Exp Brain Res (2005) 164: 387–394 DOI 10.1007/s00221-005-2262-5
The original publication is available at www.springerlink.com

Trajectory of Contact Region On the Fingerpad Gives the Illusion of Haptic Shape

Hanifa Dostmohamed and Vincent Hayward[*][†]

Abstract When one explores a solid object with a fingertip, a contact region is usually defined. When the trajectory of this region on the fingerpad is artificially controlled so as to resemble the trajectory that is normally present while exploring a real object, the experience of shape is created. In order to generate appropriate local deformation trajectories, we built a servo-controlled mechanism that rolled a flat plate on the fingerpad during the manual exploration of virtual surfaces so that the plate was kept tangent to a virtual shape at the point of virtual contact. An experiment was then designed to test which mode of exploration maximized the shape information gain: active versus semi-active exploration, where semi-active exploration is when one hand touches passively and the other moves the target object, and the use of single versus multiple points of contact. We found that subjects were able to perform curvature discrimination at levels comparable to those achieved when using direct manual contact with real objects, and that the highly simplified stimulus provided by the device was a sufficient cue to give the illusion of touching three dimensional surfaces.

Keywords Haptic Perception. Illusory Perception. Shape Discrimination.

Introduction

When an object is actively explored, cues such as proprioceptive cues, local cutaneous deformation, friction, etc., are integrated together to yield the unified experience of an object. This is the case when the object is stationary and when the exploring hand is the same as the hand through which the shape is experienced. When exploration involves two hands: one to move the object and the other to touch it, similar cues are expected to contribute to the experience of shape. In this case however, the cues can be expected to combine differently or with different weights. The understanding of these elementary cues and of their contributions to an overall percept is therefore essential to the understanding of haptic shape perception.

Artificial stimuli produced with the aid of haptic interfaces have already provided some insight in what these cues might be and how they combine (Robles-De-La-Torre and Hayward, 2001; Drewing and Ernst, 2003). However, most available haptic interface devices

---

[*] To whom correspondence should be addressed. Haptics Laboratory, Centre for Intelligent Machines, 3480 University Street, McGill University, H3A 2A7, Canada, `hayward@cim.mcgill.ca`, Fax. +1-514-398-7348.

[†] This research was supported IRIS, the Institute for Robotics and Intelligent Systems, and NSERC the Natural Sciences and Engineering Research Council of Canada. The authors thank A. M. Smith and G. Robles-De-La-Torre for insightful comments on earlier drafts of the manuscript.

Exp Brain Res (2005) 164: 387–394 DOI 10.1007/s00221-005-2262-5
The original publication is available at www.springerlink.com

relay shape information through the use of force feedback and assume that a "virtual probe" serves as an intermediary between the stimulus and the operators finger(s). Previous studies have indicated that direct fingerpad contact is critical and in fact key to many haptic tasks due to the distributed fingerpad deformation that occurs (Peine and Howe, 1998). With displays relying on the virtual probe assumption, however, judging shape and curvature information is clearly at best as inefficient as in the real condition of being forced to explore and judge the shape of a real object thought the use of a stylus (Lederman and Klatzky, 1999; Christou and Wing, 2001; Kirkpatrick and Douglas, 2002).

The contributions of elementary cues to curvature perception have rarely been studied in isolation, however, many related aspects of tactile shape perception have been documented in the past. Several studies have shown that cutaneous receptors, and in particular Type I SA receptors, in the glabrous regions of the hand are highly tuned to curvature information (Srinivasan and LaMotte, 1991; LaMotte and Srinivasan, 1993; Vierck, 1979). Pont et al. (1997) classified the various roles played by different parts of the hand for the haptic discrimination of curvature. They found that not only is cutaneous stimulation important for curvature perception, but the size of the area of the skin in contact with the stimuli also plays a significant part in increasing discrimination performance. Goodwin et al. (1991) showed that constant curvature information could be judged from static curvature information presented to fingerpad to a high degree of precision. When physical objects with constant curvature were presented to subjects, they found the detection threshold to be $+4.9$ m^{-1} for convex shapes presented to the fingerpad and -5.4 m^{-1} for concave shapes.

In the present study, we were interested in demonstrating that curvature and shape information could be perceived through the sole production of a contact region trajectory on the fingerpad designed to resemble that caused by the interaction with a physical object. To test this, we built a device that rolled a flat plate on the fingerpad of a subject during the exploration of the surface of a virtual object. The principle of this technique is illustrated by Fig. 1. It shows how a plate can cause a deformation trajectory on the fingerpad that resembles the pattern created by the exploration of a real object, simply by driving the plate to be tangent to the surface of the virtual shape being explored.

