A change in the fingertip contact area induces an illusory displacement of the finger

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Abstract. Imagine you are pushing your finger against a compliant object. The change in the area of contact can provide an estimate of the relative displacement of the finger, such that the larger is the area of contact, the larger is the displacement. Does the human haptic system use this as a cue for estimating the displacement of the finger with respect to the external object? Here we conducted a psychophysical experiment to test this hypothesis. Participants compared the passive displacement of the index finger between a reference and a comparison stimulus. The compliance of the contacted object changed between the two stimuli, thus producing a different area-displacement relationship. In accordance with the hypothesis, the modulation of the area-displacement relationship produced a bias in the perceived displacement of the finger.

Keywords: Area of Contact, Proprioception, Finger Displacement

1 Introduction

Imagine you are pushing your finger against a compliant object, such as the sponge in Figure 1a. Due to the deformation of the object and the skin, the area of contact (A) between them increases as the finger keeps pushing toward the center of the object, until it reaches a plateau. The change in the area of contact can provide an estimate of the *relative* displacement of the finger (Δx) among two instances t_1 and t_2, such that if $A_1 > A_2$, then $x_1 > x_2$. The area of contact would also provide an estimate of the *absolute* finger position x (i.e., an estimate in units of lengths), if the perceptual system can internalize

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[⋆] These authors contributed equally to this work the relationship between A and other intrinsically absolute cues, such as the proprioceptive-based estimate $\tilde{x}_p$:

$$\tilde{x}_p = f(A)$$

Where $f(\cdot)$ is the relationship between the two cues, and $\tilde{x}_p$ provides an absolute estimate of x. To clarify the issue, the change in the contact area in haptics can be considered as an analog of the perspective cue in visual depth perception. The perspective cue is a relative depth cue, since it provides the observer with the depth relationships, and not with an absolute estimate (in units of lengths) of the distance with the object. In order to estimate the absolute depth, the perceptual system needs a scaling factor (e.g. from accomodation) to promote the relative depth cue into an absolute depth cue. This mechanism is known as *cue promotion* [1]. Whether relative or absolute, the evolution of the area of contact would provide a fair estimate of the displacement only assuming that the compliance of the object does not change over time. This leads to our experimental questions:

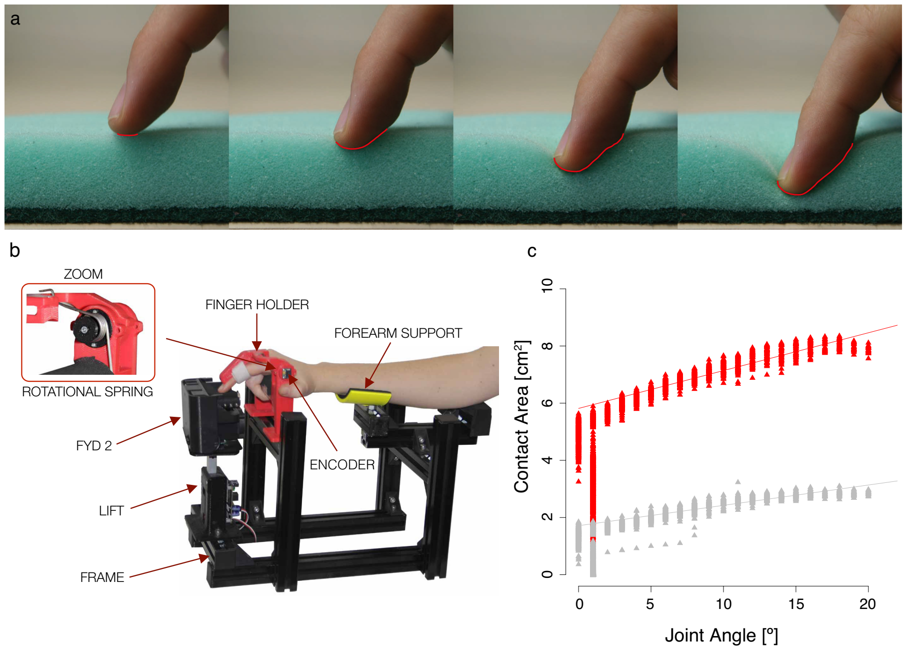

Fig. 1. (a)The area of contact between the skin and the sponge (marked in red in the figure) increases as the finger moves towards the bottom edge of the object. (b)The setup including the lift, the FYD-2 device and the angle encoder. (c) The area of contact changes as a function of the displacement of the finger and of the stretching state of the fabric, i.e. the rotation angle of the FYD-2 motors (in red $\theta = 10°$ and in grey $\theta = 80°$; results from a representative participant).

Does the human haptic system use the change in the area of contact as a cue for estimating the displacement of the finger with respect to an external object?

