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Conveying virtual tactile feedback via augmented kinesthetic stimulation

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Abstract— **In real object manipulation, the deformation of the fingerpads along the contact surfaces provides local information about the geometry of the object the subject is manipulating, even in absence of vision and any exploratory movement. In virtual reality with haptic feedback this kind of stimulation is not available because the haptic devices currently available allows to simulate a contact point force interaction thus preventing the deformation of the fingerpads. The aim of this work is that of proposing a novel contact model to augment the information conveyed during kinesthetic interaction with single-point haptic devices. We extended the classic god-point algorithm by using a pseudo-ellipsoidal force field that creates anisotropic compliance in the neighborhood of the contact point. We performed several experiments in order to verify that such contact model can provide information about contact surface orientation even in absence of vision and of free voluntary exploration. 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 penalty-based contact model.**

I. INTRODUCTION

Manipulating objects featuring a large variety of shapes, physical characteristics and usages is one of the most common activities in the daily life. Human beings with no sensory-motor impairments are able to correctly perform such tasks thanks to feedback information from the visual and haptic perceptual systems, which allow then to suitably control contact forces and torques between fingers and object surfaces.

The haptic sense is mainly divided into two components: *passive touch* (mediated by cutaneo- and mechano-receptors distributed in the skin and underlying tissues) and *kinesthesia* (the sense of bodily movements that is mediated by sensory organs located in the muscles, tendons, and joints). The former provides immediate information about the coefficient of friction of the contact surface [1], [2], the orientation of the contact surface[3], or even the direction of the contact force relative to the normal [4]. The latter plays a crucial role to integrate tactile information during the exploration of the shape of object that exceeds the size of the tactile receptive fields. In fact, psychophysical experiments have demonstrated that, in absence of vision, sliding one's finger across the surface is the preferred method to perceive the shape of an object [5].

Fig. 1. Wide view (left) and detail (right) of an actuated pin array for direct stimulation of the fingerpad.

In virtual reality, the usual combination of tactile and kinesthetic flux of information is not always available, mainly due to technological limitations of force feedback devices. On the one hand, there are the so-called *tactile interfaces* such as the actuated pin arrays [6], that aim at conveying local information about surface features such as textures, bumps or holes by stimulating primarily the skin and its receptors, but strongly limit the movements of the finger (see Figure 1). On the other hand, there are the so-called *haptic devices*, such as the PHANToM [7] and the Omega [8], that provide dynamical feedback to the user, generally featuring single-contact-point interaction and mediating reaction forces by styluses or finger thimbles.

In spite of a great deal of technological progress during the last decade, the research approaches on kinesthesia and on tactile stimulation are still almost disjoined. The first contribution aiming at integrating them is represented by [9], where authors replace the usual end-effector of single contact point haptic devices with an actuated finger thimble (see Figure 2). This approach joins the contributions of kinesthestetic and tactile receptors by rendering information about the orientation of contact surface in addition of the direction of the contact force. Although the idea which supports this approach is novel and significant, the proposed device is still affected by some drawbacks. First, it may affect the overall system transparency, due to the inertia of its mechanical parts. Secondly, it is still a prototype and it is not yet available for commercial distribution.

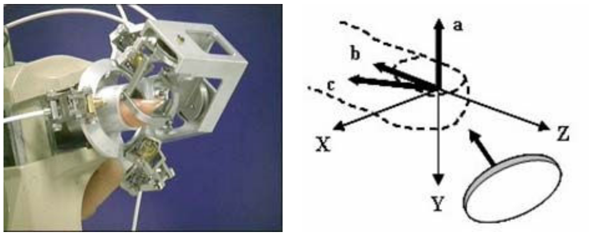

Fig. 2. The three actuated DoFs finger thimble.

