Is it possible to perceive the shape of an object without exploring it?

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ABSTRACT

The deformation of the fingerpads along the contact surfaces in a real grasp provides local information about the shape of the object, which is crucial for the stability of the grasp. Several experiments were performed to investigate whether it was possible to transmit information about the shape of a virtual object grasped via a single-contact haptic interface, in spite of the fact that thimbles prevent the deformation of the fingerpads. To that end, we modified the classic god-point algorithm by using a pseudo-ellipsoidal force field that provides information about the object's shape by increasing the compliance along the normal or tangential direction. The position of the god-point was held fixed during the whole contact. The main finding was that participants could identify the orientation of the contact surface when the compliance was maximum in the tangential plane by using small exploratory movements allowed by the contact model.

Keywords: haptic interface, shape perception, contact model, god-point algorithm

1 INTRODUCTION

In absence of vision, the shape of an object is usually perceived via the movements of the finger on its surface [1]. While such movements are obviously necessary to perceive the shape of the object in its globality given the limited size of tactile receptive field, it is important to note that cutaneo- and mechano-receptors distributed in the skin and underlying tissues can yield local information about the object'shape *in the absence of any exploratory movements*. In particular, previous studies have shown that these receptors can provide information about the orientation of the contact surfaces under the fingerpads [4] or the direction of the contact force relative to the normal [5] in addition of information about the coefficient of friction of the contact surface [2, 3]. Such information is crucial to control the direction of the contact forces during the grasp of real objects in order to avoid a slip of the object.

The general objective of this study is to examine ways of transmitting information about the orientation of the contact surface under the fingertip to an observer who is touching a virtual object via an haptic interface without moving the finger. Such a question is challenging because the contact with the virtual object is mediated by thimbles that do not allow the finger pads to deform as they would at the contact with real objects. The only information that can be transmitted is the direction of the applied force.

In this study, we report preliminary results of four pilot experiments. The first experiment shows that contact forces tend to be oriented perpendicularly to the contact surfaces. The following experiments examine the capacity of human operators to discriminate shapes perceived via an haptic device. In these experiments, we tried to provide information about the objects' shape by increasing the compliance along the normal (Experiment II) or tangential direction (Experiments III and IV). To that end, we modified the classic god-point algorithm by using a pseudo-elliptical force field instead of central force field to compute the contact forces.

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2 REAL PINCH GRASP: EXPERIMENT I

The direction of the contact forces cannot differ too much from the contact surface normal without causing a slip of the finger. Previous studies have shown that humans have internalized this constraint and, as a result, tend to apply forces in directions that provide a reasonable safety margin against a finger slip [6, 7]. The objective of the first experiment is to show that this tendency holds true in the particular grasping context of this study, that is when a fixed object is squeezed by the thumb and index finger.

2.1 Methods

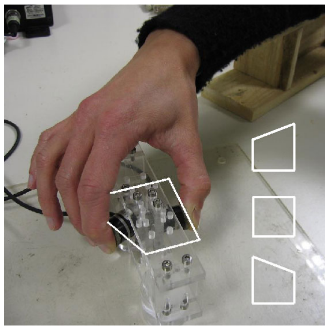


Figure 1: Experimental set-up used to measure finger forces in Experiment I (the screen hiding the view of the device to the subject is not shown). Inset: The three shapes shown at the end of the experiment.

Three males and two females participated in this experiment (mean age: 30 years). Participants were seated in front of the instrumented device (Figure 1). The forearm was supported by the experimental setup a few centimeters above the object. The gasping axis corresponded to the sagittal axis. A screen (not shown) hid the view of the object. Contact surfaces (17 mm diameter) were covered with falter.

The orientation of the index contact surface was varied across experimental conditions. The experiment comprised three blocks of trials that differed by the angle (-27^o, 0^o or 27^o) between the two contact surfaces. Each orientation was presented 10 times consecutively inside a block. The order of presentation of the blocks was reversed between participants.

