0.17	58.62	1.91e-14
Depth	1.09	0.14	60.74	6.55e-15
Hardness	0.18	0.065	7.60	0.0058
Correlation Parameter	0.12	0.067		

Table 3

First order coefficients for each stimulus dimension in subgroup model for 82 kPa stiffness.

	Coefficient	SE	Wald St.	Pr(> W)
Intercept	-8.43	1.32	41.07	1.5e-10
Size	1.25	0.17	54.89	1.3e-13
Depth	1.13	0.16	47.71	4.9e-12
Hardness	0.24	0.08	8.92	0.0028
Correlation Parameter	0.07	0.08		

Table 4

First order coefficients for each stimulus dimension in subgroup model for 21 kPa stiffness.

	Coefficient	SE	Wald St.	Pr(> W)
Intercept	-7.50	1.87	16.10	6.0e-05
Size	1.75	0.40	18.68	1.5e-05
Depth	1.24	0.20	37.70	8.2e-10
Hardness	0.15	0.11	1.76	0.18
Correlation Parameter	0.20	0.34		

Table 5

First order coefficients and selected interactions.

	Coefficient	SE	Wald St.	Pr(> W)
Intercept	-11.20	2.10	28.46	9.57e-08
Stiffness	3.54	0.87	16.57	4.70e-05
Size	0.90	0.20	20.32	6.53e-06
Depth	0.72	0.27	7.20	0.007
Hardness	0.54	0.17	10.75	0.001
Size-Depth	0.18	0.05	13.39	0.0002
Stiffness-Hardness	-0.23	0.09	7.05	0.008
Stiffness-Depth	-0.06	0.11	0.31	0.57
Correlation Parameter	0.12	0.08		