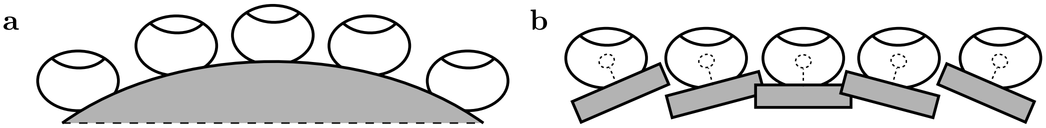

Figure 1: **a**) Traversal of fingerpad over a physical object. **b**) A fingerpad deformation trajectory similar to when traversing a real object can be created by rolling a plate on it. This can be accomplished by rotating the plate around a point located at the apex of the bone of the distal phalanx (dashed circle), and by keeping the plate tangent to the virtual shape at the point of virtual contact.

Although the entire set of the cues used by humans to acquire shape by touch is not known, those that were reliably eliminated by our experimental method include: proprioceptive cues due to vertical finger movement during exploration of a surface, all force cues correlated to object geometry, all cues related to skin deformation within the area of

Exp Brain Res (2005) 164: 387–394 DOI 10.1007/s00221-005-2262-5
The original publication is available at www.springerlink.com

contact, as well as all cues due to sliding. The only cue left was the contact trajectory.

With this method, we investigated whether varying modes of exploration had an effect on the overall performance of curvature discrimination. Doing so, we found that subjects were able to perform a typical shape discrimination task at levels of performance which were similar to those which have already been reported in the literature for subjects exploring actual objects (Goodwin et al., 1991).

Active touch was defined by Gibson (1962) to be where the subject actively controlled the movement over a target surface and passive touch to be where the subject remained stationary and a stimulus was imposed. These two modes of exploration have been studied by various groups, demonstrating that significant differences exist in judging the attributes of physical stimuli when comparing active versus passive touch (Loomis and Lederman, 1986; Lederman and Klatzky, 1987; Pont et al., 1999). The majority of studies in this area have shown that self-controlled exploratory movements generally play a role in increasing performance in the judgment of object attributes.

To these previously described modes, we suggest adding a third that we termed “semi-active touch”, where a subject uses one hand to touch passively, and uses the other hand to hold and move the target object. This happens frequently when an object is small enough to be held with one hand and explored by the other. It is also a mode often used when dealing with flimsy objects. To appreciate the flatness of a sheet of metal, for example, it is quite practical to touch the sheet with one hand and to use the other to slide it under the stationary finger(s).

The specific aims of the present study were (1) to demonstrate that three dimensional shapes can be experienced through the movement of the deformed region of contact area on the fingerpad as a subject traverses over a virtual shape in a manner that is similar to traversing over a real physical object, (2) to find the threshold of curvature detection at which subjects could identify the stimuli presented as either convex or concave with an accuracy of 75%, (3) to examine the effect of active versus semi-active exploration using our device, and (4) to examine the effect of using a single versus multiple points of contact.

Materials and Methods

Apparatus

A device was designed to orient a flat plate around a fixed point under servo control. This was accomplished through the use of a spherical five-bar parallel linkage having the property of constraining its links to move on spherical surfaces (see Appendix A for more detail). The links drove a high-adhesion non-slip plate around a fixed point which we located 3 mm above its upper surface. As illustrated in Fig. 1b, this situated the center of rotation inside the subject’s fingerpad when resting on the plate, thus reducing the finger’s rigid motion to a small amount, perhaps less than 1 mm (it would be very difficult to eliminate it completely). Fig. 2 illustrates how the plate can interact with the fingertip.

In a first mode of exploration, the device, see Fig. 3a, was mounted on a gantry rolling without friction on a table in the x and y directions as shown in Fig. 3b. The gantry allowed subjects to explore arbitrarily large virtual objects. The position over a virtual surface was

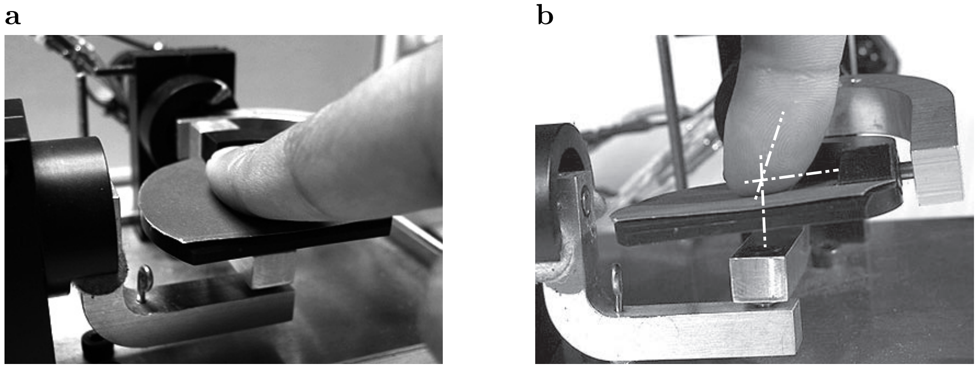

Figure 2: **a**) Nominal finger position. **b**) Exaggerated finger position to show how the plate can roll on the fingertip with dashed white lines to show center of rotation.

measured by the optical tracking system of a computer mouse (Logitech™ M-BJ69 800 dpi optical mouse) attached to the underside of the plate supporting the device. In a second mode, the device rested on a table. In this configuration, subjects used a computer mouse to explore virtual objects with their free hand.

