Friction and curvature judgement

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Abstract

Local shape is an important attribute that can be sensed by exploratory movements of the finger. Normally this involves a blend of tactile and proprioceptive cues. A curved surface will deform the pad of a single finger and so tactile cues can indicate whether a surface is convex or concave or whether it slopes one way or another. When more subtle discriminations must be made between different degrees of curvature, scanning motions are made in which the finger sweeps along the surface. In this case the cue to curvature is the change in position of the finger tip over time and here proprioceptive input is important. We have been examining how curvature judgements are affected by the force reflected back from the curved surface during scanning. Normally when you run your finger over a surface, you experience resistance to motion due to friction. This resistance creates a force vector which varies in direction with friction. But the vector also varies in direction with the curvature of the surface traversed by the finger. We used a two-alternative forced-choice (2AFC) task in an adaptive staircase in which subjects made comparisons between various test curvatures and a reference curvature in order to find the point of subject equality (PSE) between the two. Differences in friction between reference and test stimuli were found to alter the PSE in a consistent manner. In particular, we found that the reference curvature was only closely matched when no frictional disparity existed between reference and test surface. Reference surfaces that exerted high frictional forces produced smaller curvatures as PSEs while surfaces with low friction produced high curvature matches. These results suggest that forces experienced in palpating a surface may be utilised in the comparison of curvature.

1. Introduction.

Curvature is an important local shape descriptor that may vary continuously across the surface of an object. In terms of the sensation of touch, curvature may be assessed by either the cutaneous receptors of the glabrous skin (finger pads or palm) of the hand or through proprioception supported by several types of receptors in the muscles of the hand, or both. Evidence for the former type of sensitivity to curvature has been provided by LaMotte et al (1998); see also Bisley et al (2000) who showed that slowly adapting type 1 mechanoreceptors in the monkey hand respond to the curvature of a raised bump on an otherwise flat surface. Psychophysical experiments have also shown that human subjects are very good at judging curvature using only the finger pads (Goodwin et al, 1991; Goodwin & Wheat, 1992). Evidence for the ability to perceive curvature through proprioception has been studied using psychophysical experiments on humans. Such experiments involved curvature discrimination based on active touch or passive deformation of the whole hand (e.g. Vogels et al, 1999; Pont et al, 1998). Surface curvature, it seems, may be assessed equally well by both static placement of the hand across the surface or by active touch with the hand or fingers (Pont et al, 1999). However, it has been argued elsewhere that active touch is better than passive touch in the discrimination of shape and recognition of objects because the former can yield continual pick-up of information from the surface (Gibson, 1966). Differences in the discrimination of curvature in different parts of the hand were also studied by Pont et al (1997) who found that the palmar side of the hand is more adept at this task than the dorsal side. Pont et al. attribute this to the preponderance of cutaneous input from the palm although the task clearly involves both (cutaneous and proprioceptive) types of input.

A notable feature of the visual sense is that of maintaining shape invariance or shape constancy. That is, a shape may be encoded in geometrical terms equally well regardless of which visual cues are being used to depict it. There is active debate in the vision community whether this is the case with human vision and we may ask whether such an ability is found in active touch as well. So what physical factors might influence the perception of shape from visually unaided active touch? Imagine that a convex bump on a flat surface is being stroked by a single finger that does not provide cutaneous input. Both the horizontal, scanning and vertical velocity of the finger and the reactive force of the surface acting on the finger may be affected by the object impeding motion of the finger. These physical variables may be encoded by the mechanoreceptors to the muscles of the upper limb and therefore, if curvature can be encoded by through proprioception, then it may be through changes in these variables. Surfaces of real objects also exert an additional, frictional force on the finger in a direction opposite to the direction of motion. If the force applied through the finger is greater than the tangential force exerted by friction the finger starts to slide across the surface. In this case, dynamic frictional forces act on the finger to impede its motion. This resistive force depends on the normal force at the contact surface but is also a function of the coefficient of dynamic friction of the surface. It is therefore possible that the perception of surface curvature is influenced by the frictional properties of the surface.

We isolated proprioceptive cues to curvature by using the Phantom haptic interface. The Phantom is essentially a robot arm controlled by three motors and connected to a computer that can control the exertion of reactive forces to a single finger placed in a thimble. These forces can be used to simulate solid objects, friction and viscosity. The useful feature of using the Phantom is that sensory input is provided by active palpation without local tactile information and this in turn allowed us to focus on the contribution of proprioceptive cues.

2. Method.

2.1 Simulation of Solid Shape.

The Phantom is a haptic rendering system that uses 3D force feedback to generate the impression of 3D solid shape, viscosity, friction and surface texture. The haptic rendering process is similar to that in computer graphics (Salisbury et al. 1995; see also Ho et al, 1999). For instance in the rendering of solid shape the position of the cursor or stylus is tracked at a frequency of 1 kHz until an intersection with a virtual surface is detected. Once an intersection is detected various forces can be applied to the finger to give not only the impression of solidity but also of surface compliance, texture and surface friction. It should be noted that the perception of solid shape is generated only as a function of the observers active movements of a single finger inserted into a thimble. If there is no movement (and therefore no exerted force) then no haptic feedback can be provided. This allowed us to isolate the proprioceptive sense that results from active movement.