The deformation of the contact surface and the ratio between the applied force and the displacement of the finger are the two major cues to discriminate the compliance of an object [2, 3]. The tactile cue is responsible for a large part of this perceptual acuity; under the assumption of optimal combination of the two cues, nearly 90% of the information depends on the local surface deformation [3]. The spread of the contact area conveys important information about the deformation of a compliant surface. There is a strong empirical evidence that the central nervous system decodes the contact area information [4]. Accordingly, artificially modifying the relationship between the contact force and the overall contact area is sufficient to elicit the sensation of compliance of an object. Bicchi and colleagues called this force-area relationship the Contact Area Spread Rate (CASR) [2, 5].

In the studies cited above, the compliance is the unknown quantity varying between different stimuli. However, in our daily experience we can reliably assume that the compliance of a given object will remain nearly constant over time. Reasoning along this line, when the compliance of the contacted object unexpectedly changes, the perceptual system could misestimate the indentation of the finger into the object — and therefore, misestimate the position of the finger. Here we conducted a psychophysical experiment to test this hypothesis. Participants compared the passive displacement of the index finger between a reference and a comparison stimulus. The compliance of the contacted object changed unexpectedly between the two stimuli, thus producing a different area-displacement relationship (i.e., a different indentation of the finger into the object). If participants rely on the the cutaneous cue $f(A)$, this would induce a bias in the perceived finger displacement, such that the wider would be the contact area, the larger the perceived displacement.

2 Methods

2.1 Participants

Six healthy volunteers participated to the experiment (2 Females and 4 Males, Age: 26 ± 4, $mean \pm SD$). All participants were naïv̈e to the purpose of the experiment and they gave informed consent prior to participating. The experiment was approved by the Ethical Committee of the Universitá di Pisa.

2.2 Apparatus

The apparatus (Figure 1b) simulates the interaction between the fingertip and a compliant object. It consists of three components: The *FYD-2 device* [6], a *vertically-moving platform* and a *hand-and-finger holder*.

The FYD-2 mimics the compliance of the surface by changing the stretching state of an elastic fabric in contact with the fingertip. The extremities of the fabric are connected to two rollers, which are rotated independently by two motors. Rotating the motors in opposite directions, it produces a stretching of the fabric, and thus increases its stiffness [6]. The contact area, the normal force, and the indentation of the finger were recorded.

As showed in Figure 1b, the FYD-2 is placed on a platform, which is moved upward and downward with constant velocity of 10 mm/s using a linear actuator (Firgelli L16, Victoria, BC Canada). The fingerpad of the user is placed in a finger-holder, which restricts the movements to the flexo-extension of the metacarpo-phalangeal (MCP) joint. An absolute magnetic encoders (12 bit magnetic encoder by Austria Microsystems - Unterpremstaetten, Austria - AS5045 with a resolution of 0.0875 degree) placed on the finger-holder is used to read the extension of the MCP joint. During the lifting phase, the FYD-2 contacts the fingerpad of the user. When the MCP angle reaches the desired value, the linear actuator stops to lift up the FYD-2 and hence the finger, and it starts to move down, while MCP joint angle begins to decrease, i.e. to flex. Both the signal reading and control phases were performed using a custom made electronic board (PSoC-based electronic board with RS485 communication protocol).

A rotational spring (elastic constant of 5 N/deg; see zoom of Figure 1b) is used to connect the finger-holder and the frame of the structure. In this manner, the force that the finger produces over the FYD-2 surface increases linearly with the MCP joint angle thus producing an increase in the contact area (Figure 1c). Note that, without this spring, the contact area would increase only at the very beginning of the lift movement and immediately saturate as soon as the reaction force of the fabric deformed by the finger would reach an equilibrium with the weight of the finger. The area-angle relationship changes with the stretching state of the fabric of the FYD-2, which depends on the angular position of the two motors θ.The larger is the value of θ, the stiffer is the fabric.

2.3 Stimulus and Procedure

Participants were blindfolded and sat on an office chair, placing the right arm on an arm rest in front of the device. Headphones playing pink noise prevented the noise generated by the device to be used as a cue. In a *forced-choice procedure*, participants performed a finger-displacement discrimination task. The device displaced the finger up-and-down twice, in subsequent intervals corresponding to the reference and comparison stimulus. The rotation of the finger joint was equal to 12° in the reference stimulus. It was chosen pseudo-randomly between 5 possible values (range: $4^\circ - 20^\circ$) in the comparison. The order of presentation of the reference and the comparison varied in a pseudo-random fashion between trials. After the presentation of the stimuli, participants reported in which of the two intervals the displacement of the finger was larger. Participants received no information about the compliance of the contacted object.