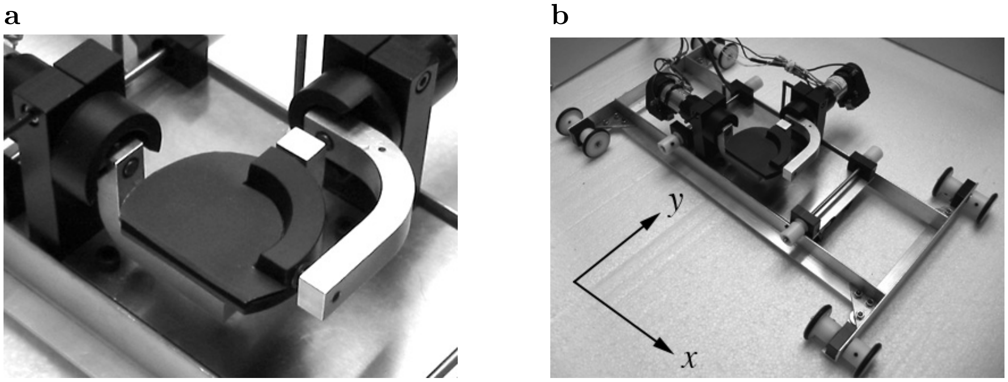

Figure 3: **a**) Servo controlled spherical linkage device. **b**) The device mounted on a lightweight gantry used for active exploration.

The device operated by servoing the plate orientation to be tangential to the virtual surface being explored at a given point. In the first mode, exploration was accomplished by moving the entire device in the horizontal plane with one or two fingerpads and experiencing the results with the same finger(s). This mode approximated closely the condition illustrated by Fig. 1b where the finger movements have no vertical component. In the second mode, the device was stationary and the virtual contact point with the surface was determined by the position of the mouse that was moved using the hand that was not touching the plate. This mode was equivalent to the actual case where one hand would slide an object under the stationary fingerpad(s) of the other hand. In this second mode the, touching finger experienced no significant rigid motion, just deformation.

Exp Brain Res (2005) 164: 387–394   DOI 10.1007/s00221-005-2262-5
The original publication is available at www.springerlink.com

Subjects

Seven subjects participated in the experiment. They were right handed individuals with no known perceptual or motor disorders. Two female and five male subjects in their twenties participated. Six of the subjects were naive as to the purpose and design of the experiment whereas one of the subjects had knowledge of the device from working in the same laboratory as the authors. No subject had any prior information regarding the experimental protocol or the purpose of the experiments. All subjects gave informed consent for participation in the experiments and were compensated for their time. The procedures were approved by the McGill University's Faculty of Education Ethics Review Committee.

Stimuli

The stimuli consisted of virtual sections of spheres with varying curvatures (where curvature is defined as the inverse of the radius). Both positive and negative curvatures were utilized (i.e. convex and concave shapes). Curvatures of the virtual spheres presented ranged from ±2.5 to ±10 m^{-1} (i.e. $1/r = \pm2.5$, 2.85, 3.33, 4.00, 4.50, 5.0, 5.5, 6.67, 8.33, 10.0 m^{-1}; spheres of radii ranging from 0.4 m to 0.1 m) in order to bracket the discrimination threshold which for most subjects was about 4.0 m^{-1} in the active conditions and 5.0 m^{-1} in the semi-active conditions. The range of curvatures to be used were based on a decision made from the results of a pilot study that was conducted with 3 subjects and from a comparison with real objects such as glass condenser lenses.

Experimental Setup

Subjects were seated in front of a table with their forearm resting on the table and their fingerpad(s) resting on the plate of the device. A curtain placed between the subject's body and their forearm prevented them from seeing their hand. The computer was placed out of the sight of the subjects. The virtual stimuli presented were rendered with a personal computer running the Linux® operating system with real-time extensions. The thread that updated the orientation of the device ran at a frequency of 1 kHz.