At the beginning of each trial, an initial beep instructed the participant to squeeze the object with a comfortable force. Four seconds later, a second beep indicated the time to release the object. Forces and torques were measured by two 6 DoFs sensors placed under each finger (Nano-17, ATI Technology) with a sampling rate of 200Hz and saved for off-line analysis. At the end of the experiment, participants were asked to match each block of trials with one of three possible shapes presented on a sheet of paper (see inset in Figure 1).

2.2 Results

Contact forces peaked shortly after the initial contact before stabilizing at a plateau level until release time (see Figure 2A). The direction of the contact forces changed little during the whole trial. The index contact force tended to remain perpendicular to the contact surface as expected (see Figure 2B,C). This change was accompanied by a smaller rotation of the thumb in the opposite direction, creating a significant torque around the vertical axis, as if the subject tried to screw or unscrew the object. None of the participants had difficulty matching each block of trials with the correct shape at the end of the experiment.

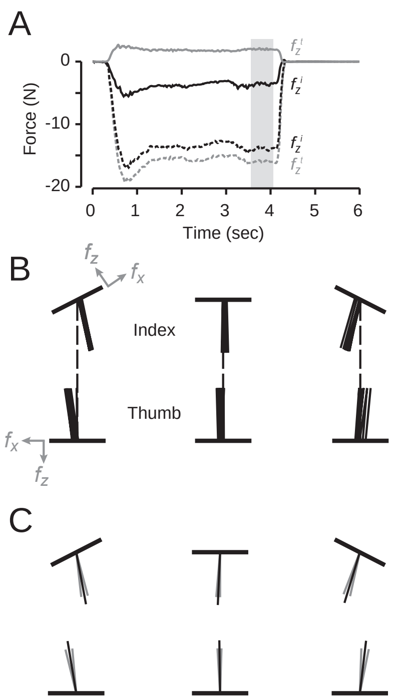


Figure 2: A: Thumb (gray lines) and index (black lines) forces recorded during a single trial. The solid and dotted line correspond to the normal and horizontal force components respectively. The index contact surface orientation was oriented at 27^o relative to the thumb contact surface. The contact forces were averaged over a 500ms time-window at the end of each trial (gray area). B: Directions of the contact forces in the horizontal plane produced by one subject. The orientation of the index contact surface was varied across experimental conditions (left: 27^o, middle: 0^o, right: -27^o). Each line corresponds to a different trial. C: Average direction of the force (data from all subjects, $N = 5$). The shorter gray lines denote the standard deviation of the force direction.

2.3 Discussion

The results of this experiment confirmed that contact forces tend to be oriented perpendicularly to the contact surfaces. In particular, this experiment showed that this observation holds true when a fixed object is grasped with a pinch grasp. While expected, this result needed to be confirmed experimentally because the direction of the contact forces in the pinch grasp are normally constrained by the position of the contact points when the object is free. In this experiment, however, the equilibrium condition did not need to be satisfied because the object was fixed.

3 Experimental setup and force rendering model

3.1 Introduction

As mentioned in the Introduction, human operators are usually able to perceive the shape of the grasped object even in absence of any exploratory movements. This perception is lacking in virtual grasping via haptic interfaces, where thimbles prevent the deformation of the fingerpads on the contact surfaces, which is crucial for the transmission of information about the object's shape.

In the following sections, we will present the preliminary results of several psychophysical experiments where participants squeezed a virtual object between the thumb and index finger. The objective of these experiments was to find a way of transmitting information about the shape of virtual objects via a single contact point haptic device and without exploratory movements. In this section, we present the elements of the experimental procedure that were common to all haptic experiments.

3.2 Experimental procedure

The experimental setup consisted of a fixed (passive) thimble and of the three DOFF haptic device that was used to simulate the contact force between the index finger and the virtual object. The participants inserted the thumb in the fixed thimble and the other index in the thimble mounted at the extremity of the haptic device via a cardanic joint.

At the beginning of each trial, the index finger did not touch the virtual object. A beep instructed the participant to flex the index finger. Participants were instructed to maintain the contact until a second beep, 3sec later, indicated the moment of releasing the object by extending the index finger. The level of squeezing force was selected freely by the subject. At the end of each trial, the participant was asked to match the perceived shape of the virtual object with one of several shapes depicted in a figure. The only difference between the depicted objects' shapes consisted in the orientation of the index contact surface.