The position of the rollers θ was always equal to 50° in the reference stimulus — this value is approximately in the middle of the compliance range that the device is capable to mimic. In the comparison stimulus, the device simulated an object that was either more ($\theta = 10^\circ$) or less ($\theta = 80^\circ$) compliant than the reference. The participants were not aware that the compliance of the object changed between different stimuli. The two compliance conditions were tested in two different blocks; each one consisting of 100 trials. The order of the two blocks was counterbalanced among participants.

2.4 Analysis

We modeled the responses of each participant using psychometric functions. We applied the following model, separately in the two experimental conditions:

$$\Phi^{-1}\left[P(Y_j = 1)\right] = \beta_0 + \beta_1 x \tag{1}$$

In a given trial j, $Y_j = 1$ if the participant reports that the displacement was larger in the comparison than in the reference and $Y_j = 0$ otherwise. $P(Y_j = 1)$ is the probability of perceiving a larger displacement in the comparison and Φ^{-1} is the *probit* transform of this probability. On the right side of the equation, x is the physical displacement of the finger in the comparison stimulus. β_0 and β_1 are the intercept and the slope of the linearized equation, respectively. The *point of subjective equality* ($PSE = -\beta_0/\beta_1$) is an estimate for the accuracy of the percept. Next, we extended the analysis to the whole population (n = 6) by means of a *generalized linear mixed model* (GLMM; see [7, 8]). The GLMM is similar to the psychometric function, with the advantage of allowing the analysis of clustered data—as in our case the collection of repeated responses in several participants. As described in [7] we estimated the PSE and the 95% confidence interval in the two experimental conditions. If the difference in the *spread of the contact area* would affect the perceived displacement of the finger, then the PSE would be significantly different between the two compliance conditions. In particular, we expected that a simulated softer object (i.e. $\theta = 10°$) would increase the perceived finger displacement compared to the reference stimulus. This would predict that $PSE_{\theta 10} < 12°$ (the PSE would be smaller than the finger displacement of the reference stimulus). Similarly we expect that $PSE_{\theta 80} > 12°$.

3 Results

Figure 2 shows the perceived finger displacement in a representative participant, for the stretching state of the comparison $\theta = 10°$ (in red) and $\theta = 80°$ (in grey). The PSE is significantly different in the two experimental conditions ($PSE_{\theta 10} = 9.7 \pm 0.5, PSE_{\theta 80} = 12.8 \pm 0.6; Estimate \pm SE$). Note that, in accordance with our predictions for a mimicked soft object ($\theta = 10°$) the estimated PSE is smaller than the reference finger displacement. *Vice versa*, for $\theta = 80°$ the PSE was larger than the reference. We extended the analysis to the whole population (n = 6) with the GLMM. The analysis confirmed the same response pattern as in the representative participant. The estimated PSE is equal to 10.5 for $\theta = 10°$ (95% $CI : 9.9 - 11.1$), and 12.8 for $\theta = 80°$ (95% $CI : 12.1 - 13.6$). The 95% $confidence\ intervals$ are not overlapping between the two experimental conditions and significantly different from the value of the reference displacement.

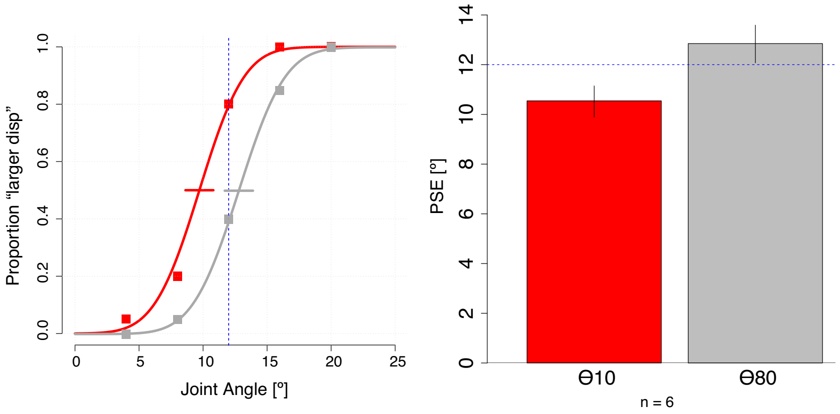

Fig. 2. (a) The psychometric functions for a representative participant, in the two experimental conditions (red: $\theta = 10$; gray: $\theta = 80$). The reference finger displacement (12°) is indicated with a dashed blue line. (b) The *point-of-subjective-equality* (PSE) in the two experimental conditions (n = 6).