The virtual shapes were presented to the subjects' fingerpad(s) in a 25 × 25 mm window using the device described above. If the boundary was exceeded, then the plate was brought to rest. Although the device was able to traverse a range of 280 × 280 mm, we limited the stimulus window because previous studies have shown that the spatial length of a stimulus that is haptically explored can directly influence the judgment of haptic curvature discrimination (Pont et al., 1996). Another important consideration was to limit the effect of proprioceptive cues since previous studies have demonstrated these cues can affect haptic shape identification performance (Voisin and Chapman, 2002).

Subjects were instructed to keep their arm straight so that the nail(s) of their digit(s) would remain facing upward and stationary. Because it was not practical in this study to constrain the exploratory trajectories, subjects were free to move the mouse (when the gantry was not used) or the entire device (when the gantry was used) to explore the virtual surface in any particular direction they chose. Commonly used exploration movements were fore-aft, lateral and spiral motions. In all of the cases however, the fingerpad(s) remained

Exp Brain Res (2005) 164: 387–394   DOI 10.1007/s00221-005-2262-5
The original publication is available at www.springerlink.com

stationary on the plate and did not undergo any significant rigid motion with respect to the mechanism's ground link.

Training Phase

The experimental phase was preceded by a brief training phase in which subjects were presented with 12 trials of convex stimuli and 12 trials of concave stimuli. Its purpose was to familiarize them with the condition under which they were to be be tested and with the virtual shapes. During the training, subjects were given beforehand a list of the sphere sizes that were to be presented so they knew what profiles would be presented, however, no feedback was given.

Subjects were asked to experience the randomly presented virtual stimuli (using the experimental condition that would be immediately following the training) and to judge whether they felt convex or concave. Once they were ready to make a decision, they entered their response by pressing keys on a keyboard. One key was marked with a symbol of a convex shape ∩, and another key was marked with the symbol of a concave shape ∪. No time limit was imposed, however subjects were instructed to respond as soon as they were ready to make a choice and were timed. This was measured by the time between which a new profile was presented to the subject signaled by a computer generated "bell sound" to the time when the subject entered their response.

Experimental Phase : Effect of mode of exploration

'Active' exploration conditions were created when the device was mounted on top of the gantry so the hand used to experience the shape was the same as the hand that was used to move the device over the virtual surface. 'Semi-active' exploration was in effect when the device was immobilized (i.e. the gantry was not used) and the subjects used their left hand to move the mouse cursor over a virtual surface while experiencing the surface with the right hand. A 'single point of contact' condition was when the subject used the fingerpad of the index finger to experience the virtual surface, and 'multiple points of contact' was defined to be the case when the subject used the fingerpads of the index finger and of the middle finger to experience the virtual surfaces.

Combining these cases led to four conditions illustrated in Fig. 4. Condition 1: 'Active exploration using a single point of contact', Condition 2: 'Active exploration using multiple points of contact', Condition 3: 'Semi-active Exploration using a single point of contact', and Condition 4: 'Semi-active exploration using multiple points of contact'. These four conditions entailed four training phases and four experimental phases.

Subjects were first tested in Condition 1 (active exploration, single point of contact), then in Condition 3 (active exploration, two points of contact), then in Condition 2 (semi-active exploration, single point of contact), and finally in Condition 4, (semi-active exploration, two points of contact). Subjects were given a five minute rest after completion of each experimental phase.

Similar to the training phase, during the experimental trials for each condition, subjects were asked to judge the curvatures presented and enter their responses (convex or concave)