As well as generating the impression of solid shape the Phantom can also be programmed to simulate static and dynamic friction (Salisbury et al. 1995). Friction is simulated by detecting the collision between the finger/stylus and an object in the scene and applying an appropriate tangential force to the finger. The tangential force serves to restore the finger to an initial position as the finger attempts to slide across the surface. Thus the finger sticks on the surface. If the tangential force required to restore the finger becomes greater than the normal force times the coefficient of static friction then sliding occurs. During sliding a tangential force (proportional to the coefficient of dynamic friction) is applied to the finger in the direction opposite to the direction of motion, which provides the sensation of dynamic friction. In this manner, the surface is made to feel either slippery like ice (i.e. low friction) and feels sticky like rubber (i.e. high friction).

2.2 Stimulus definition.

The curvature (or more correctly the normal curvature) of a surface at a point is the curvature of a section of the surface in a given direction and perpendicular to the tangent plane at that point. On a sphere the normal curvature is the same in all directions. On a cylindrical surface, which is what we shall be using here, the normal curvature is zero along the elongated axis and maximal in a direction perpendicular to this axis. Cross sections of a right circular cylinder are circular in form and the maximal normal curvature of the cylinder is therefore given by the curvature of a circular section which is inversely dependent on the radius.

The stimulus in this experiment was a virtual cylinder that the subject was allowed to stroke twice. This virtual surface was generated by the Phantom force-feedback system. This was implemented using the application programming interface GHOST. The Phantom was programmed to generate cylinders with variable cross-section and it was the radius of these cross sections that served as the independent variable in these experiments. The cylindrical surface was defined within a virtual space measuring 5cmx20cmx20cm (see figure) with the X axis set as the horizontal axis perpendicular to the desk at which the subject sat. The Y axis was the gravitational vertical axis and the Z (depth) axis defined the forward-backward direction with respect to the subject. The principal axis of the cylindrical segment was oriented along the X axis and the subject stroked the segment from the top in the forward-backward (Z) direction. Movement in the X direction was restricted so that strokes across the surface followed a similar trajectory each time.

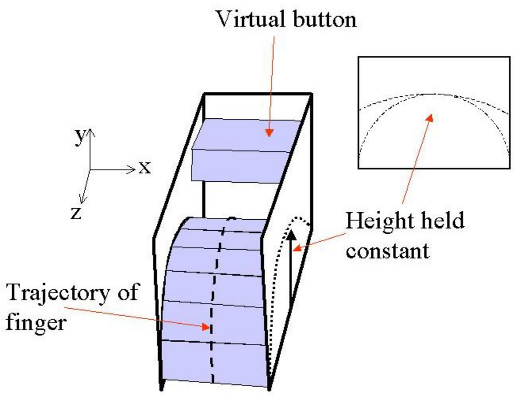

Figure 1: Schematic representation of object surfaces created by haptic rendering.

2.3 Task.

The aim of this experiment was to determine how well a subject could discriminate between the curvature of two circular strips and to test whether this ability is affected by friction. The only curvature information was through proprioceptive sources arising from the Phantom. We measured the point of subjective equality (PSE) for two curvatures (0.013/cm and 0.008/cm). The curvature was manipulated by varying the radius of the cross sections of a circular cylinder (i.e. 75mm and 125mm) however for a constant position of the centre of curvature this manipulation of radius would have resulted in an additional height cue in the y direction (see Figure 1). This was controlled by allowing the centre of curvature to move up or down in the Y direction so that the maximal height of the cylinder remained constant.

The subject was asked to determine which of two (sequentially presented) curvatures was greater. One of the two stimuli was the constant reference (radius = 75mm or 125mm) and the other varied according to a 1-up/1-down adaptive staircase. After having stroked both strips the subject had to respond using a computer keyboard which had the greater curvature. Using this method the PSE was estimated as the average of six reversals. In order to bring the test stimulus quickly to the PSE each staircase measurement was preceded by 4 'reducing reversals' in which the increment or decrement of the test was varied as a function of the reducing reversal number.

The influence of dynamic friction was tested by introducing disparities in simulated friction coefficient between the reference and test stimuli. Two friction coefficients were used (μ=0.2 and μ=0.8) for both the reference and test stimuli. The μ=0.2 stimuli felt slippery, rather like moving ice on ice. The μ=0.8 stimuli felt rubbery. In both cases the friction coefficients were low enough that smooth and uninterrupted movement of the finger across the strip was still possible.

