DISPLAYING SMALL SURFACE FEATURES WITH A FORCE FEEDBACK DEVICE IN A DENTAL TRAINING SIMULATOR

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This paper describes two algorithms for representing small (< 100 μm) step edges with a force feedback simulator. The first algorithm is the traditional spring-damper force feedback model that represents the cursor's present position as a point. The second, new, model represents the cursor as a small sphere. A forced-choice experiment with eight participants indicates that people can judge the height of small edges more reliably with the sphere model. The results are useful for the development of simulators for training fine haptic skills. They are more generally useful to human factors professionals in the haptics community because they describe how to overcome a fundamental perceptual challenge with haptic stimulators.

INTRODUCTION

To assess the fit of a dental crown, a dentist slides a sharp-tipped, curved, steel probe across the junction between the crown and the tooth. If the crown fits well, the joint is flush and the tip slides smoothly across. If there is a gap or a step edge between the tooth and the crown, the probe will catch and the dentist may decide that the crown must be repaired. Typically, a crown is judged to be clinically acceptable if it has a gap or step edge of less than 100 μm. There is some debate about how reliable this test is; anecdotal evidence suggests that using a dull probe can make the gaps feel smaller. However, the details of the gap geometry and the mechanical interaction with the probe have never been studied. Nor is it clear exactly what sensations the dentist uses as perceptual cues in making this decision. Nevertheless, the accurate perception of crown margin gaps is an important skill for dentists and is part of their certification examination.

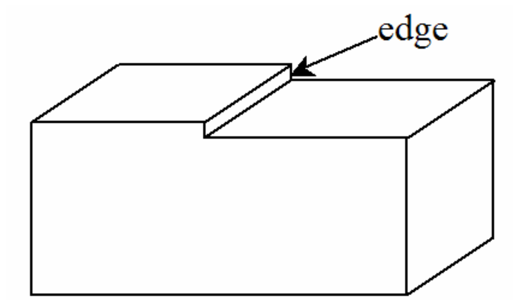

Figure 1. A step edge on a block surface illustrates the geometry of the edge-like junction between a crown and a tooth. The size of the edge is exaggerated in the drawing.

For several years we have been developing a dental training simulator based on a force-feedback device (Johnson, Thomas, Stanford, & Dow, 2001; Thomas, Johnson, Dow, & Stanford, 2001; Wagner et al., 2000). This previous work emphasized the detection of crown margin gaps. The current goal is to simulate the interaction between a Shepard's Hook dental explorer dragged across a simple step edge, such as that pictured in Figure 1.

Determining and reproducing the characteristic signal for this task has proven to be far more elusive than the signal for the carious lesions.

One of the reasons that the crown margin gap simulation has been so challenging is the small size of the gap. The critical size for the clinical determination is 100 μm, which is close to the 23 μm position resolution of our force feedback device (a PHANTOM Desktop Model, Sensable Technologies) (Sensable Technologies, 1999).

Both the standard force feedback programming model and the physical design cost conspire to make presenting small surface features a challenge. The default technique to simulate a hard surface with a force feedback device is based on a spring-damper model. The position and position derivatives of the cursor position with respect to the surface are measured at each update rate and a response force is sent to device's motors to provide a response force. Adjusting the model parameters can make the surface feel hard, soft, sticky, viscous or spongy (Adams & Hannaford, 1999; Klatzky, 2003; Luecke & Edwards, 1996). The stiffness parameter in particular is limited to a given maximum value beyond which the control loop becomes unstable and the device vibrates. Although this model is effective for simulating features much larger than the device's spatial resolution, it is less effective with small features because there may not be enough discrete levels to provide continuously increasing force response. Spatial resolution and update rate are critical parameters in any feedback device's design (Klatzky, 2003; MacLean, 2000). Higher spatial resolution requires stiffer structural members and more expensive gears and encoders. Higher update rates make the electronics more complex and increase the computational demands of the application. Consequently, it is likely to be more expensive and difficult to design a force feedback device to represent small features with current approaches.

This paper describes an alternative algorithm developed to overcome this challenge. It proposes a mathematical alternative to the spring-damper model which is applicable in the special case of a step edge probed by a spherical object. The model is supported by an experiment indicating that participants were better able to perceive a small step edge with the new model than they were with the traditional model.