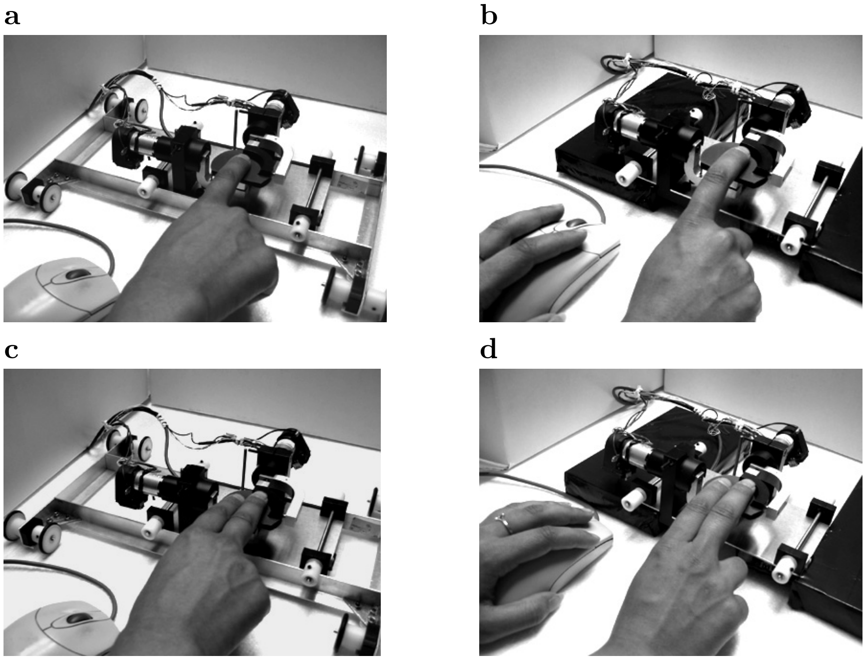

Figure 4: The four conditions that were employed: **a,c**) Moving the device over the virtual surface with one or two fingers, **b,d**) moving a mouse with the free hand of over the virtual surface and touching the stationary device with one or two fingers.

using the marked keys on the keyboard. This phase differed from the training however in that no prior information was given, and profiles were randomly presented.

One experimental trial consisted of either a convex or concave profile having a specific curvature which the subjects were asked to judge. Blocks of trials were administered under one specified condition. In order to maximize the data and minimize the time required from the participants, the number of times stimuli were presented for each curvature category was varied. Curvatures which from the pilot study which were observed to be easier to discriminate (i.e. curvatures greater than 5.5 m^{-1}) were presented less often than those that were more difficult to discriminate. Each block consisted of 110 trials and was dedicated to one of the four exploration methods.

Data collection and analysis

We calculated the probability of correctly classifying stimuli to be either convex or concave for each curvature level under each of the four conditions for all subjects. The probabilities were averaged for each independent conditions (within subjects) since the number of stimuli presented varied across curvatures as described above. The data for each subject were then fit to a Weibull psychometric function in order to determine the thresholds of curvature detection at the 75% accuracy level. The psychometric function parameters were obtained using maximum likelihood estimation and subsequent Monte Carlo simulations were run in order to assess the goodness of fit. These analysis were carried out using the SPSS™ package and the `psignifit` toolbox (Wichmann and Hill, 2001a; Wichmann and Hill, 2001b). Representative examples of how the threshold values were obtained from fitted psychometric functions are illustrated in Fig. 5a.

A two factor with repeated measures analysis of variance test (ANOVA) was then carried out in order to assess whether differences between methods used for exploration of the virtual surfaces were significant.

Results

Table 1 summarizes the performance of subjects under Conditions 1–4. A trend could be observed in the thresholds at which subjects were able to identify the stimuli presented at an accuracy of 75%. Table 1 also shows the time subjects required to judge the various virtual stimuli. The percentage of correct responses that subjects gave were tabulated for each subject and averaged across subjects. The mean score for participant accuracy are also presented in Table 1.

The number of contact points as well as semi-active and active modes for the exploration of the virtual stimuli were found to have an effect on the overall performance for curvature discrimination. The two factor repeated measures ANOVA showed that a significant difference existed between the use of single and multiple points of contact when subjects explored the virtual surfaces [$F(1, 6) = 5.69$, $p = 0.05$]. The two factor repeated measures ANOVA also showed a significant difference between the use of active and semi-active modes of exploration of curvature [$F(1, 6) = 13.69$, $p < 0.05$]. On average, when actively exploring the stimuli, subjects could detect smaller curvatures using multiple points of contact than when using one point of contact (i.e. 3.96 m^{-1}vs 4.40 m^{-1}). Similarly, during semi-active exploration, the threshold of curvature detection decreased when using multiple points of contact compared to those detected with a single point of contact (i.e. 5.02 m^{-1}vs 5.18 m^{-1}).

Fig 5b shows the psychometric functions for average data across subjects obtained under the four conditions of the experiment. The thresholds at which subjects were able to correctly identify 75% of the stimuli were found to be $\mathrm{T}_{75} = 3.96$ when using multiple points of contact and active exploration, $\mathrm{T}_{75} = 4.40$ when using a single point of contact and active exploration, $\mathrm{T}_{75} = 5.02$ when using multiple points of contact and semi-active exploration, and $\mathrm{T}_{75} = 5.18$ when using a single point of contact and semi-active exploration.

Discussion

This study has shown that the single cue of trajectory of the contact region on the fingerpad(s) could be integrated over time by the brain to give rise to the experience of curvature. The thresholds at which curvatures could be discriminated and the time required using this cue alone were observed to be impressive. The consistently short times required for subjects to make a decision coupled with the fact that most of the subjects had never seen or heard of the device before the experiments makes it very unlikely that cognitive processes could have been at play.

Goodwin et al. (1991) conducted a study similar to ours in which the goal was to

Table 1: Performance (in m^{-1}) at T_{75}, average time (in seconds) for each subject, and score averaged across subjects under all conditions.