3.3 Force rendering model

The haptic rendering of the contact force was performed via the classic god-object algorithm [11]. The position of the god point was held constant during the whole contact, i.e. the finger could not slip along the virtual surface.

In order to provide information about the orientation of the index contact surface, we modified the classic god point algorithm by using a "pseudo"-ellipsoidal force field instead of a spherical force field to compute the contact force.

Let $p_F = (x_F, y_F, z_F)$ be the position of the fingertip expressed in a local reference frame with its origin at the god point p_G, as shown in Figure 3. We define the ellipsoidal stiffness matrix $E = diag\{k_1, k_1, k_2\}$, where k_1 and k_2 are the stiffness along the tangential and normal direction, respectively.

Hence, the contact force for an ellipsoidal force field is computed as

$$F_e = -E p_F \tag{1}$$

It is worth noting that the direction of the force F_e computed via equation 1 is not always directed toward the god point, and this might yield a "glue-like" or "repellent-like" behavior when the main axes of the force field are not aligned with the contact surface. To overcome this undesired effect, we defined the pseudo-

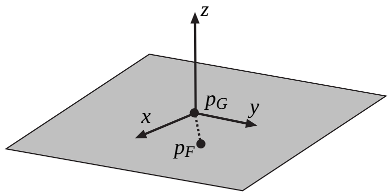
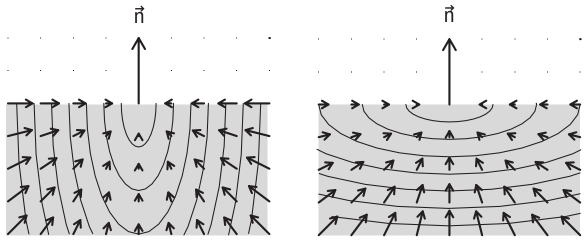


Figure 3: Local frame of reference associated with the contact surface. p_G and p_F denote the position of the god point and the position of the fingertip inside the object.

ellipsoidal force field as

$$F = \frac{\|F_e\|}{\|p_F\|} p_F \tag{2}$$

From this definition, it is clear that, for every position p_F of the fingertip, the magnitude of the force F is the same as F_e, but its direction is always oriented toward the god point as in a spherical force field.



(*a*) (*b*)

Figure 4: Pseudo-ellipsoidal force fields. The arrow denotes the force vector. The compliance is maximum along the normal (*a*) or tangential direction (*b*). See text.

A convenient way to characterize the ellipsoidal force field is represented by its *eccentricity* e and *total stiffness* k:

$$\begin{aligned} e &= \frac{k_2}{k_1} \\ k &= \sqrt{\frac{k_1^2+2k_2^2}{3}}. \qquad \left[\frac{N}{mm}\right] \end{aligned} \tag{3}$$

The reciprocal equations to compute the values of the stiffness along the tangential and normal direction are:

$$\begin{aligned} k_1 &= \frac{k_2}{e} \\ k_2 &= \sqrt{\frac{3k^2e^2}{1+2e^2}}. \end{aligned} \tag{4}$$

For $e > 1$ the direction of maximum compliance is oriented along the normal to the surface at contact point (i.e., $k_2 > k_1$, see Figure 4-(a)). On the contrary, $e < 1$ determines maximum compliance in tangential direction (see Figure 4-(b). When $e = 1$, the pseudo-ellipsoidal force field degenerates to a common spheric field with stiffness k, $\forall k > 0$.

In the haptic experiments presented in the following sections, we manipulated the compliance of the contact by varying the eccentricity e and the stiffness k of the ellipsoidal force field. In Experiment II (Section 4), the direction of maximum compliance was aligned with the normal, i.e. $e > 1.00$. In the last two experiments (Sections 5 and 6), the direction of maximum compliance was tangentially aligned, i.e. $e < 1.00$. In all experiments, the eccentricity and stiffness of the force field were systematically varied in order to identify the optimal values of the parameters for the task.

