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# Perceived compliance in a pinch

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ABSTRACT

Handling a compliant object using a pinch grasp provides sensory information about deformation and resistive force from both index finger and thumb. In this paper, an object with rigid surfaces and composed of two compliant materials fixed on a central position is used to address how information from the two fingers is integrated into a holistic percept of compliance. Results indicate that with small differences in material compliance there is a small tendency to rely more on the information at the index finger. With larger differences in material compliance participants adopt different movement patterns with the two fingers to explore the objects. Compliance judgments depend on the relative amount of motion and force exerted—the finger that presses more contributes more to the final estimate. This tendency is consistent with the utilization of a unique force signal for the two fingers. The uneven contribution of the sensory information in the pinch leads to predictable compliance discrimination performance from the performance obtained using the fingers independently.

## 1. Introduction

Humans can obtain information about many properties of objects through haptic interaction: shape, weight, mass distribution, surface characteristics, and material composition. Different postures and movements can be used to better acquire information about one or more of these properties (Lederman & Klatzky, 1996). It is possible to acquire sensory information even while handling objects. Here it will be investigated how material properties are perceived when the object is held between two fingers using a pinch grasp and the object is stationary, it cannot move with respect to the hand. This type of grasp is obtained by opposing index finger and thumb and by applying a force to squeeze the object. Analyzing the pinch grasp of stationary objects provides a relatively simple approach to understanding how information about force and position from the two fingers is combined to obtain a percept of the material properties. This type of interaction resembles some forms of interaction with everyday objects. Think of choosing a ripe fruit from a vendor stand. To do this, one would gently squeeze each fruit in the box until finding the one with the right firmness. The material properties of the fruits, however, are not uniform throughout. Some fruits might have a rotten part, for example. Combining information from the two fingers in this case might not be straightforward, as we will see below. For the purpose of this paper, such objects where the material in contact to the two fingers has different properties are defined to be "composite" in contrast with "uniform" objects, which are instead made of one material throughout.

When manipulating objects with deformable surfaces like a ripe fruit, tactile information provides sensory signals related to material properties even when considered alone (Srinivasan & LaMotte, 1995). Such information can be combined with sensed force and position signals into a unified more reliable percept of the material (Bergmann Tiest & Kappers, 2009; Scilingo, Bianchi, Grioli, & Bicchi, 2010). When manipulating objects with rigid surfaces, instead, the contribution of tactile information for the perception of the deformation is limited to providing force-related signals (i.e. Srinivasan & LaMotte, 1995). A spring cell is the most extreme example of a non-rigid object with rigid surfaces used in scientific experiments. Stiffness, or its inverse compliance, is defined as the change in the amount of deformation of the object's surface $dx$ divided by the change in force applied to the object $dF$. For material with linear characteristics, such as linear springs, it is possible to use the changes with respect to the unperturbed object, $x$ and $F$, so that compliance $c$ is defined as

$$c = x/F. \tag{1}$$

For objects with rigid surfaces, perception of compliance (also referred to as softness perception, i.e. Bergmann Tiest & Kappers, 2009) must be based on these two sources of information alone—position and force. We commonly manipulate objects that exhibit some amount of compliance but have rigid surfaces (think of push buttons, which are nowadays very common in electronics products). The situation analyzed here is however not the most frequently encountered in everyday activities as it involves constrained objects with rigid surfaces squeezed using two fingers.

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The action performed can be compared to the use of quick-release buckles that have two side-release tabs pressed using the index finger and thumb contemporarily. The analysis of such particular interaction is motivated to try expanding the study of softness perception beyond the use of one contact point (Di Luca, Knörlein, Ernst, & Harders, in press; Friedman, Hester, Green, & LaMotte, 2008; Jones & Hunter, 1990; Srinivasan & LaMotte, 1995). Work that has employed interactions with more than one contact point, as it happens in cases where an object is held with fingers of the two hands (Chen & Srinivasan, 1998) or grasped with a precision grip (i.e. Freyberger & Färber, 2006; Kuschel, Di Luca, Buss, & Klatzky, 2010; Roland & Ladegaard-Pedersen, 1977; Tan, Durlach, Beauregard, & Srinivasan, 1995), did not identify the relative contribution of the information available at each finger. In the case of a composite object having rigid surfaces and with material compliances $c_1$ and $c_{2,}$ the equivalent compliance $c_e$ is defined as the compliance of a uniform object that matches the values of force $F$ and deformation $x$ (which is the sum of $x_1$ and $x_2$, the deformation on either side). The equivalent compliance value is

