CLARIFICATION OF SOFTNESS PERCEPTION MECHANISM USING TETRA-PEG GEL

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ABSTRACT

This study tested the hypothesis regarding how physical interaction parameters - applied force, penetration, and contact area - between the object and the stiffer finger (4 out of 10 participants in this study had finger elastic moduli exceeding 50 kPa) influence softness perception. To this end, participants pressed Tetra-PEG gel with varying elastic moduli under two conditions: tool-based active touch and bare-based active touch, and during these interactions, applied force, penetration, and contact area were measured. The hypothesis was supported across nearly all participants.

Keywords: *softness, perception, active touch, deep sensation, cutaneous sensation*

1 INTRODUCTION

During the perception of object softness, research indicates that under bare-based active touch conditions, humans perceive softness using both cutaneous sensation and deep sensation, whereas under tool-based active touch conditions, they perceive softness using deep sensation alone (Lamotte & Srinivasan, 1995). Previous studies have shown that cutaneous sensation relies on contact area, while proprioception relies on force and penetration (Metzger et al., 2015; Scilingo et al., 2022; Bicchi A et al., 2000). Numerous existing studies on softness perception (Lamotte et al., 2000; Srinivasan & LaMotte, 1995; Bergmann, Tiest & Kappers, 2009; Xue et al., 2018) have measured one or two of the force, penetration, and contact area, with very few studies measuring all three simultaneously. Li et al. (2020, 2023) revealed that under bare-based passive touch conditions, significant differences between sample pairs emerge in the order of penetration, contact area, and force as the indentation depth increases. However, the relationship between force, penetration, contact area, and softness perception under bare-based active touch conditions remains unclear. During bare-based active touch, although cutaneous

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sensation serves as one of the cues, individuals with stiffer fingers have difficulty distinguishing softness based on contact area (Li et al., 2021), likely relying more on deep sensation. Therefore we hypothesize that participants with stiffer fingers perceive softness in a manner similar to conditions in which only deep sensation is available, even when cutaneous sensation is available. Specifically, we hypothesize that participants with stiffer fingers exhibit similar perceptual responses under both tool-based active touch and bare-based active touch conditions.

2 MATERIALS AND METHODS

Because object rigidity and elasticity influence softness perception (Bergmann, Tiest, & Kappers, 2009), this study utilized nine Tetra-PEG gels with equal rigidity but varying elasticity (32.9–64.6 kPa). Ten students (5 males, 5 females; mean age = 22.9 ± 0.83 years) participated. Their finger elastic moduli, measured following Han and Kawamura (1999), exhibited a bimodal distribution with a clear gap between 40.98 and 50.18 kPa (Table 1). Based on a 50 kPa threshold, four participants (Participants 3, 5, 7, and 9) were categorized into a higher stiffness group for the experiments.

During active touch, compressive force was measured using a semiconductor strain gauge. Penetration (maximum sample displacement) was recorded laterally via a camera (α9 (ILCE-9), Sony Corporation; Figure 1). Contact area was captured by a second camera viewing the finger-sample interface through a 45-degree mirror beneath the force plate; the pressure-darkened region (luminance $\leqslant$ 55 cd/m^2) was modeled as an ellipse to calculate this area.

For the procedure, participants first familiarized themselves with the samples by pressing all nine using tool-based active touch with their dominant index finger. Next, they alternately pressed paired samples five times each and selected the softer one, while force, penetration, and contact area were recorded. In total, 40 randomized trials were conducted (8 pairs of adjacent elastic moduli, tested five times each). This entire procedure was then repeated for bare-based active touch.

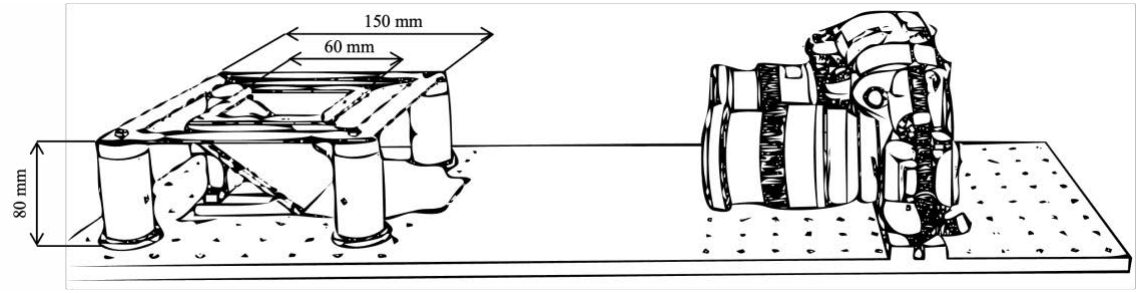


Figure 1. Apparatus for measuring penetration

Table 1. Size and Elastic Modulus of finger

Participant	1	2	3	4	5	6	7	8	9	10
Elastic modulus / kPa	38.82	40.98	62.97	37.57	56.92	38.22	50.18	35.68	68.91	33.19