3.4 Data Analysis

For each combination of shape, eccentricity and stiffness values, we computed the proportion of correct responses. The main effect of each one of these factors as well as the interaction between eccentricity and stiffness were analyzed with a repeated-measure ANOVA, after using the $arcsin(\sqrt{x})$ transformation on the proportion of correct responses to stabilize the variance. The degrees of freedom were adjusted with Greenhouse-Geisser's epsilon ε in order to account for a possible deviation from sphericity.

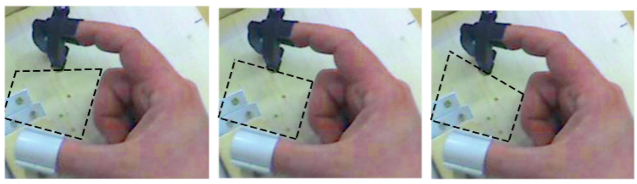
4 HAPTIC PINCH GRASP: EXPERIMENT II

4.1 Introduction

This experiment aimed at inducing the participant to squeeze the object with contact forces similar to the ones observed in a real grasp. To that end, the direction of maximum compliance was aligned with the direction of the normal. The idea was (1) that the participant's fingertip would penetrate the virtual object along the direction of maximum compliance and would therefore also produce a force along this direction, and (2) that participants would infer the orientation of the contact surface from the direction of the force on the basis of past experience with grasping real objects, as in Experiment I.

4.2 Methods

4 adults, aged between 22 and 28, participated in the experiment. All participants were right-handed with no known sensorimotor impairments. Their prior experience with haptic devices varied from naïve to expert.



(*a*) (*b*) (*c*)

Figure 5: Top view of the shape of the virtual objects displayed in second experiment. Figures (*a*), (*b*) and (*c*) correspond to the -27^o, 0^o , and 27^o conditions.

The experiment comprised three virtual objects with shapes featuring an angle of -27^o, 0^o, and 27^o between the thumb and index contact surfaces (see Figure 5). The index contact surface was titled around the vertical axis. The setup was arranged so that the index and the thumb were laying on the same plane as the normal directions to the surfaces. The task consisted in touching the virtual object for the preset time interval, and in reporting the perceived shape as described in Section 3.2.

Each virtual object was rendered with different parameters of the pseudo-elliptical force field. Each shape was combined with three stiffness values ($k = 0.7$, 1.00 and 1.25N/mm) and three eccentricity values ($e = 1$, $e = 2$ and $e = 3$) to yield a total set of 27 different stimuli. The experiment comprised 10 blocks of 27 runs. Inside a block, all stimuli were presented once in a random order.

4.3 Results

To analyze the effect of the stiffness and eccentricity values, we performed a repeated-measure ANOVA on the percentages of correct responses (see Section 3.4). None of the factors was statistically significant (see Table 1).

Figure 6 shows that the percentage of correct responses did not differ markedly from the chance level (33%). Participants often

Factor	DF hyp	DF error	F	ε	P value
Shape	2	6	0.406	0.712	0.627
Eccentricity	2	6	0.985	0.650	0.407
Stiffness	2	6	1.029	0.647	0.396
Ecc:Stiff	4	12	1.026	0.456	0.411

Table 1: Effects of the main experimental factors in experiment II (repeated-measure ANOVA)

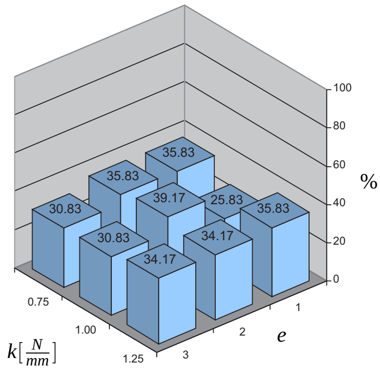


Figure 6: Percentage of correct response rates for each eccentricity and stiffness value (all shapes and subject pooled together).