$$C_e = x/F = x_1/F + x_2/F = c_1 + c_2. \tag{2}$$

Notice that in this formulation there is the assumption that the force at the two sides of the object is equal. Indeed there is a close coupling of the forces generated by a horizontal pinch grasp (Moerchen, Lazarus, & Gruben, 2007). But with an object that is not free to move this coupling diminishes significantly especially with low level of force or large grip apertures (Sharp & Newell, 2000). Moreover, despite interdependencies between fingers (Schieber, 1996), it is possible to generate independent finger movements (i.e., Smeets & Brenner, 2001) and participants differ in the movement they perform. For example, the data of Matsuoka, Brewer, and Klatzky (2007) indicate that the pinching movement pattern that participants usually perform is not symmetric between index finger and thumb and this asymmetry varies across participants. If an asymmetric pinch grasp movement is used to assess compliance of a stationary and composite object, the fingers will collect different information about the force in addition to the deformation. The definition of equivalent compliance $c_e$ should be modified from Eq. (2) as such:

$$C_e = c_1 + c_2 = x_1/F_1 + x_2/F_2. \tag{3}$$

The question is whether humans are able to correctly estimate forces and position at the two sides of the object to judge overall compliance. Informal observations with real composite objects seem to indicate that compliance is not perceived consistently for a single object if the object is grasped in different ways. The measurement of such perceptual distortion could be informative about how the brain processes sensory information. In the present paper, a setup is employed that allows the presentation of virtual composite objects, with two simulated materials in accordance with Eq. (1). The objects are fixed at the center and participants squeeze them with a pinch grasp with the index finger above the thumb. The task is to compare the compliance of two successively presented objects.

In Experiment 1 the difference in compliance is kept to a minimum so that it is not noticed (as determined in a pilot experiment). In order to compare integration of information from different fingers with small and large differences in compliance, in Experiment 2 composite objects with larger compliance difference are employed. Participant's finger movements are also recorded and related to the PSE. Finally, to determine how effectively information from the two fingers is integrated, in Experiment 3 discrimination performance is compared when participants use each of the two fingers alone and when they use the pinch grasp.

## 2. Method

Participants were naïve as to the purpose of the study and took part in only one of the experiments. Ten participants took part in Experiment 1, 12 in Experiment 2, and 7 in Experiment 3. They were all right handed, reported not to have a history of sensory-motor disorders, had normal or corrected-to-normal vision (Snellen-equivalent of 20/25 or better), and had normal stereopsis of 60 arcsec or better (Stereotest circles; Stereo Optical, Chicago). They were recruited from the MPI Tübingen Subject Database and in return for their participation they received payment of 8 €/h.

Experiments were undertaken with the understanding and consent of each participant, with the approval of the Ethik-Kommission der Medizinischen Fakultät und am Universitätsklinikum Tübingen, and in compliance with national legislation and the Code of Ethical Principles for Medical Research Involving Human Subjects of the World Medical Association (Declaration of Helsinki).

### 2.1. Stimuli

Participants viewed a virtual scene presented on a GDM-F500R Sony CRT monitor, 38.2 × 29.8 cm, refresh rate of 120 Hz. The monitor was reflected on a first-surface mirror and through CrystalEyes shutter glasses (StereoGraphics) as shown in Fig. 1. Total viewing distance was 60 cm and forehead and chin rests limited head movements. The virtual scene comprised a stereoscopic rendering of a cylindrical surface on a flat background (4 cm diameter, 10 cm tall). The cylindrical surface was presented with the main axis orthogonal to the line of sight (with a 45° angle away from the vertical). Participants also saw two spheres co-located with the fingertips of their index finger and thumb (2 cm diameter).