The main objective of this work is to find a way to

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convey *local* information about the orientation of the contact surface that does not require any hardware upgrade and that might be implemented with common impedance devices. To that end, we propose an alternative approach referred to as *augmented kinesthetic stimulation*. The basic idea consists in manipulating the rendering of the contact force by the device during the small penetration of virtual contact surfaces, which characterize common penalty-based rendering algorithms. The kinesthetic feedback is augmented to supplement the missing tactile information in a way that would allow an observer who is touching a virtual object via an haptic interface to feel the orientation of the contact surface under the fingerpad *without making any voluntary exploratory movements*. To this purpose, we propose an impedance contact model whose stiffness depends on the orientation of the contact surface and on the direction of the contact force. We modified the classic god-point algorithm [10] by using a pseudo-ellipsoidal force field instead of a spherical one. Four psychophysical experiments involving a shape discrimination task were performed to evaluate the contact model reliability. Results are encouraging, since in most cases participants were able to discriminate the orientation of different virtual surfaces without vision and without free exploratory movements.

The remainder of this paper is structured as follows. Section II introduces the motivation which led us to design the new contact model. In Section III, such model is mathematically formalized. Sections IV and V present experiments and related results, respectively. Finally, the Section VI concludes this work.

II. ANISOTROPIC CONTACT COMPLIANCE

Before introducing the basic idea of the proposed model, let us briefly recall the principles of classic haptic rendering algorithms.

One of the most common algorithms used to compute the force during the contact with a virtual object is the god-object algorithm [10]. It exploits a penalty-based rendering technique, i.e. the reaction force is generally proportional to the penetration depth (i.e., the penalty) of the probe into an object surface. To deal with possible movements of the fingertip on the surface of the object, the god-object algorithm is often combined with the Friction Cone algorithm that simulates tangential friction force [11]. According to the Friction Cone algorithm, the god point (in this case referred to as *stiction point*) slips along the surface only if the force lies outside the friction cone (for more details on this part, please refer to [11]). Now let us suppose that the contact force lies within the friction cone, i.e. the stiction point does not slip (see both cases depicted in Figure 3). This situation is very common: it occurs, for example, in virtual grasping applications every time that the user holds a virtual object with a stable grasp. In this case, the rendered force does not depend on the geometry of the target object but only on its physical features (stiffness). Even if the orientations of surfaces (a) and (b) depicted in Figure 3 are quite different, the virtual penetration vector $p_F - p_S$ (where p_F and p_S are the fingertip position and the stiction point, respectively) is the same with respect to the global reference frame Σ_w, and since the force field is spherical the reaction force F perceived by the user will be identical for both contacts. In this situation, an user would have no chance to discriminate surface (a) from surface (b) without exploring them.

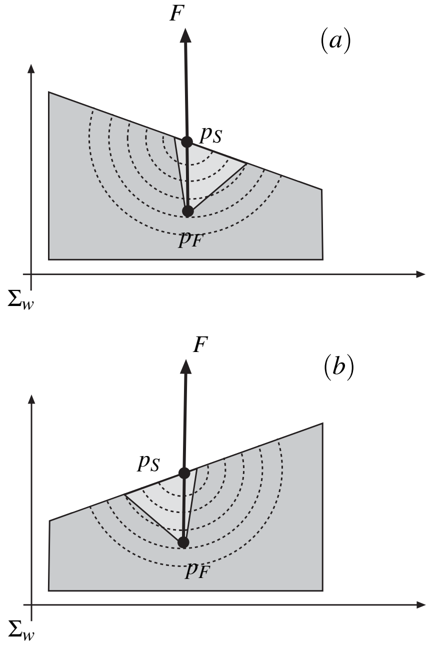


Fig. 3. Two cases of contact surfaces featuring different orientation but yielding the same reaction force F for the same penetration vector. p_F is the fingertip position, p_S is the stiction point and Σ_w is a base reference frame

The contact model we propose depends on the geometry of the object, in order for reaction force F to depend on the direction of the penetration vector. To this purpose, we replace the spherical force field with an ellipsoidal one, so that the contact compliance is no more isotropic with respect to the direction of virtual penetration vector. In order to motivate this choice, we briefly recall a result that in literature is referred to as the *Force Constancy Hypothesis* [12]. It states that the users tend to maintain a constant penetration force when stroking virtual surfaces. If during exploration an user encounters zones with different stiffnesses, he will adapt penetration depth accordingly in order to hold the contact force constant. We hypothesize that Force Constancy may hold true also when only allowed movements are within the friction cone. In other terms, using anisotropic contact compliance, the depth of penetration vector may vary with its orientation, generating a pattern of contact forces which could induce the human operator to perceive the orientation of virtual surface. Several psychophysical studies showed that rendering particular patterns of force on the fingertip during the exploration of a planar surface can induce illusory perceptions, such as a tilt of the plane [13] or a bump [14].