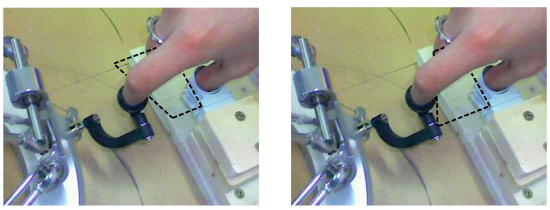
seemed confused during the experiment and expressed frustration at not being able to explore the surface of the object. In fact, visual observation of the subjects' behavior and verbal reports revealed that participants were actively moving the finger along the direction of maximum compliance as if trying to explore the surface of the object.

5 Haptic pinch grasp: experiment III

5.1 Introduction

On the basis of the results of the previous experiment, we decided to modify the design of the experiment: first, the compliance of pseudo-ellipsoidal force was maximum in the tangential plane. Second, only two shapes were included in the experiment, and the amplitude of angle between the orientations of the thumb and index contact surface was increased (45^o instead of 27^o). Finally, the posture of the hand with respect to the object was modified, so that the index and the thumb would be laying in a plane orthogonal to the one defined by the normals of the contact surfaces (see Figure 7).

5.2 Methods



(a) (b)

Figure 7: Top view of the shape of the virtual objects displayed in third experiment.

5 adults, aged between 22 and 28 (3 of them participated also in the Experiment II), performed the experiment. All participants were right-handed with no known sensorimotor impairments. Their prior experience with haptic devices varied from naïve to expert.

The parameters of the pseudo-elliptical force field were systematically varied. Three stiffness values ($k = 0.75$, 1.00 and 1.25N/mm) and three eccentricity values ($e = 0.4$, 0.7 and 1.0) were used. These parameters were combined with the two orientation angles (-45^o and 45^o) to yield a set of 18 different stimuli.

The experiment comprised 10 blocks of trials. Each stimulus was presented in a random order once inside each block. Stimuli were presented according the experimental procedure described in Section 3.

5.3 Results

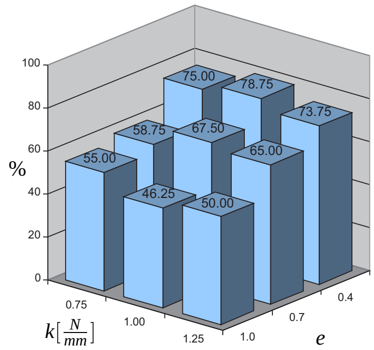


Figure 8: Behavior of correct response rates over stiffness and eccentricity for the third experiment.

As in previous experiment, we computed the percentages of correct responses with respect to stiffness and eccentricity of the ellipsoid. Figure 8 shows that these percentages increased markedly when eccentricity decreased, that is when the compliance along the tangential direction increased relatively to the compliance along the normal direction. In contrast, these percentages remained approximately constant across stiffnesses for a same eccentricity value. For eccentricity $e = 1.00$ the pseudo-elliptic force field degenerates to the classic spherical field, i.e. the compliance is constant along all directions. As expected, the percentages are close to chance level (50%), which indicates that participants were unable to perceive the object's shape.

Factor	DF hyp	DF error	F	ε	P value
Shape	1	3	0.099	1.000	0.774
Eccentricity	2	6	15.414	0.604	0.020*
Stiffness	2	6	0.008	0.980	0.992
Ecc:Stiff	4	12	0.699	0.469	0.935

Table 2: Effects of the main experimental factors in Experiment III (Repeated-measure ANOVA).

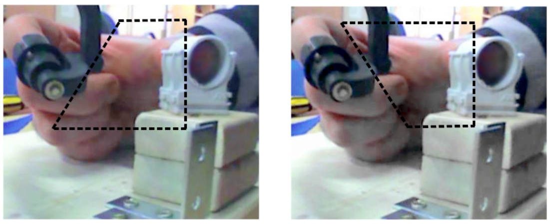
The repeated-measure ANOVA confirmed that the percentage of responses depended only on the eccentricity of the force field ($P < 0.05$, see Table 2). The absence of effect for the shape factor indicates that the proportion of correct responses was the same for both shapes.