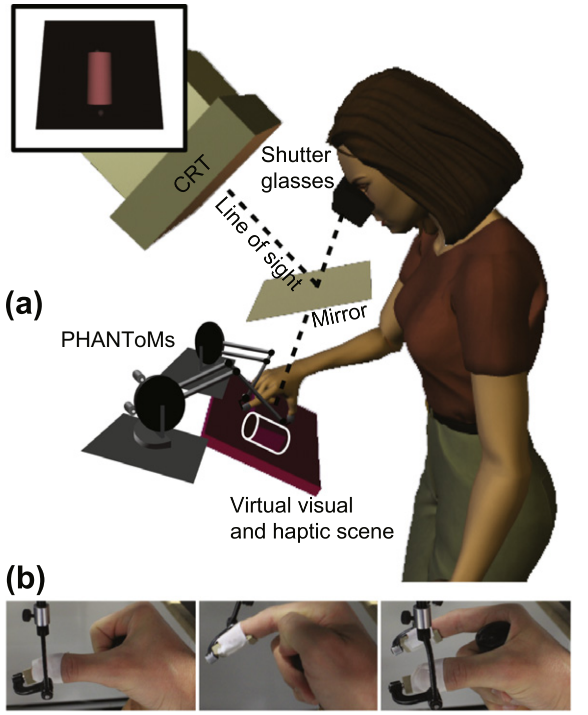

**Fig. 1.** (a) Apparatus employed for the presentation of the stimuli. Participants saw two spheres co-located with their fingers and a cylinder lying on a frontoparallel background rectangle (insert shows the monitor's image). They judged compliance by pressing their fingers from the top and bottom of an object hidden in a hollow cylinder. Force was applied to the participants' fingers only when the spheres were fully occluded by the cylindrical surface. (b) Fingers position on the handle employed in the three conditions of Experiment 3.

The haptic stimulus was generated using two PHANToM Premium 1.5 force-feedback devices (Sensable), one for the index finger and one for the thumb as shown in Fig. 1a. The remaining fingers were kept flexed. Medical tape was used to fix the fingers to the thimbles attached to the end of each PHANToM arm. The haptic stimulus was an 8 cm tall object with parallel flat surfaces lying on a stiff background. Average compliance across the simulated objects in the experiments was 1.0 cm/N (see Tables 1 and 2 for individual values).

### 2.2. Procedure

Participants were asked to report which of two objects inside the cylinder was perceived harder (two interval forced-choice task). In order to do so, participants squeezed the object with a vertical pinch grasp so that the index finger produced a downward force and the thumb an upward force. The visual rendering of the cylinder remained unchanged while subjects squeezed and the placeholders disappeared behind the cylinder surface. Since the base of the cylinder was not visible (the main axis of the cylinder was frontoparallel), participants perceived the cylinder as a container of a smaller compressible object that they squeezed. During the 2 s from the first contact with the cylinder, participants could squeeze multiple times. Then, a change in color indicated that it was time to release. Once the fingers were outside the cylinder, or after 3 s, the cylinder disappeared. The second cylinder appeared after a 1 s pause. Following the exploration of the second cylinder, two virtual buttons were presented saying “First harder” and “Second harder” to let the participant decide which of the two objects felt overall harder.

In Experiments 1 and 2 participants performed the same type of exploration using the pinch grasp. Experiment 3 comprised instead three blocked conditions where the participant either used the index finger, or the thumb, or both fingers using the pinch grasp. To increase comfort, facilitate movements with one finger, and make the movement comparable in the three exploration conditions, participants were required to grasp a handle with the remaining fingers on the hand (see Fig. 1b).

The method of constant stimuli was used. In each trial, one of the composite standard and one of the uniform comparison stimuli was randomly chosen. Each pair was presented an equal number of times across trials. In Experiment 1 and 2 there were 7 conditions randomly interleaved (see Table 1) and paired with 7 uniform comparison stimuli (see Table 2). In Experiment 3 there were 9 conditions blocked in 6 sessions which were presented in randomized counterbalanced order: 3 standards with index finger interaction, 3 standards with thumb interaction, and 3 standards with pinch grasp. The 3 standards in each block were randomly paired with 6 comparisons. Each pair of standard and comparison was repeated 6 times in Experiment 1, 10 times in Experiment 2, and 20 times in Experiment 3. Participants’ responses were fitted with a cumulative Gaussian using psignifit (Wichmann & Hill, 2001). Given the small number of repetitions, in Experiments 1 and 2 we computed only the Point of Subjective Equality (PSE). The data collected in Experiment 3 was used to estimate the Just Noticeable Difference (JND) corresponding to the compliance leading to 75% responses. These values were in turn used to calculate Weber fractions $W$ according to $W = \mathrm{JND}/c$, where $c$ indicates the simulated compliance of the standard (equivalent compliance according to Eq. (3) was used for composite standards).