The following section presents the mathematical formalization of the ellipsoidal force field.

III. THE CONTACT MODEL: FORMALIZATION

In order to provide information about the orientation of the index contact surface, we modified the classic god-object algorithm [10] by using a "pseudo"-ellipsoidal force field instead of a spherical force field to compute the contact force.

For the sake of clarity, we assume that the position of fingertip p_F is expressed in a local reference frame $\Sigma_F(x_F, y_F, z_F)$, having its origin at the stiction point p_S, as shown in Figure 4. In order to model the force field, let us consider a generical ellipsoid featuring axes a_1, a_2 and a_3. Let a_1, a_2 and a_3 be aligned along x_F, y_F and z_F, respectively. We define the ellipsoidal stiffness matrix $E = diag\{k_1, k_1, k_2\}$, where k_1 is the contact stiffness along the tangential plane (x_F, y_F), and k_2 is the stiffness along z_F, i.e. the normal direction at the contact point.

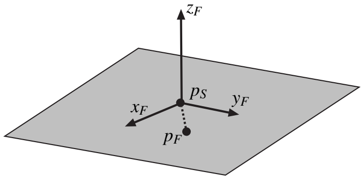


Fig. 4. Local reference frame associated with the contact surface. p_S and p_F denote the position of the stiction point and of the fingertip, respectively.

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

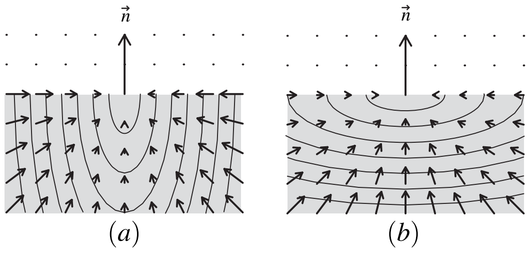
$$F_e = -E p_F \tag{1}$$

where p_F corresponds to the virtual penetration vector inside the surface.

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-ellipsoidal force field* as

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

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 towards the god point as in a spherical force field.



(a) (b)

Fig. 5. Pseudo-ellipsoidal force fields and related force vectors. Maximum compliance can be along the normal (a) or tangential direction (b)

For reason of simplicity, the term ellipsoidal force field will henceforth refer to the modified force field defined by the equation 2.

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

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

For $e > 1$ the ellipsoid is cigar-shaped, i.e. the direction of maximum compliance is oriented along the normal to the surface at contact point (i.e., $k_2 > k_1$, see Figure 5-(a)). On the contrary, for $e < 1$ the ellipsoid is lens-shaped, i.e. the maximum compliance is along the tangential plane (see Figure 5-(b)). When $e = 1$, the pseudo-ellipsoidal force field degenerates to a common spherical field with stiffness k, $\forall k > 0$.

IV. EXPERIMENTS

As mentioned above, tactile sense reveals to be crucial in object grasping tasks, hence we chose virtual grasping as experimental context, where the contact was modeled using a pseudo-ellipsoidal force field.

Recalling the definition of the force field given in Section III, two main questions naturally arise:

1) in order to convey information about virtual surface orientation, is it better to align the direction of maximum compliance along the normal or the tangential direction to the surface?
2) how do eccentricity e and stiffness k influence the perception of virtual shapes?

The experiments aimed at finding an answer for both questions. During each experimental trial, participants squeezed a fixed virtual object between the thumb and the index fingers without doing any exploratory movement. The task for the participants consisted in matching the shape of the object felt with the hand with one of two possible visual templates. In the next subsection, we present the methods that were common to all experiments.

A. General methods

1) Experimental setup and procedure: The experimental setup consisted of a fixed (passive) thimble for the thumb and of a three DoFs haptic device (Omega, Force Dimension) that was used to simulate the contact between the index finger and the virtual object (see Figure 6).