These results show that it is possible to convey information about surface orientation via a single contact point by setting small values of eccentricity, i.e. increasing the compliance of contact along the tangential direction.

6 HAPTIC PINCH GRASP: EXPERIMENT IV

6.1 Introduction

This experiment aimed at extending the results of the previous experiment by changing object position and hand posture. In this experiment, the index contact surface was tilted around an horizontal axis. Moreover, participants grasped the virtual object from aside, i.e. the hand was sideways with respect to the virtual object, as shown in Figure 9. Note that the positions of the hand relative to the object did not change: the plane defined by index and thumb was orthogonal to the plane defined by the normal directions as in the previous experiment (see Figure 9).



(a) (b)

Figure 9: Side view of the shape of the virtual objects displayed in the fourth experiment.

6.2 Methods

4 adults, aged between 22 and 28 (all of them also performed Experiment III), participated in the experiment. All were right-handed with no known sensorimotor impairments. Their prior experience with haptic devices varied from naïve to expert.

The stimuli were similar to the one of the previous experiment, except for the fact that the index contact surface was titled around an horizontal axis instead of a vertical one (see Figure 9). As previously, the two shapes were combined with three stiffness values and three eccentricity values to yield a total of 18 stimuli.

The experimental procedure was the same as in previous experiment. Each subject performed 10 experimental blocks, each of them consisting of displaying all 18 stimuli in a random order.

6.3 Results

The results of this experiment were very similar to those of the previous one. Figure 10 shows the percentage of correct response rates for each value of the parameters of pseudo-elliptic force field.

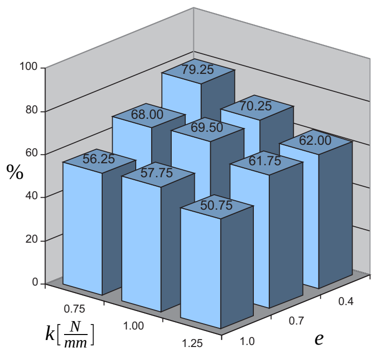


Figure 10: Behavior of correct response rates over stiffness and eccentricity for the fourth experiment.

Factor	DF hyp	DF error	F	ε	P value
Shape	1	3	0.503	1.000	0.517
Eccentricity	2	6	10.975	0.637	0.018*
Stiffness	2	6	8.094	0.909	0.015*
Ecc:Stiff	4	12	1.547	0.481	0.272

Table 3: Effects of the main experimental factors in Experiment IV (Repeated-measure ANOVA).

The statistical analysis of the responses confirmed that increasing the compliance of contact in the tangential plan helps the subject to perceive the shape ($P < 0.05$, see Table 3). In addition, this analysis revealed that the stiffness factor was also statistically significant ($P > 0.05$), indicating that lower stiffness values might slightly facilitate the task by allowing larger movements.

Note that the small increase of correct responses for the stiffness value corresponding to a spherical force field (i.e., $e = 1.00$), which provides no information about the orientation of the shape, is mostly likely to be due to the limited number of subjects who performed the experiment. With a larger sample, one would expect to find percentages closer to chance level as well as a statistically significant interaction between the eccentricity and stiffness factors.

7 GENERAL DISCUSSION AND CONCLUSIONS

In a real grasp, sensory feedback from tactile and mechano receptors distributed in the skin and underlying tissues play a double role in absence of vision: first, they provide information about the shape of the object to the perceptual system and, second, they allow the motor system to control finger forces, in particular their direction, in an optimal way. In contrast, as mentioned in the Introduction, such sensory feedback is absent in a virtual grasp because the fingertips are usually inserted in thimbles mounted at the extremity of the devices used to simulate the contact forces.

This fact that thimbles prevent the deformation of the fingerpads led us to consider using the direction of the contact forces as a cue about the orientation of the contact surface. As a matter of fact, previous studies have shown that contact force tend to be oriented perpendicularly to the contact surfaces when a real object is grasped [7]. The first experiment (see Section 2) demonstrated that this observation holds true when the grasped object is fixed. Such a behavior is obviously beneficial to prevent a slip of the finger.