3 RESULTS AND DISCUSSION

3.1 Result

First, we present the results for tool-based active touch. For each presented sample pair, a paired t-test (one-tailed) was performed by specifying the force and penetration measured when pressing high-modulus samples as the tF1 and tP1 groups, and those for low-modulus samples as the tF2 and tP2 groups. The alternative hypotheses were that the means of the tF1 and tP1 groups were greater than those of the tF2 and tP2 groups. Box-and-whisker plots showing the means, standard deviations (error bars), and t-test results for the tF1 vs. tF2 and tP1 vs. tP2 groups across all participants are presented in Figure 2. Here, * and ** denote significance levels of 0.05 and 0.01, respectively. This clearly shows that no significant difference is observed for force, whereas a significant difference is observed for penetration.

Next, regarding bare-based active touch, corresponding one-tailed t-tests were performed. The force, penetration, and contact area for high-modulus samples were designated as the bF1, bP1, and bC1 groups, and those for low-modulus samples as the bF2, bP2, and bC2 groups. The alternative hypotheses for force and penetration were the same as previously stated, while for contact area, the bC1 mean was hypothesized to be greater than the bC2 mean. Box-and-whisker plots showing the means, standard deviations (error bars), and t-test results for all participants in groups bF1 vs. bF2, bP1 vs. bP2, and bC1 vs. bC2 are presented in Figure 3. Significance levels are indicated as described earlier. Figure 3 reveals that for Participants 3, 5, and 9, no significant difference is observed for force, whereas a significant difference is observed for penetration;

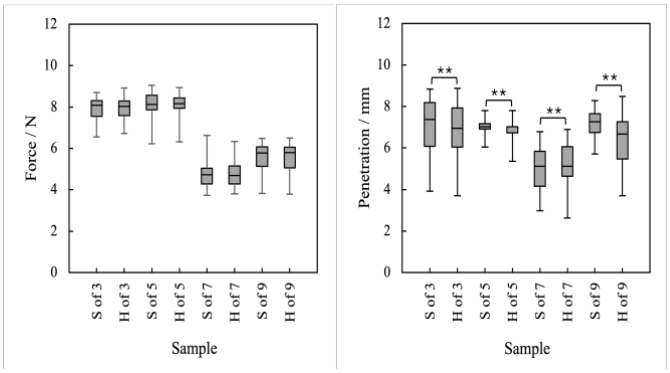


Figure 2. Force results (left) and penetration results (right)

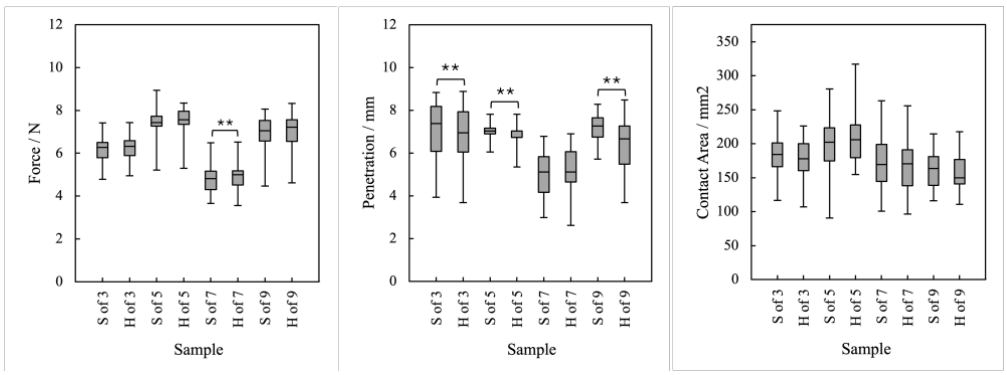


Figure 3. Force results (left), penetration results (center) and contact area results (right)

Participant 7 exhibits the opposite trend. Furthermore, no significant difference in contact area is observed for any participant.

To corroborate these findings, a logistic regression analysis was conducted on the experimental data. The results show that penetration has the largest partial regression coefficient (0.213) and demonstrates a marginally significant trend ($p = 0.083$).

3.2 Discussion

Participants 3, 5 and 9 evaluated the magnitude of penetration differences while maintaining similar compression forces under both conditions, yielding results that support Hypothesis. In contrast, participant 7 evaluated the magnitude of the difference in compression force while maintaining similar penetration, yielding results that do not support Hypothesis. One possible factor contributing to this is that, as revealed in the post-experiment questionnaire, this participant pushed the gel to the point where penetration no longer increased during bare-based active touch, and therefore likely thought they perceived the compression force at that stage. However, due to the limited number of participants in the high stiffness group (N=4), these findings should be considered preliminary observations. Future studies with a larger sample size are necessary to draw robust conclusions and further verify the present hypothesis.

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