The procedure and task were common for all experiments. At the beginning of the experiment, the participants inserted the thumb in the fixed thimble and the 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 indicated that subject could flex the index finger and squeeze the virtual object. 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

Fig. 6. The experimental setup. The figure shows the fixed thumb thimble as well as the index thimble mounted on the extremity of the haptic device via a cardanic joint. A screen (not shown in the picture) hid the view of the experimental setup to the subjects.

end of the trial, subject matched the perceived shape of the grasped object with one of two possible visual templates (see Figure 7, bottom). Finally, in order for participants to focus only on haptic stimulation, no visual feed-back or graphical display was provided to the subjects during the experiment.

2) Stimuli: Stimuli consisted of virtual parallepiped-shaped objects. The virtual surface at index was rendered using the pseudo-ellipsoidal force field directed towards the stiction point. In order to avoid possible exploratory movements, the position of stiction point was held constant during the whole contact. We considered two different configurations of the force field by changing its orientation with respect to a reference frame attached to the object. Let a_1 be the axis of maximum compliance. The angle α between a_1 and the virtual surface took on values 45^o and 135^o (see Figure 7, top). Let P_f be the plane where a_1 lies for both values of α. P_f was orthogonal with respect to the surface of the virtual object. Henceforth we will refer to P_f as *field plane*. Both values of orientation angle α were combined with three stiffness values ($k = 0.75$, 1.00 and 1.25N/mm) and three eccentricity values ($e = 0.40$, $e = 0.70$ and $e = 1.00$), yielding a total set of 18 different stimuli. For the eccentricity $e = 1.00$, we expected that participants would respond at chance level.

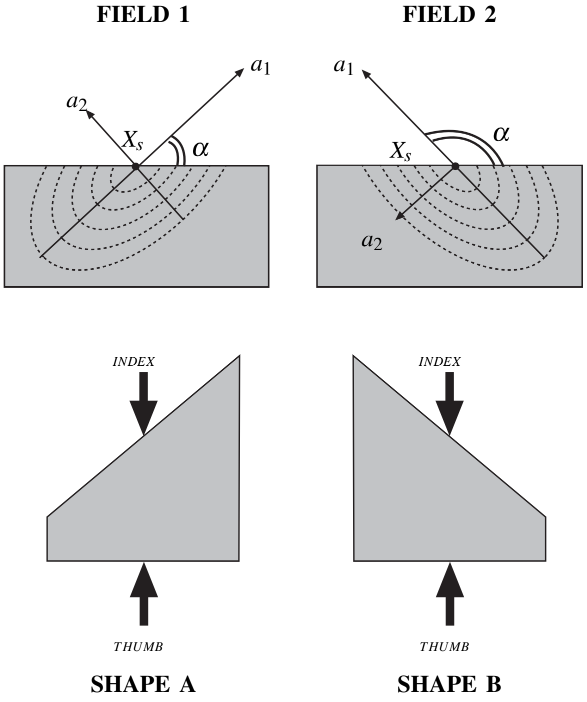


Fig. 7. Top: side view of the haptically rendered object. Two different orientations of the force field: $\alpha = 45^o$ (left) and $\alpha = 135^o$ (right). X_s is the stiction point; a_1 and a_2 are axes of maximum and minimum compliance, respectively. Bottom: the visual templates, i.e. a top view of two possible objects which subjects can associate to the haptically perceived shape.

B. Conditions of Experiments I, II, III, IV

Given the kinematical complexity of human hand, we took into account the possibility that aspects such as the posture of the hand and the relative displacement between hand and virtual object could in some way affect the ability to correctly perceive the information about virtual surface orientation. Nevertheless we aimed at achieving results as general as possible, therefore we performed four experiments which accounted for different configurations of hand posture and relative displacement between hand and object. In order to describe such conditions, we define the *hand plane* P_h, i.e. the plane where thumb and index fingers approximatively lie during a pinch grasp. The four experiments combined two different orientations of hand plane P_h with two different orientation of the field plane P_f (see Figure 8).

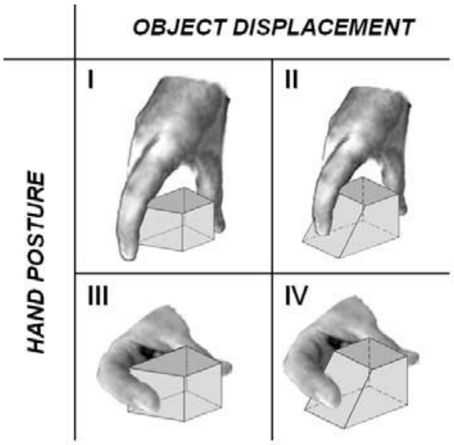


Fig. 8. Experimental conditions. The hand plane is vertical for Experiments I and II, and horizontal for Experiments II and IV. The field plane is horizontal for Experiments I and III, and vertical for experiments II and IV. The virtual object shown in the panel corresponds to one of the two possible shapes that might be perceived in the corresponding Experiment.