**Table 2**
Equivalent compliance of the comparison stimuli (uniform objects) [cm/N].

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Experiment 1 | 0.864 | 0.905 | 0.950 | 1.000 | 1.055 | 1.117 | 1.187 |
| Experiment 2 | 0.679 | 0.731 | 0.792 | 1.000 | 1.356 | 1.581 | 1.896 |
| Experiment 3 | 0.731 | 0.864 | 0.950 | 1.055 | 1.187 | 1.581 | |

Before the beginning of the experiment, participants performed a training session by making 60 discriminations of uniform objects with the same range of compliances presented during the experiment. Participants received feedback about the correctness of their answers. No feedback was given during the rest of the experiment. In Experiment 3 the training was done in each of the three finger configurations.

## 3. Results

Results of Experiment 1 are shown in Fig. 2 in terms of difference between PSE and equivalent compliance $c_e$ of the composite object. The deviation between perceived and equivalent compliance changes depending on the condition (one-way Repeated Measures (RM) ANOVA on the difference PSE-$c_e$: $F(6, 54) = 2.7$, $p = 0.022$). In particular, the PSE with composite objects changes depending on orientation (two-way RM ANOVA on the PSE with

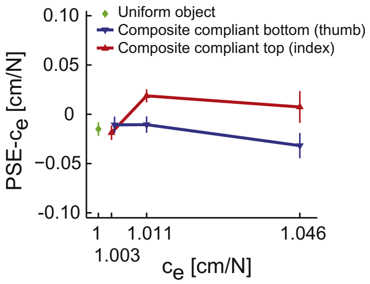

**Fig. 2.** Results obtained in Experiment 1 in terms of the difference between the point of subjective equality (PSE) and the equivalent compliance as a function of the equivalent compliance of the composite object. Error bars represent one standard error of the mean across participants.

**Table 1**
Compliance of the standard stimuli (composite and uniform objects) [cm/N].

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Experiment 1 | Up (index) | 0.632 | 0.559 | 0.528 | 0.500 | 0.475 | 0.452 | 0.413 |
| | Down (thumb) | 0.413 | 0.452 | 0.475 | 0.500 | 0.528 | 0.559 | 0.632 |
| | Difference | 0.219 | 0.107 | 0.053 | 0.000 | 0.053 | 0.107 | 0.219 |
| | Equivalent compliance | 1.046 | 1.011 | 1.003 | 1.000 | 1.003 | 1.011 | 1.046 |
| Experiment 2 | Up (index) | 0.948 | 0.791 | 0.678 | 0.500 | 0.396 | 0.366 | 0.340 |
| | Down (thumb) | 0.340 | 0.366 | 0.396 | 0.500 | 0.678 | 0.791 | 0.948 |
| | Difference | 0.602 | 0.425 | 0.282 | 0.000 | 0.282 | 0.425 | 0.602 |
| | Equivalent compliance | 1.287 | 1.156 | 1.074 | 1.000 | 1.074 | 1.156 | 1.287 |
| Experiment 3 | One finger/Up (index) | | | 0.633 | | 0.500 | | 0.413 |
| | Down (thumb) | | | 0.413 | | 0.500 | | 0.633 |
| | Difference | | | 0.220 | | 0.000 | | 0.220 |
| | Equivalent compliance | | | 1.046 | | 1.000 | | 1.046 |

factors object orientation vs. difference magnitude: orientation $F(2, 18) = 3.9$, $p = 0.039$; difference magnitude $F(1, 9) = 3.3$, $p = 0.10$; interaction $F(2, 18) = 2.1$, $p = 0.15$) such that the composite object appears harder when the stiff end is at the top (index finger) than when it is at the bottom (thumb), particularly for the composite object with intermediate difference in compliance (paired-sample *t*-test on the PSE for the three differences in compliance: $t(9) = 0.3$, $p = 0.8$; $t(9) = 3.6$, $p = 0.0098$; $t(9) = 1.8$, $p = 0.11$).

For Experiment 2, which employed composite objects with much larger differences in compliance, the pattern of results (Fig. 3a) differs from Experiment 1. No consistent difference in PSE from equivalent compliance is found (two-way RM ANOVA on PSE-$c_e$: $F(2, 18) = 0.5$, $p = 0.6$; $F(1, 9) = 0.2$, $p = 0.6$; $F(2, 18) = 0.6$, $p = 0.6$). The lack of a deviation could either indicate that each participant adopted a different strategy or that there is no significant difference in the utilization of information between the two fingers with large difference in compliance. In order to separate these two alternatives, the movement performed while exploring the objects is analyzed by determining the difference in the maximum indentation and maximum force of the two fingers. The individual value of the difference in indentation and force are correlated with the deviation of the PSE from equivalent compliance as shown in Fig. 3b and c. The pattern indicates that there is a tendency across participants to perceive the object to be softer when the finger towards the compliant side moves more than the finger towards the stiff side ($r^2 = 0.62$, $p < 0.001$). Moreover, participants report softer composite objects when the more compliant side is directed towards the finger that applies more force ($r^2 = 0.77$, $p < 0.001$).