ALGORITHM COMPARISON

The two modeling techniques differ primarily in their assumption of the geometry of the cursor representing the device's current position relative to the model. The standard spring-damper model represents the cursor as an ideal point. The new model represents the cursor as a sphere.

Point Model

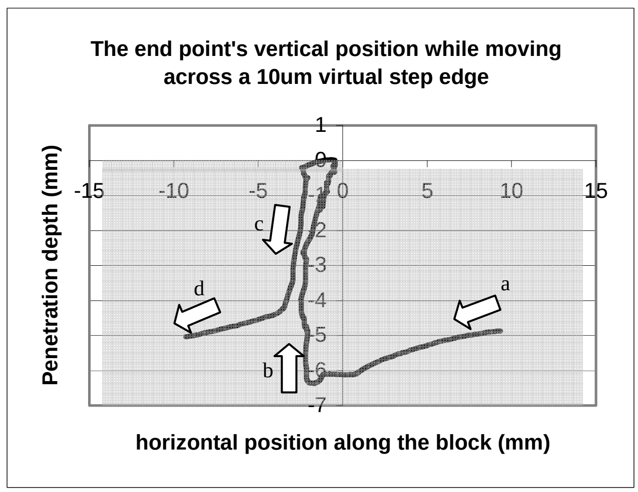

Figure 2. Trace of the cursor position as the force feedback is directed across a step edge located at the origin. The arrows indicate the direction of travel. The grey area indicates the block's position.

Figure 2 demonstrates the limitation of the point model in representing a small step edge. The figure traces the position of the cursor as the operator moves the cursor from right to left (in the direction of the arrows) across a simple 10 μm step edge. Note that the figure exaggerates the size of the step edge near the origin. At position a, the cursor is embedded between 4.8 mm and 6.3 mm into the surface of the object. At this depth the force feedback provide a response force that approximately matches the downward force exerted by the operator. At position b, the operator has encountered the vertical surface representing the step edge. The operator's incursion into this surface is met with a resistance force that increases until equilibrium is reached approximately 2 mm into the surface. The operator is reacting to this vertical resistance force so long as the point is caught on the vertical edge. Consequently, the cursor must rise approximately 6.3 mm until the cursor passes over the topmost edge of the vertical riser before the model of the left horizontal surface resumes control at position c. At position d the operator moves further to the left with an equilibrium condition similar to that at point a. It is important to note that to overcome the 10 μm step edge, the cursor actually needed to be raised by 6.3 mm using the point model. This is generally caused by a combination of the need for the cursor to sink into the surface before it generates an appropriate response force and because of the manner in which the horizontal riser maintains control of the cursor until the cursor passes above the y = 0 position.

The principle challenge with the point model is reducing the depth to which the cursor must penetrate the surface before a satisfactory response force may be supplied. This is controlled by the stiffness parameter. A higher stiffness parameter provides greater force response for smaller incursions into the surface. Figure 2 was generated with the stiffness set at the company-recommended maximum stiffness. Depth penetrations on the order of millimeters are relatively common. As a result, representing a small vertical feature requires the operator to physically lift the cursor several millimeters to cross even very small step edges. As a consequence only perceivable difference between a 20 μm and an 80 μm step edge is that the cursor must be lifted perhaps 6.08 rather than 6.02 mm. Furthermore, the perception of a step edge becomes similar to the perception of a narrow ridge because of the discontinuous change in force response experience just after crossing the top of the step edge at the origin. The expected response force is generated once the cursor falls back to a similar position below the surface. Such small differences are too small to be reliably perceived. This is not a realistic representation of the salient cues available in the real task.

Sphere model

The sphere model represents the cursor as a sphere. As a consequence, the magnitude and direction of the forces generated by the sphere model are different than those generated by the point model. This is because when the sphere contacts the top part of the step edge all of the forces are assumed to pass through the center of the sphere

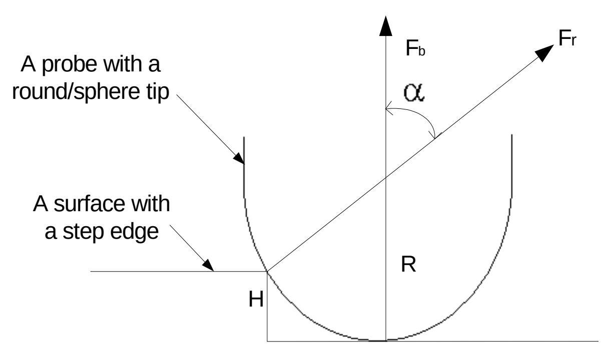

Figure 3. Illustration of the direction of the reaction force from a step edge.