Conditions	active two finger		active one finger		semi-active two finger		semi-active one finger	
Subject	T_{75} m^{-1}	Time s	T_{75} m^{-1}	Time s	T_{75} m^{-1}	Time s	T_{75} m^{-1}	Time s
A	3.96	10.7	4.14	14.2	3.91	17.3	4.47	13.7
B	3.78	8.6	4.37	16.2	4.17	16.2	4.58	13.0
C	4.04	10.6	4.40	11.7	4.20	10.2	5.01	13.0
D	4.02	10.0	3.96	9.3	4.29	12.4	4.74	12.2
E	3.33	12.1	3.83	15.8	5.38	15.5	3.96	10.4
F	4.26	12.7	5.35	11.2	5.81	9.7	6.71	13.5
G	4.72	7.7	5.01	9.4	5.52	12.8	6.71	10.0
av.		10.3		12.5		13.4		12.3
s.d.		1.7		2.9		3.0		1.5
av. [a]	4.01		4.44		4.75		5.16	
av. [b]	3.96		4.40		5.02		5.18	
s.d.	0.43		0.56		0.78		1.10	
radii [c]	0.25		0.23		0.20		0.19	
av. score	73%		74%		65%		63%	

[a] Thresholds from simple average of T_{75} values for each subject across each condition.

[b] Thresholds from Weibull function fit obtained from averaging individual probabilities across subjects and conditions.

[c] Radii of the virtual spheres corresponding to the curvature thresholds.

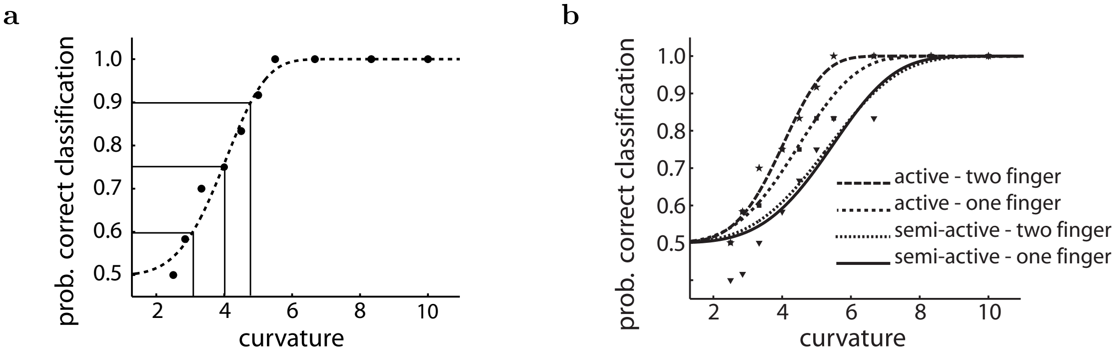

Figure 5: **a**)Representative sample of the Weibull psychometric function fit to data points representing a subject's performance with varying curvature when exploring the virtual surface. **b**) Average data obtained from subjects in the four conditions.

Exp Brain Res (2005) 164: 387–394 DOI 10.1007/s00221-005-2262-5
The original publication is available at www.springerlink.com

bracket the threshold of curvature detection when real physical objects were statically presented to the fingerpad. To our knowledge, this is the only other study that has quantified the threshold for curvature detection of large stimuli in this manner, and so it was used as a benchmark for comparing the results that we obtained. The study reported that subjects could discriminate curved surfaces from flat surfaces with discrimination thresholds of $+4.9\ \mathrm{m}^{-1}$ and $-5.4\ \mathrm{m}^{-1}$ at an accuracy of 75% when passively touched. Although we did not analyze convex and concave stimuli separately, we obtained similar results in terms of discrimination thresholds when exploring virtual stimuli using our device under the semi-active condition. We may attribute the differences to the stimuli delivery methods. In our study, for the semi-active condition, while the right hand of the subject remained stationary and passively received the stimuli (as in the Goodwin study), we allowed the subject to move over the virtual shape with their free hand. Although still passively experiencing the stimuli, the subjects had control over how they were explored. Furthermore, our stimulus delivery method gave no information related to shape via skin deformation in the area of contact. Such deformation occurs when using physical stimuli as it was the case in previous studies.

A small, but significant advantage was observed with the use multiple points of contact compared to the use of a single one during the active and semi-active exploration of stimuli. We hypothesize that this was due to a number of combined factors such as a larger population of cutaneous afferents that are stimulated when more than one fingerpad is used, and a small differential vertical motion between the two fingers that occurs when two fingers contact the plate simultaneously.

In our study, we did not find any significant differences in the amount of time needed to arrive at judgments across the four different conditions, however, the time required to arrive at a judgment was observed to be much shorter than reported in similar studies using haptic devices for shape perception (Kirkpatrick and Douglas, 2002).