V. RESULTS

Data from experiments consisted of the matching responses reported by subjects, fingertip trajectories inside the virtual surface and reaction forces saved for each experimental trial. However, in the scope of this work we only focused on statistically analyzing subjects'responses, while trajectory and force analysis are left to future works. As an example of experimental results, we first report data from Experiment I.

A. Experiment I

For for each pair (e,k), we built 2×2 contingency tables reporting subjects' responses pooling together all repetitions of all subjects. The two entries for each table are field orientation and perceived shape, respectively. Values in the tables represent the number of times that a certain matching orientation-shape has been reported throughout the whole experiment. As an example, we report the contingency table obtained for stiffness $k = 0.75$ and eccentricity $e = 0.40$ (Table I). F1 and F2 represent the field orientations 45^o and 135^o, respectively (see Figure 7, top). SA and SB are the template shape A and B, respectively (see Figure 7, bottom).

	SA	SB
F1	**41**	9
F2	3	**47**

TABLE I

CONTINGENCY FOR THE PAIR $k = 0.75$ AND $e = 0.40$ IN EXPERIMENT I

The sum of values on the same row is always equal to 50, which is the number of times that each stimulus was displayed during the whole experiment (5 participants × 10 repetitions). From data reported in Table I, it stems that the associations F1-SA and F2-SB are clearly predominant (values in boldface) with respect to the others. This means that in most cases, subjects tended to perceive the virtual surface as it was oriented as the direction of maximum compliance of the force field, as shown in Figure 9.

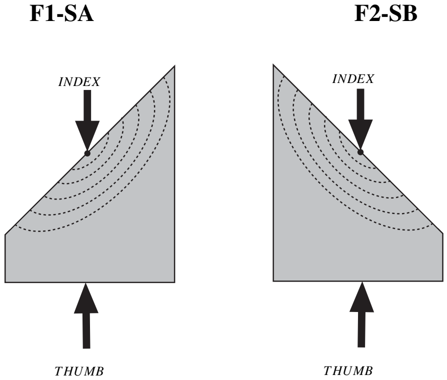


Fig. 9. Predominant associations between the orientation of virtual surfaces and visual templates selected by the subjects.

From the whole data set of Experiment I, it stems that such tendency holds true for all stimuli featuring eccentricity $e = 0.40$ and $e = 0.70$. As we expected, for $e = 1.00$, subjects were not able to discriminate shapes and gave casual responses.

This first analysis provides an answer to the first question we addressed in Section IV: in order to haptically convey information about virtual surface orientation the direction of maximum compliance of the pseudo-ellipsoidal force field must be aligned along the surface tangential direction at the contact point.

As regard the second question, results from Experiment I show that the perceptibility of different surface orientations mainly depend on eccentricity, while the relationship with stiffness is less evident. In order to quantitatively analyze these dependencies, we compute so called *Cramer's* φ coefficient, which measures the strength of the relationship between two variables. By definition, the values of coefficient φ range between 0 and 1: $\varphi = 0$ means not any dependency, $\varphi = 1$ means perfect relationship. We computed the *Cramer's* φ to measure the dependency between field orientation and perceived shape, for each pair (e,k), pooling all subjects and all repetitions of Experiment I. In Figure 10.(a) we plotted the curves of *Cramer's* φ over eccentricity, parametric with respect to stiffness. For low values of eccentricity e, the *Cramer's* φ is high, i.e. the relationship between field orientation and perceived shape is strong. While e increases, φ rapidly decreases, and for $e = 1.00$. it is near to zero, i.e. there is no dependency between field orientation and perceived shape. On the other hand, the curves corresponding to the three stiffness values are almost similar to each other, independently from stiffness.