The angle of the reaction force is determined by angle α, where $\alpha = \cos^{-1}\left(\frac{R-H}{R}\right)$. H is the size of the step edge and R is radius of the probe tip. Measurements of real Shepard's Hook

Explorers indicate that typical values for R range between 100 μm and 150 μm. The magnitude of the reaction force is the sum of a vertical force from the planar right-hand surface, F_b, and an angled force from the edge, F_r. The vertical force is determined by the material stiffness times the incursion depth of the bottom of the sphere into the surface. The magnitude of the angled force is proportion to the horizontal distance between the leftmost side of the sphere and the vertical edge. The generated force is the sum of F_b and F_r. As the cursor moves further to the left, the vertical component of the response force increases. When the cursor's velocity turns upwards, the cursor is assumed to have crossed the edge.

The hypothesis was that participants would be able to perceive the differences in small step edges more effectively with the sphere model than with the point model because the sphere model allows participants to infer H by estimating α.

METHOD

Eight participants participated in a simple forced-choice experiment in which two step heights (20 μm and 80 μm) were presented with either the point model or the sphere model. In order to allow the participants to grow accustomed to a particular edge model, the experiment was presented in two sessions, one occurring in the morning, the other in the afternoon. In each session only one edge model was used. Half of the participants used the point model first, and the other half used the sphere model first. In each trial the participant was invited to use the force feedback device to explore a block with a step edge and report whether the large or small step edge was presented. Each group of experiments began with 10 practice trials. Each practice trial was followed by feedback about the correctness or incorrectness of the participant's response. Then the participant responded to 24 randomized, balanced stimulus presentations without feedback.

RESULTS

All eight participants completed all the trials. One of the participants mentioned a small perceptual cue of one pixel which predicted the size of the step edge. This participant's responses were unusually accurate, so the participant was removed from further analysis.

An analysis of variance of the participant response as a function of model, step height, model-by-step-height interaction and participant indicated that step height ($F = 21.77$, 1, $p < .001$) and model-by-step-height interaction ($F = 4.68$, 1, $p = 0.031$) were significant. The step height term suggests that the participants were able to determine whether the step was large or small with greater than random accuracy. Figure 4 presents the interaction plot for the model-by-step-height interaction. The plot indicates that the participants had more difficulty distinguishing large steps from small steps with the point model than they did with the sphere model.

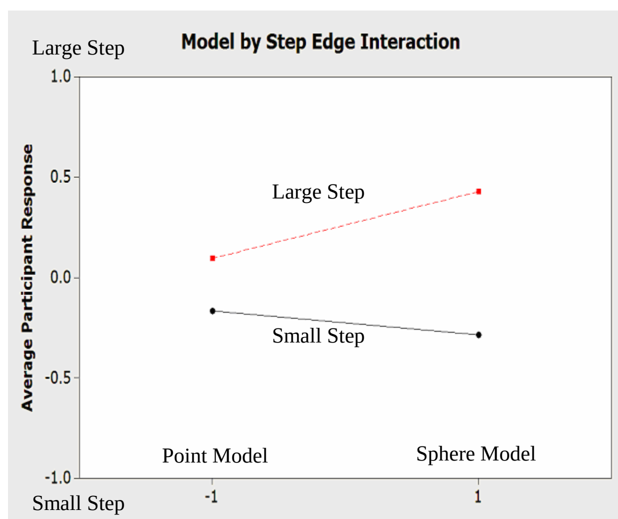

Figure 4. Interaction plot for the significant model by step height term.

CONCLUSION

The sphere model allows small step edges to be perceived more effectively than the point model. The current experiment does not prove that the sphere model presents a more veridical presentation of the stimulus than does the point model. However, the assumptions of the sphere model appear to be quite reasonable based our analysis of the physics of the probe-step interaction with a real Shepard's Hook explorer and manufactured steel blocks. At this scale the specific geometry of the probe is significant and the sphere model creates a plausible explanation of its shape and the resulting forces. Independent of whether future experiments prove that the sphere model accurately reflects the forces presented by a small step edge, the current experiment indicates that the proposed algorithm enables haptic devices to present features that are smaller than can be reliably presented with current approaches.

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