These results indicate that participants move and use differently the information derived from the two fingers performing a pinch grasp. What is still to be determined is the performance in the judgment of compliance—the ability to discriminate the compliance of a composite object. For this, Experiment 3 tests discrimination performance with pinch grasp and with each finger alone on the same objects. Here, the Weber fractions change depending on the condition (one-way RM ANOVA: $F(8, 48) = 6.2$, $p < 0.001$). To analyze this factor, one- and two-finger interactions are considered separately. For one-finger interactions, Weber fractions indicate that there is no difference in sensitivity for the two fingers ($F(1, 6) = 0.3$, $p = 0.56$), for different simulated compliance ($F(2, 12) = 2.3$, $p = 0.14$), and no interaction between the two terms ($F(2, 12) = 3.5$, $p = 0.064$). The values of the Weber fraction with the pinch grasp are also equal for the three objects (one-way RM ANOVA on Weber fraction $F(6, 2) = 0.7$, $p = 0.50$). From the value of sensitivity obtained by each participant in the one-finger condition it is possible to calculate what the value would be for the pinch grasp conditions if all sensory signals were independent. The testing conditions, especially the use of the handle introduced in Experiment 3, are favorable to make sensory signals independent for the two fingers and thus statistically-optimal performance can be calculated as such (see Ernst, 2006; Ernst & Banks, 2002; Knill, Kersten, & Yuille, 1996):

$$W^2_{\text{predicted}} = \frac{W^2_{\text{thumb}} \cdot W^2_{\text{index}}}{W^2_{\text{thumb}} + W^2_{\text{index}}}.$$

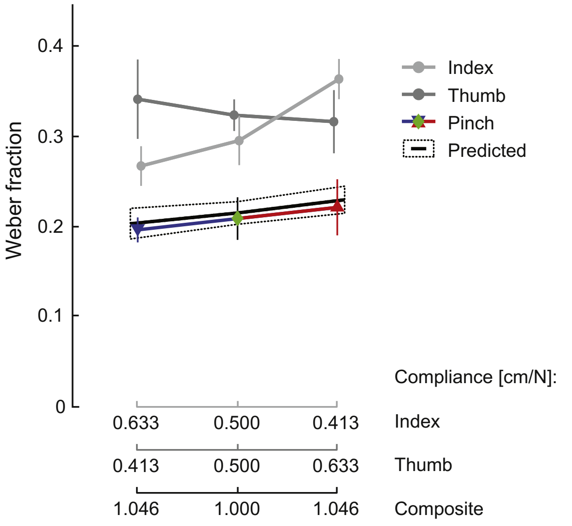

**Fig. 4.** Results obtained in Experiment 3 in terms of Weber fraction and prediction for statistically-optimal performance. Error bars and dotted area represent one standard error of the mean across participants.

Predicted and empirical values are shown in Fig. 4. Discrimination performance with pinch grasp does not deviate from the predictions (two-way RM ANOVA predicted/empirical vs. equivalent compliance shows no significant main effect $F(1, 6) = 0.1$, $p = 0.74$ or interaction $F(2, 12) = 0.01$, $p = 0.99$) and it is better than the best performance with one finger (two-way RM ANOVA pinch/best vs. equivalent compliance has significant main effect of number of fingers $F(1, 6) = 10$, $p = 0.019$ and no interaction $F(2, 12) = 1.6$, $p = 0.25$).