B. Experiments II, III and IV

The same analyses have been performed for all experiments. Results were very similar to those of Experiment I. The relationship between field orientation and perceived shape holds true also for different configurations of hand posture and relative displacement between virtual shapes and hand.

Figure 10 shows the strength of the relationship for all values of stiffness k and eccentricity e. As in the previous case, the relationship is more evident for the most eccentric force field (*Cramer's* φ = 0.6 for e=0.4).

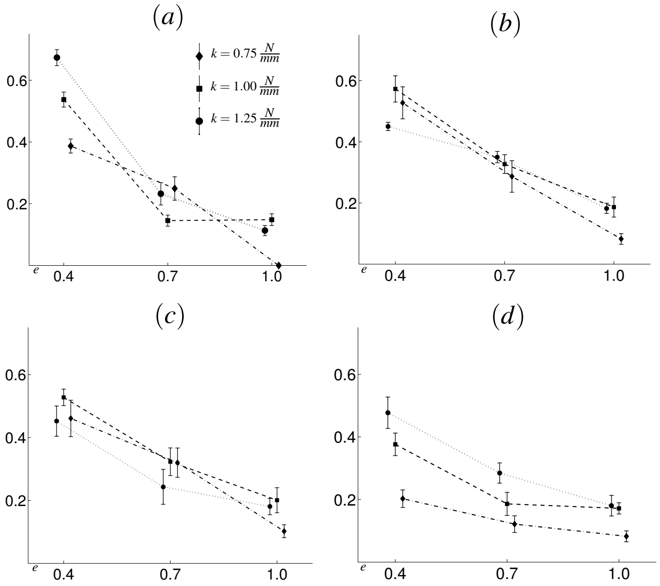


Fig. 10. Plots (a), (b), (c) and (d) represent *Cramer's* φ curves for experiment I, II, III and IV, respectively

Relying on all results discussed so far, it is our belief that both predominant associations F1-SA and F2-SB shown in Figure 9 can be considered as correct responses by the subjects. Hence a further and simpler representation of data can be now presented. The percentages of correct associations for all pairs (e,k), pooling all repetitions of all subjects and all experiments have been reported in Figure 11. The bars represent the percentages of correct responses over eccentricity, and are parametric with respect to stiffness.

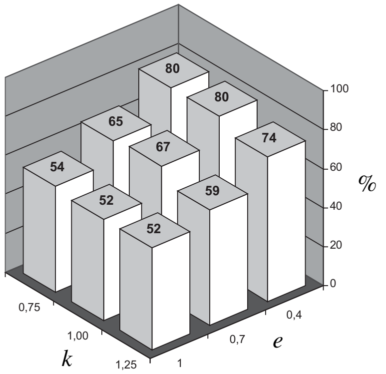


Fig. 11. Average percentages of correct responses pooling all data from all experiments.

Summarizing, all results indicate that the eccentricity of the pseudo-ellipsoidal force field is, by far, the main factor that allow the subjects to discriminate between shapes. A much weaker dependency on stiffness can be observed: discrimination for softer contacts ($k = 0.75$ or $k = 1.00$) is only slightly better than for more rigid contact ($k = 1.25$). The similarity of the results for the four experiments shows that participants were able to discriminate between the two shape whatsoever the posture of the hand and the orientation of the object.

VI. CONCLUSION AND FUTURE WORKS

This work presents an approach to augment kinesthetic stimulation in order to create a pattern of contact which the human operator can associate to a specific orientation of the virtual surface even in absence of free exploration. Such patterns are generated by using a contact model which originates from classic haptic rendering algorithms such as God-Object and Friction Cone, but which is characterized by non isotropic compliance in the neighborhood of the contact point. This feature has been achieved by creating a pseudo-ellipsoidal force field directed towards the stiction point. This contact model is suited to work with one-point haptic devices such as the PHANToM or the Omega.

Four experiments have been carried out in order to verify the effectiveness of the proposed model and to evaluate the dependency between shape perceptibility and ellipsoid parameters such as eccentricity and global stiffness. Experimental results demonstrated that participants were able to haptically perceive the shape of the object as it was oriented along the direction of maximum compliance of the contact. This tendency holds true independently from the hand posture and from the relative displacement between hand and virtual object. Furthermore, 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 revealed to have almost no effect throughout all the experiments we performed.

Finally, the results of this study show that the 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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