Our first idea for transmitting information about the orientation of the contact surface was therefore to increase the compliance of a pseudo-ellipsoidal force field along the direction of the normal in order to induce the subject to penetrate the object along this direction. According to the classical god-point algorithm, such a penetration of the object would be accompanied by a contact force in the same direction (Section 3). On the basis of the results of this initial experiment, we hypothesized that participants would be able to perceive the shape of a virtual object from the pattern of contact forces produced when grasping it.

It is important to note that this hypothesis rests on two assumptions: first, that a pseudo-ellipsoidal force field will induce the participants to squeeze the object along a direction that corresponds to the normal and, second, that participants will associate this pattern of contact force with a specific shape.

The second assumption is supported by a growing body of evidence supporting the idea that motor processes are involved in the identification of meaning of the sensory signals. Functional imaging techniques in humans and single-cell electrophysiology studies in monkeys have shown that motor areas are activated during perceptual tasks (reviews in [13, 12]). This theory explains the observation that perception is often influenced by action. For example, psychophysical experiment have shown that the velocity profile of the movement can influence the perception of the trajectory's shape

[8] or that the application of tangential force on the extremity of the fingertip during the exploration of a planar surface can induce illusory perceptions, such as a tilt of the plane [9] or a bump [10].

The first assumption took for granted that the participants would squeeze the virtual object as a real object and that, during contact, the fingertip would stabilize at some distance of the virtual contact surface. The results of the second experiment (Section 4) suggest however that this was not the case. Participants were unable to identify the shape of the virtual object when the direction of maximum compliance was aligned with the normal. Responses were at chance level for all eccentricity and stiffness values. Visual observation and verbal reports pointed out that participants, contrary to our expectations, did not squeeze the virtual object as they would have with a real object. In fact, some participants reported making micro exploratory movements along the direction of maximum compliance in order to identify the object's shape.

The recourse to such a strategy might explain the negative results of this experiment and the confusion of the participants. As a matter of fact, the direction of maximum compliance made an angle of -27^0, 0^o or 27^o with respect to the normal in this experiment. If subjects perceived these directions as parallel to the surface as is the case during the free exploration of a real object's shape, then the virtual objects would have been perceived likewise it was featuring two contact surfaces making an angle of 63^o, 90^o and -63^o respectively, which does not make much sense indeed and, in any case, did not correspond to any of the visually presented reference shapes. In addition, it might also be possible that the difference between the experimental conditions was too small to be perceived clearly enough.

In the two following experiments (Sections 5 and 6), the direction of maximum compliance of the pseudo-ellipsoidal force field was align with the tangential plane. In addition, the experimental paradigm was simplified by including only two shapes. Finally, the contrast between the experimental conditions was starkened by increasing the angular difference (-45^o and 45^o) between the thumb and index contact surfaces.

The result of these experiments demonstrated that participants were able to haptically perceive the shape of the object. This results held true whether the orientation was tilted around a vertical axis (Experiment III in Section 5) or around an horizontal axis (Experiment IV in Section 6). Here again, visual observation and verbal reports suggest that participants moved the fingertip laterally to the extent allowed by the contact model. A detailed look at the results showed that the main experimental factor pertaining to the performance level was the eccentricity, that is the ratio between the compliances along the tangential and normal direction. In contrast, stiffness had almost no effect in the Experiment III and only a small effect in Experiment IV.

To conclude, this work reported some preliminary results demonstrating that it is possible to convey information about the orientation of a virtual surface even via single-contact haptic device. This study also revealed that percepts were likely to be based on micro-movements allowed by the contact model. Currently, we are examining the fingertip trajectories recorded during the contact in order to find out if it is possible to predict the performance at the trial or subject level on the basis of the characteristics (e.g., number or extent of the to-and-from movements realized during the exploration of the object's shape). In addition, this analysis will also be aimed at finding out whether participants, after an initial exploration phase, stabilized the position of their fingertip and whether the contact force at this position corresponds to the one observed during a real grasp.

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