Active versus passive exploration has previously been studied for tactile recognition of objects (Gibson, 1962; Loomis and Lederman, 1986; Lederman and Klatzky, 1987; Pont et al., 1999). Whereas the large amount of literature on this topic suggests that self-controlled exploratory finger movements increase performance, Pont et al. concluded the opposite: that similar mechanisms underlie static and dynamic curvature comparison for curvatures ranging from $-4\ \mathrm{m}^{-1}$ to $+4\ \mathrm{m}^{-1}$. Our study, however, confers with the former view and demonstrates that actively exploring a surface provides significant advantage on the performance of curvature discrimination over passive exploration of the same stimuli. Differences between our study and that of Pont's may be accounted for by the fact that certain cues such as friction and speed of exploration are variable attributes between the exploration of real and virtual stimuli. We would like to investigate this possibility as a source of discrepancy.

In our study we tried to minimize the amount of joint movement in order to limit the use of proprioceptive information for the curvature discrimination tasks. Studies have previously reported that cutaneous information and in particular compression of the fingerpad is a major contributing factor in discrimination of two dimensional angles (Voisin et al., 2002). They add that proprioceptive cues are important in increasing performance. In future work, we would like to incorporate these proprioceptive cues in a controlled manner into the design

Exp Brain Res (2005) 164: 387–394 DOI 10.1007/s00221-005-2262-5
The original publication is available at www.springerlink.com

of our device in order to be able to quantify their contributions.

Kappers and Koenderink (1996) found that dynamic curvature discrimination of cylindrical surfaces did not follow a Weber law and that performance increased as did curvatures. Using our device, we also observed a similar phenomenon: subjects' performance increased as the curvatures of the virtual spheres decreased. We however have not yet tested for the threshold at which objects with large curvatures can be perceived at the 75% level accuracy as was done for stimuli with low curvatures. We suspect that the conditions which would enhance subjective performance using smaller stimuli would be quite different from those conditions which were seen to be optimal for the perception of stimuli with small curvatures. We would like to investigate these questions in future work as well.

Appendix A

The device was made of a closed-loop five-bar spherical mechanism, having two degrees-of-freedom, Fig. 6a. While many mechanisms and structures can orient a plate around a point, this design is particularly parsimonious and efficient. The stationary link is labeled `Link-0`. The plate of the device is assigned to `Link-3`. We gave the name of "Morpheotron" to this device because of its ability to deform (morph) the skin in a manner that elicits a sensation of shape.

The center of rotation, shown in the figure at the intersection of the axes of the motors, is such that the axes of all five joints always meet there. It was set at 3 mm above the upper surface of the plate. Plate orientation resulted from controlling the motors angles via proportional-derivative feedback control and kinematic transformations. The motors were Maxon™ 3 W DC motor with 19:1 gear-head reduction. They produced torques that were largely sufficient to counteract the load created by the subject's finger. The Morpheotron was used stationary or mounted on a light weight rolling gantry schematized in Fig. 6b.

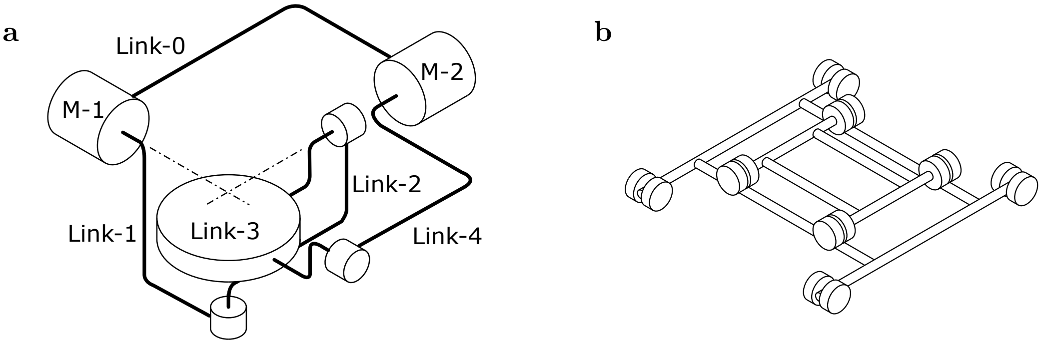

Figure 6: **a**) Schematic kinematic arrangement. **b**) Rolling gantry sketch.