## 4. Discussion

Haptic interaction provides information about object properties that are important for survival, like properties related to edibility of food (i.e. freshness, Barnett-Cowan, 2010). For example, we can quickly become aware of whether a fruit is immature, ripe, or rotten. There are several ways of haptically assessing the

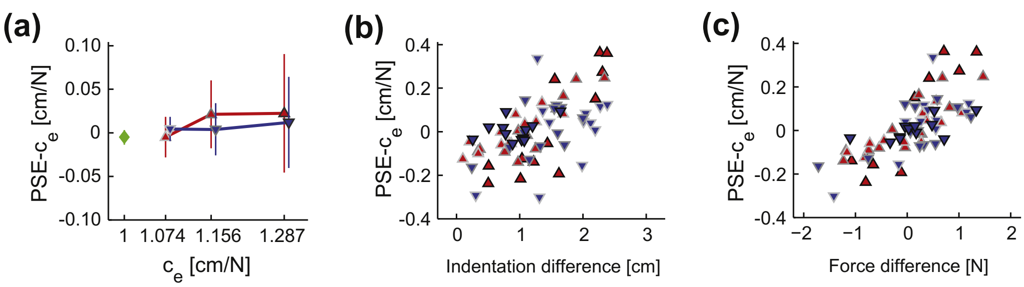

**Fig. 3.** Results obtained in Experiment 2. Colors correspond across the panels (outline color indicates the equivalent compliance of the composite object). (a) Difference between the point of subjective equality (PSE) and the equivalent compliance of the composite object plotted as a function of equivalent compliance. Colors correspond to Fig. 1; error bars represent one standard error of the mean across participants. (b) Deviation of PSE from equivalent compliance plotted as a function of the difference in indentation between the compliant and the stiff side for each of the participants and condition in Experiment 2. (c) Deviation of PSE from equivalent compliance plotted as a function of the difference in force applied to the compliant side minus the one to the stiff side.

material properties of small objects like fruits. We could press a finger against the object, hold it in the palm of the hand, or squeeze it between index finger and thumb. For this, multiple sources of information need to be combined into a unique estimate of material properties (i.e., see Kuschel et al., 2010), but the sources multiply when using more than one finger for the interaction. It has been shown that the perceptual system possesses efficient ways of integrating redundant sources of information depending on the precision of the sensory estimates they provide (Ernst & Banks, 2002; Knill et al., 1996) and here we analyze whether this happens also in the case of perceived compliance of objects fixed to the background and grasped using a pinch grasp. The situation analyzed was constrained in the type of information available by rendering virtual objects using only position and force signals (Bergmann Tiest & Kappers 2009; Scilingo et al., 2010). Such type of interaction resembles what one would experience using tools like tweezers or scissors, where compliance information about the object cannot be obtained from tactile information alone (Srinivasan & LaMotte, 1995).

In a pinch, with such type of interaction the information about perceived compliance depends critically on the active indentation of the object material: fingers need to move to sense force and position changes necessary for the perception of compliance. For composite objects having small differences in compliance the information at the index finger is slightly but consistently overweighed. Switching around such composite objects induces a small but consistent change in perceived compliance (Fig. 2, effect magnitude is about 5% of the simulated compliance). Switching around composite objects with larger differences in compliance, instead, leads to a non-consistent pattern of responses across participants (Fig. 3a). Objects with large differences in compliance lead participants to perform different movements with the two fingers, with larger movements of the finger corresponding to the more compliant side. Data indicates that the percept depends on such difference of movement—information coming from the finger that exerts more force is contributing more to the percept (Fig. 3c).

Such type of perceptual distortions can be used to infer how the brain processes sensory information. Deviation of perceived compliance from the simulated equivalent value could be caused by two factors: incorrectly sensing the force or position information ("bias"), or an erroneous integration of the information at the two sides ("confusion"). Let's look at these possibilities in order.

First, let's analyze the case of biased sensory information. As the difference in sensed information between the fingers is important, we will consider the case of a bias in the sensed force and/or position at one finger only. In this case, the perceptual estimate of simulated compliance $c$ sensed using the finger affected by the bias is $\chi$ which is obtained using different values of force and position than the veridical values $x$ and $F$ (Eq. 1) according to:

$$\chi = (xb_x)/(Fb_F) = cb, \tag{4}$$

where $b = b_x/b_F$ represents the bias on perceived compliance (the numerical values of $b$, $b_x$, and $b_F$ are all close to 1). With such a bias, the perceived equivalent compliance $_e$ when pinching a composite object differs from Eq. (3) and it can be expressed as:

$$\chi_e = c_1 b + c_2. \tag{5}$$

Since the same distortion applies to both stimuli to be compared, a bias does not change the PSE unless one object is a composite and the effect increases with the difference in compliance at the two sides. To test whether such bias can account for perceptual distortions, the value of $b$ is calculated in each condition by applying Eq. (5) to the comparison of a composite object with simulated compliances $c_1$ and $c_2$ with a uniform object according to:

$$bc_1 + c_2 = (b+1)PSE/2. \tag{6}$$

The average value of bias $b$ for each participant is compared across the two orientations of the composite object as shown in Fig. 5a. No systematic correlation emerges across the two orientations ($r^2 = 0.33$, $p = 0.28$) suggesting that a single value of bias (one for each participant) cannot account for the patter of results in Experiment 2. Moreover, the predicted change in perceived compliance should be proportional to the difference in compliance between the two sides of the composite object and the comparison of results in Experiments 1 and 2 indicate instead that deviations decrease with increased difference in compliance. Finally, if a bias would be responsible for the perceptual distortions it would be independent of the difference in movement patter of the two fingers. Instead, data indicate that the effects depend on the difference of movement (Fig. 3b).

The alternative account of perceptual distortions is the confusion of sensory information from the two fingers into a unique signal that is in turn used to obtain a compliance estimate. We will consider the more likely case of a unique estimate of force, as independent estimates of the fingers positions can be normally obtained from vision. The confusion of the force signals can be thought as the application of Eq. (2) in a case where Eq. (3) should have been applied (overall force $F_{12}$ for both sides of the object is used for the estimate). In this case, softness estimates $\chi_1$ and $\chi_2$ at the two sides can be expressed according to Eq. (1) after substituting the position estimates $x$ with CF (the veridical values of compliance multiplied by force) as such Because only the:

$$\chi_1 = x_1/F_{12} = c_1F_1/F_{12} \quad \text{and} \quad \chi_2 = x_2/F_{12} = c_2F_2/F_{12}. \tag{7}$$

If force $F_{12}$ is obtained with the average of the forces at the two sides of the object $F_A = (F_1 + F_2)/2$, then the estimate of compliance for the whole object becomes

$$\chi_e = x_1/F_A + x_2/F_A = c_1F_1/F_A + c_2F_2/F_A. \tag{8}$$

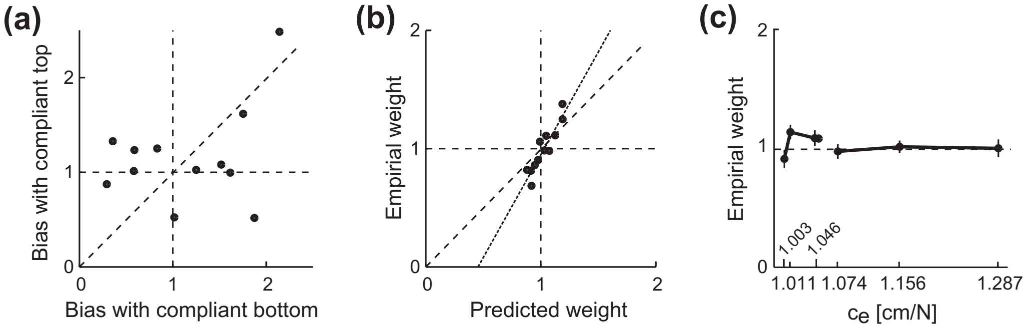

**Fig. 5.** (a) Bias for each participant for the two orientations of the composite object. (b) Predicted and empirical weight for each participant. The dotted line represents a least-square regression line fitted to the data. (c) Average weight in the three experiments.

In this formula the force ratios can be considered as weights in the sum of the compliances at the two sides so that

$$w_1 = F_1/F_A \quad \text{and } w_2 = F_2/F_A = 2 - F_1/F_A. \tag{9}$$

Thus the resulting formula

$$\chi_e = w_1c_1 + w_2c_2, \tag{10}$$

is similar to perceptual accounts that consider integration of redundant estimates as a weighted average (Knill et al., 1996). The weights, however, do not implement an average but rather an addition and accordingly they add to 2 and not to 1.

To test whether confusion could be responsible for the perceptual distortions, the average predicted weights for each participant (calculated from the force levels using Eq. (9)) have been compared to the empirical weights obtained by applying Eq. (10) to the PSE according to

$$w_1c_1 + (2 - w_1)c_2 = PSE. \tag{11}$$

The result of this comparison is shown in Fig. 5b. There is a significant correlation between the two values obtained across participants ($r^2 = 0.90$, $p = 0.0001$) indicating that confusion of the force sensed by the two fingers into one estimate can account for the perceptual distortions. Moreover, if confusion of sensory signals is in place, Eq. (8) predicts that by using only force-position information the brain has still access to sensory signals that allow to assess whether the sides of an object indented with two fingers differ in compliance, however the difference in perceived compliance is smaller than what would be perceived using one finger at the time. Results from Chen and Srinivasan (1998) agree with this prediction showing also that the pattern is reversed when there is direct finger contact with the deformable surfaces of the object.