4 Model

In this study we showed that a modulation of the spread of the contact area produces a bias in the perceived displacement of the finger. The result is consistent with a weighted sum of the tactile and proprioceptive cues. That is, we assume a linear relationship between the contact area A and the finger angular displacement x.

$$A = k(x - \bar{x}) + \bar{A},$$

where $\bar{x} = 12^\circ$ is the reference displacement used in the current study. The parameters k and $\bar{A}$ depend on the stiffness of the display (angle θ) and on the finger properties of the individual subjects. The average values of these parameters and their standard deviations were computed across subjects from the experimental data

$$\begin{array}{llll} \bar{A}_{10^\circ} = 4.8 \pm 0.8 & \bar{A}_{50^\circ} = 2.8 \pm 1.0 & \bar{A}_{80^\circ} = 2.2 \pm 0.9 & (\mathrm{mm}^2) \\ k_{10^\circ} = 0.16 \pm 0.05 & k_{50^\circ} = 0.10 \pm 0.03 & k_{80^\circ} = 0.09 \pm 0.02 & (\mathrm{mm}^2/^\circ) \end{array} \quad (2)$$

Then the unimodal, cutaneous-based estimate of the displacement is:

$$x_A = \frac{1}{k_\theta}(A - \bar{A}_\theta) + \bar{x},$$

and the perceived finger movement is:

$$\tilde{x} = W_A[(A - A_\theta)/k_\theta] + W_x x,$$

where A_θ, k_θ are the priors on the parameters of interaction with the surface and W_A, W_x are the tactile and proprioceptive weight terms, respectively.

The cutaneous-based estimate x_A would introduce a bias, if the participant would assume *a priori* that the two coefficients A_θ, k_θ were the same among different stimuli. For the parameters $\Theta = 10°, 50°, 80°$ of the device (position of the FYD-2 motors) and the actual finger position x_Θ, the perceived finger position $\tilde{x}_\Theta$ is:

$$\tilde{x}_\Theta = W_A \frac{1}{k_\theta} \left[k_\Theta (x_\Theta - \bar{x}) + A_\Theta - A_\theta \right] + W_x x_\Theta .$$

where $x_{10°}$ and $x_{80°}$ are the actual positions of the fingers in each condition.

The perceptual bias can be estimated by determining the actual displacements $x_{10°}$ and $x_{80°}$ resulting in the same perceptual values as the reference, i.e.

$$\tilde{x}_{10°} = \tilde{x}_{50°}, \qquad \tilde{x}_{80°} = \tilde{x}_{50°}.$$

These equations can be easily solved if the coefficients k_Θ are the same for all Θ. Indeed, as it can be seen from Equation 2, the range of their values is much narrower that that of the parameters $\bar{A}_\Theta$. We thus make a simplifying assumption that $k_\Theta = k_\theta = 0.1$ mm^2/degree. Then,

$$\begin{aligned} x_{50°} - x_{10°} &= W_A / k_\theta [\bar{A}_{10°} - \bar{A}_{50°}], \\ x_{50°} - x_{80°} &= W_A / k_\theta [\bar{A}_{80°} - \bar{A}_{50°}]. \end{aligned}$$

From these equations immediately follows the prediction on the sign of the bias: positive for $\Theta = 10°$ (since $\bar{A}_{10°} > \bar{A}_{50°}$) and negative for $\Theta = 80°$ (since $\bar{A}_{80°} > \bar{A}_{50°}$), in accordance with the empirical data. Moreover, the model predicts the magnitudes of the bias to be proportional to $\left|\bar{A}_{10°} - \bar{A}_{50°}\right|$ and $\left|\bar{A}_{80°} - \bar{A}_{50°}\right|$, respectively. For the estimated values of parameters, the model predicts the magnitude of the bias for $\Theta = 10°$ to be approximately 3.9 times greater than for $\Theta = 80°$. In the experimental measurements the bias magnitudes differ by the factor of 1.9. The weight W_A can be estimated from the bias magnitudes. It equals to 0.07 when computed using the bias for $\Theta = 10°$ and 0.15 for $\Theta = 80°$, respectively.

5 Conclusion

In this study, we showed that a modulation of the spread of the contact area produces a bias in the perceived displacement of the finger. In our setup, the normal force did not vary with the compliance of the surface, that is, it was the same between the two experimental conditions. Due to the change in the contact area, it follows that the normal pressure was different between conditions. However, it is unlikely that this produced the effect, since the tactile system is not sensitive to pressure [9].

The model relies on the assumption that the compliance of a contacted objects is roughly constant over time. For most of the daily-life objects, the change in compliance due, for example, to the viscoelastic properties of the surface is negligible, at least in a short time window (see for examples silicons characterized in [10]). The study further reinforces the possibility that cutaneous cues contribute to proprioception. In [11], the participants accurately reported the relative displacement between the finger and a surface in an horizontal plane. The present new findings complement the previous study along the third, vertical dimension. These findings may provide guidelines to reduce the working space in haptic device, substituting partially the kinesthetic with tactile cues.

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