The Effect of Vision on the Augmentation of Perceived Stiffness by Adding Artificial Skin Stretch to Kinesthetic Force

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***Abstract* - We investigated how visual displacement feedback affects the augmentation of the perceived stiffness that is caused by adding artificial skin-stretch to force feedback. This experiment was a forced-choice paradigm with four different conditions: force feedback, force feedback with artificial skin-stretch, force and visual feedback, and force and visual feedback with artificial skin-stretch. We found that visual displacement feedback decreases the skin-stretch induced augmentation and improves the accuracy and precision of the perceived stiffness.**

I. Introduction

During everyday interaction with elastic objects, we concurrently control movement and receive dynamics information to formulate perception of mechanical properties, such as in the case of assessing object's stiffness. Since we do not possess stiffness sensors, the perception of stiffness requires high level integration of sensed position and force. Displacement and force are sensed via the skin (tactile modality) and via muscles, tendons, and joints (kinesthetic modality). In addition, visual feedback can be used to assess displacement and force, and may even enhance the accuracy of these estimations. How information from the tactile, kinesthetic, and visual modalities is integrated, especially in face of incongruences between them, to form stiffness estimation, is an open question.

Previous studies [1], [2], using device that augments tactile sensation without affecting the kinesthetic force, showed that adding artificial tactile feedback to force feedback causes an overestimation of the perceived stiffness. However, these studies did not provide participants with visual feedback about object deformation. Here, we aim to understand the influence of visual deformation feedback on the augmentation of perceived stiffness that is caused by adding artificial skin-stretch to force feedback. We hypothesized that adding visual feedback about object deformation will enhance the ability to accurately perceive stiffness, and thus, decreasing the overestimation of the perceived stiffness caused by the artificial skin-stretch. In addition, we expected that with visual feedback, the participants would be more sensitive to small differences between the stiffness levels.

II. Methods

A. Experimental setup

The participants sat in front of a virtual reality system and held a skin-stretch device [2] that was mounted on a PHANTOM® Premium 1.5 haptic device (Geomagic) with the index finger and thumb of their dominant right hand. Two tactors came into contact with the skin of the fingers and moved in the vertical direction to stretch the skin. The participants looked at a semi-silvered mirror showing the projection of an LCD screen placed horizontally above it. An opaque screen was fixed under the mirror to block the view of the hand. The force and the skin-stretch stimulation were proportional to the amount of penetration distance, and were applied along the same direction only after participants were in contact with the object. During the experiment, the participants wore noise cancelling headphones (Bose QC35) to eliminate auditory cues from the motor.

B. Protocol

12 participants conducted in the experiment after signing an informed consent form approved by the Human Subject Research Committee of Ben-Gurion University of the Negev, Be'er Sheva, Israel.

Participants probed pairs of virtual elastic objects, designated *standard* and *comparison*, and indicated which object had a higher level of stiffness. Participants could probe the objects as many times as they desired and switch between them to make their decision. In each trial, we either provided or prevented visual feedback about the object's deformation, and in addition, we manipulated the tactile stimulation on predetermined trials. Thus, we had four conditions that differed in the visual feedback that the participants received and the presence of tactile stimulation: (1) force feedback (F), (2) force feedback with artificial skin-stretch (FS), (3) force and visual feedback (FV), and (4) force and visual feedback with artificial skin-stretch (FVS).

The *standard* object had a constant stiffness value of 85 N/m and the skin-stretch gain was 80 mm/m (only in conditions with skin-stretch stimulation). The *comparison* object stiffness was selected from a range of eight values, evenly spaced between 40-130 N/m. When participants received visual feedback it was veridical with the hand movement and was presented in both the *standard* and *comparison* objects. Each of the 32 different comparison-standard pairs was repeated 10 times throughout the experiment. Each participant therefore performed 360 trials: 40 training trials (to allow participants to become familiarized with the experimental setup), and 320 test trials. The experiment was completed over two days of 180 trials; half the participants completed condition 1 and 2 on the first day,

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while the other half completed conditions 3 and 4 on the first day.

C. Data analysis

For each of the 12 participants, we fitted psychometric curves for the probability of responding that the *comparison* object was stiffer, as a function of the difference between the stiffness levels of the *comparison* and the *standard* objects. We repeated this procedure for the four conditions, and computed the point of subjective equality (PSE) and the just noticeable difference (JND) of each psychometric curve. We then examined the effect of the different conditions on these two values using repeated-measures ANOVA. The independent variables were the four different conditions (fixed categorical, df=3), and the participants (random, df=11). We performed t-tests to compare between the different conditions with the Holm-Bonferroni method to correct for errors stemming from multiple comparisons.