2.4 Design.

The two sizes of reference stimulus and the two friction values for both test and reference resulted in 8 distinct conditions in a balanced design. That is, each condition consisted of a unique value of reference radius (either 75mm or 125mm), reference friction (either 0.2 or 0.8) and test friction (either 0.2 or 0.8). Mean PSEs were collected for each of these 8 conditions in random order and repeated 5 times for each subject.

2.5 Subjects.

Four subjects participated in this experiment and were rewarded with gift vouchers. All subjects were spent several minutes training on the task prior to the actual data collection. Subjects' view of their hands was occluded during the experiment and they were asked to close their eyes.

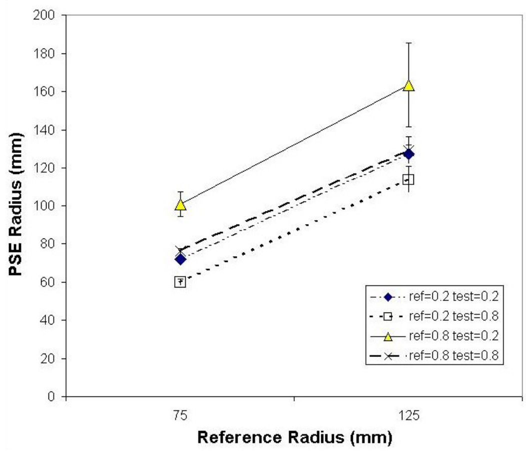

Figure 2: Effects of reference radius and surface friction on point of subjective equality (PSE)

3. Results.

The dependent measure for this experiment was the PSE radius which is defined as the radius of the test surface that subjects equate with the magnitude of a given reference radius regardless of frictional differences. We report results mainly in terms of the radius of curvature because it involves more intuitive and manageable dimensions of size in terms of millimetres rather fractional curvature quantities although it should be remembered that a smaller radius of curvature produces a larger surface curvature. Figure 2 shows the PSE radius averaged across all 4 subjects and plotted as a function of the reference radius. The four lines correspond to the four conditions used. The reference radius was matched closely only when the friction coefficients for test and reference stimuli was the same (i.e. when $\mu_r = \mu_t$). When there were disparities between the test and reference stimulus friction systematic errors in mean PSE were observed. For example, when the reference friction coefficient was greater than the test stimulus friction (i.e. when $\mu_r > \mu_t$) the mean PSE radius obtained was at least 25% higher than the actual reference radius which meant an underestimation of the radius of curvature of the reference stimulus (that is the reference appeared more curved than it really was). For trials in which the reference surface friction was less than the test surface friction (i.e. when $\mu_r < \mu_t$) the mean PSE radius was found to be at least 11% lower than that of the reference stimulus. These results mean that the radius of curvature of the reference stimulus was underestimated for high friction surfaces and overestimated for low friction surfaces.

An analysis of variance was performed on the data with three repeated measures (reference friction μ_r, test friction μ_t and reference radius) and mean PSE radius as dependent variable. Assuming an α=0.05 as our level of significance we found a significant main effect of reference friction [$F_{1,3} = 11.42$, $p<0.05$], an almost significant effect of test stimulus friction [$F_{1,3} = 11.42$, $p=0.09$], and a highly significant main effect of radius. None of the interactions (i.e. between μ_r and radius) was significant.

In terms of repeatability, we use the standard deviation of settings to assess differences in relative difficulty. Standard deviations were calculated for the five repeated settings made by subjects for each of the 8 data points. The mean standard deviations (averaged across all subjects) for the 75mm and 125mm circular segments were 11mm and 21mm respectively. A paired comparison students t-test showed that this difference in means was significant. The increased variance of settings for the 125mm radius strip reflects greater difficulty in assessing a shallower curvature (larger radius of curvature).

4. Conclusions.

We have described an experiment in which subjects made curvature comparisons between sequentially presented curved strips, simulated using the Phantom haptic interface. The results show clearly that simulated curved strips can be accurately discriminated using kinesthetic information derived from the hand joints as the finger is deflected by the surface during stroking. Our results also highlight the importance of friction, and consequently of reactive forces, on the curvature discrimination process. We found that the radius of strips with a higher frictional coefficient than the comparison stimulus was overestimated. The radius of strips with a lower frictional coefficient than the reference was underestimated. In terms of curvature, this means that the curvature of rough or high friction surfaces is underestimated relative to low friction surfaces and our results show that the converse of this is also true. When the friction coefficients of the reference and test stimuli were the same subjects settings of the two radii, and therefore curvatures, were a close match. It remains for us to explain exactly why disparities in friction cause under- and over-estimates in curvature in these experiments and we are investigating three potential sources:

1) The subjects use tangential forces to encode curvature and tangential forces arising from friction disrupt this encoding.
2) It is not force but change in velocity that is used to encode curvature. The frictional differences disrupt direct velocity comparisons.
3) The result is an artifact of the process of generating virtual shapes and virtual frictional forces.

5. References.

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