Even though with the confusion of the forces at the two fingers the weights given to the compliance estimates are a function of the difference in force applied at the two sides of the object, such weighting leans towards the more reliable sensory signal because sensed force has an increasing signal-to-noise ratio in the range of forces applied in the current experiments (a decreasing Weber fraction as a function of pedestal force, see Höver, Di Luca, & Harders, 2010; Pang, Tan, & Durlach, 1991). Weighting more the compliance estimate obtained from a larger force magnitude should improve the reliability of the final percept. This prediction is consistent with the results of Experiment 3 and with other findings of close-to-optimal performance in the case of redundant and statistically independent sources of compliance information (Di Luca et al., in press; Kuschel et al., 2010). The case analyzed in Experiment 3 is designed to reduce correlation, but in normal pinch grasp interactions this would not be the case. Performance improvement in such cases would be dependent on the amount of correlation between the signals (see Oruç, Maloney, & Landy, 2003).

According to the results of Experiment 2, weights depend on how the interaction with the object is performed (see also Di Luca et al., in press). In other words, the final estimate of compliance is not the "pure" sum of the estimates at the two sides as in Eq. (3), but it tends to be similar to the compliance sensed by the finger that exerts more force onto the object and thus provides more reliable sensory information. What remains to be determined is the reason for the overweight of the information at the index finger registered with small differences in compliance. To visualize such effect, weight has been computed across the three experiments according to Eq. (11) and average results are shown in Fig. 5c. The graph highlights the small deviation from equal weighting for Experiments 1 and 2. Such pattern is not captured directly with the proposed model of force confusion. The result would be reconciled with the model if there were evidence of higher imbalance in the force or movement produced by the two fingers with small or no differences in compliance. The range of motion of the fingers performing a pinch can differ substantially, a situation that is consistent with the deviation in weighting found in Experiment 1. Why is not this difference also influencing perception with large differences in compliance? We can speculate that in Experiment 2 participants perform different movements due to the large difference in resistive force produced by the object (i.e., see Kaim & Drewing, 2009), an effect that overpowers the one caused by differences in the range of motion. As data on finger interaction were not collected in Experiment 1, future research is necessary to confirm this possibility.

A word of caution is also in order. The perceptual distortions analyzed here are present because the object is constrained not to move (they critically depend on the difference in force at the sides of the object). The situation is very different if the object grasped with a horizontal pinch is free to move (a more common type of interaction with small objects) as the force is necessarily equal. With a pinch grasp of an object having non-negligible mass where the index finger is above the thumb, instead, the weight of the object lies entirely on the bottom finger, the thumb. This situation could make information about object compliance acquired through the thumb less reliable. It would be more efficient in this case to employ a movement of the index finger to assess compliance. Finally, the integration of sensory information can differ substantially if the object has deformable surfaces (Bergmann Tiest and Kappers, 2009; Scilingo et al., 2010).

It has been shown that incongruences between sensory information can prevent integration into a unique percept (see Ernst and Di Luca, in press, for a review). Girshick and Banks (2009) suggested that one cause of breakdown of integration might be the ability to detect discrepancies between redundant sensory information. Here, we find that (unimodal) haptic information from the two fingers is integrated in the final percept through a weighed average also in cases where the participant notices compliance differences. In fact, at the end of the experiment all participants reported to have noticed a difference in compliance at the two fingers for the stimuli in Experiment 2, while only 2 out of 7 participants reported having noticed a difference in Experiment 3, and 4 out of 10 participants noticed this difference in Experiment 1. Moreover, the almost constant Weber fraction for each type of interaction in Experiment 3 (average Weber fraction with pinch grasp is 0.22) indicates a 75% chance of detection of compliance difference starting at 0.22 cm/N. This value corresponds to the largest difference in compliance in Experiment 1.

Overall the results collected in these experiments are in line with a scheme of integration that can produce close to statistically optimal results (maximum reduction of variability) by weighting sensory information depending on precision. However, the quality of sensory information obtained through active exploration is not fixed, but determined by the movement performed. Accordingly, movement characteristics of the fingers guide the integration of sensory signals in obtaining a final estimate of compliance.

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