The plate tilted around a point located inside the fingertip as a function of any of the exploration movements. For instance, if the subject were to move 25 mm from the right to the left, the plate would change by the same amount when the subject moved 25 mm using the fore-aft motion, or along any of the "meridian" trajectories. As another example, a circular trajectory along a "parallel" of the virtual sphere would cause the plate to undergo

Exp Brain Res (2005) 164: 387–394 DOI 10.1007/s00221-005-2262-5
The original publication is available at www.springerlink.com

a full cycle at constant inclination with respect to the vertical axis, thereby creating a closed trajectory of the contact point on the fingertip. These changes in tilt of the plate, therefore simulated the exploration of sphere. Similarly, in the case of semi-active exploration, the plate tilted by an amplitude that corresponded to the distance traversed by the left hand. To give scale, when the subject moved to the right extreme of the 25 × 25 mm boundary, the plate tilted 2.86^o when a virtual curvature of 0.4 m^{-1} was present.

References

Christou, C. and Wing, A. M. (2001). Friction and curvature judgement. In *Proc. Eurohaptics*, University of Birmingham, UK.

Drewing, K. and Ernst, M. O. (2003). Integration of force and position cues in haptic curvature perception. *Abstr. Psych. Soc.*, 44:112.

Gibson, J. (1962). Observations on active touch. *Psychological Review*, 69:447–491.

Goodwin, A., John, K., and Marceglia, A. (1991). Tactile discrimination of curvature by humans using only cutaneous information from the fingerpads. *Exp. Brain Res.*, 86:663–672.

Kappers, A. and Koenderink, J. (1996). Haptic unilateral and bilateral discrimination of curved surfaces. *Perception*, 25:739–749.

Kirkpatrick, A. E. and Douglas, S. A. (2002). A shape recognition benchmark for evaluating usability of a haptic environment. In Brewster, S. and Murray-Smith, R., editors, *Proc. First International Workshop on Haptic Human-Computer Interaction*, pages 151–156. Berlin:Springer Verlag.

LaMotte, R. and Srinivasan, M. (1993). Response of cutaneous mechanoresceptors to the shape of objects applied to the primate fingerpad. *Acta Psychologica*, 84:41–51.

Lederman, S. and Klatzky, R. (1987). Hand movements: A window into haptic object recognition. *Cognitive Psychology*, 19:342–368.

Lederman, S. and Klatzky, R. (1999). Sensing and displaying spatially distributed fingertip forces in haptic interfaces for teleoperator and virtual environment systems. *Presence: Teleoperators and Virtual Environments*, 8(1):86–103.

Loomis, J. and Lederman, S. (1986). Tactual perception. In Boff, K., Kaufman, L., and Thomas, J., editors, *Handbook of Perception and Human Performance*, volume 2.

Peine, W. and Howe, R. (1998). Do humans sense finger deformation or distributed pressure to detect lumps in soft tissue? In *Proc. ASME Dyn. Sys. and Control Div.*, volume DSC-64, pages 273–278, Anaheim, California.

Exp Brain Res (2005) 164: 387–394   DOI 10.1007/s00221-005-2262-5
The original publication is available at www.springerlink.com

Pont, S., Kappers, A., and Koenderink, J. (1996). The influence of stimulus length on static haptic curvature discrimination. In Kappers, A., Overbeeke, C., Smets, G., and Stappers, P., editors, *In: Studies in Ecological Psychology*, pages 69–72. Delft University Press, The Netherlands.

Pont, S., Kappers, A., and Koenderink, J. (1997). Haptic curvature discrimination at several regions of the hand. *Perception and Psychophysics*, 59(8):1225–1240.

Pont, S., Kappers, A., and Koenderink, J. (1999). Similar mechanisms underlie curvature comparison by static and dynamic touch. *Perception and Psychopysics*, 61(5):874–894.

Robles-De-La-Torre, G. and Hayward, V. (2001). Force can overcome object geometry in the perception of shape through active touch. *Nature*, 412:445–448.

Srinivasan, M. and LaMotte, R. (1991). Information processing in the somatosensory system. In Frazen, I. and Westman, J., editors, *Handbook of Perception and Human Performance*, pages 59–69. London: Macmillan.

Vierck, C. (1979). Comparisons of punctuate, edge and surface stimulation of peripheral, slowly-adapting, cutaneous, afferent units of cats. *Brain Research*, 175:155–159.

Voisin, J., Benoit, G., and Chapman, C. (2002). Haptic discrimination of object shape in humans: Two-dimensional (2-d) angle discrimination. *Exp. Brain Res.*, 145:239–250.

Voisin, J. and Chapman, C. (2002). Haptic discrimination of object shape in humans: Contribution of cutaneous and proprioceptive inputs. *Exp. Brain Res.*, 145(2):251–260.

Wichmann, F. and Hill, N. (2001a). The psychometric function i: Fitting, sampling and goodness of fit. *Perception and Psychophysics*, 63(8):1293–1313.

Wichmann, F. and Hill, N. (2001b). The psychometric function ii: Fitting, bootstrap based confidence intervals and sampling. *Perception and Psychophysics*, 63(8):1314–1329.