III. Results

The psychometric curves of a typical participant and the averaged PSE and JND values across all the participants as a function of the different conditions are shown in Fig. 1(a), Fig. 1(b), and Fig, 1(c), respectively. In trials without skin-stretch (condition 1 and 3), the PSE (a measure of bias in the perceived stiffness) was close to zero, and the slope of the psychometric curve (as quantified by the JND) was steep. These results indicate that in conditions without tactile stimulus participants could accurately distinguish between the stiffness levels of the two objects.

In conditions with skin-stretch, both the PSE and the JND increased in comparison to the conditions without the stretch stimulus. We observed a significant effect of the condition on the PSE (rm-General Linear Model, main effect of 'condition': $F_{(3,33)} = 8.69, p = 0.0002$). Post-hoc t-tests revealed an increase in the PSE in trials with skin-stretch and without visual feedback (condition 2) relative to the other conditions ($t_{1-2} = 4.36$, $p_{h_{1-2}} = 0.0005$; $t_{2-3} = 4.42$, $p_{h_{2-3}} = 0.0006$; $t_{2-4} = 3.40$, $p_{h_{2-4}} = 0.0071$). That is, when the visual feedback was not presented, skin-stretch augmented the perceived stiffness [1], [2], but the presence of visual feedback decreased this perceptual augmentation.

Fig. 1(c) shows that in condition 4 relative to conditions 2, the participants were more accurate in distinguishing the stiffness of two objects. However, we found no statistically difference between the JND values for the different conditions (rm-General Linear Model, main effect of 'variability': $F_{(3,33)} = 2.35, p = 0.0902$).

IV. Discussion

In this study, we examined the effect of visual feedback on the perceptual augmentation caused by adding artificial skin-stretch to force feedback. Our results indicate that visual feedback improves the ability of the participants to accurately perceive stiffness by reducing this skin-stretch augmentation. Additionally, we observed a relative decrease in the JND in conditions with visual feedback. This decrease was not statistically significant and requires further investigation,

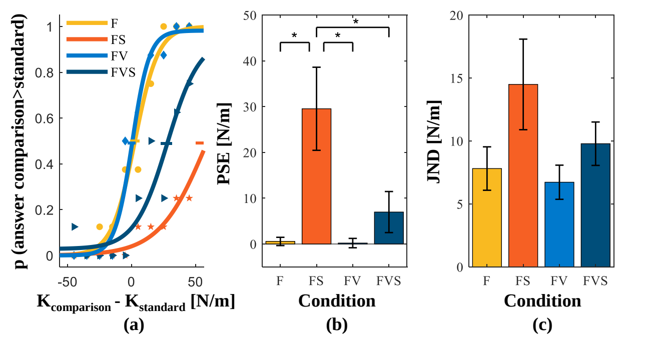

Figure 1. (a) An example of the psychometric curves of a typical participant for the different conditions. The averaged (b) PSE and (c) JND values across all the participants, as a function of the different conditions. The black bars represent the mean confidence intervals, and the asterisks indicate a statistically significant difference (p<0.05).

however, does indicate that the addition of visual feedback to skin-stretch stimulus during interactions with elastic objects enhances the discrimination accuracy.

Previous studies [1], [2] showed that skin-stretch caused an overestimation in the perceived stiffness. In [2] participants received no visual feedback, whereas in [1] partial visual feedback was provided. This might explain why larger inter-subject variability was observed in [1], supporting our claim that visual feedback may affect the perceptual illusion. Wu et al. [3] found that adding visual displacement information to haptic information enhanced the ability to accurately perceive stiffness. In contrast with our result, Varadharajan et al [4] found no significant contribution of vision to the PSE during interaction with haptic-visual conditions.

The visual feedback is speculated to be a more reliable source of information, which lowers the variability of the stiffness estimations, and therefore leads to smaller JND values [5]. Varadharajan et al [4] showed that stiffness discrimination performance is improved by adding visual rendering of the interaction. In our future work we will use these results to introduce noise into the visual information to study the integration between the visual feedback and the two haptic modalities. Understanding their integration can lead to improvements in human-robot interaction applications by providing users with a sense of touch that is tailored to their natural information processing strategies.

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