THE IDENTIFICATION OF THE CRITICAL HAPTIC STIMULUS FEATURES IN A CLINICAL DENTAL TASK

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This paper reviews evidence from a series of experiments that identify a characteristic 250-350 Hz tool vibration that may enable a dentist to make a specific clinical determination during a dental exam. The specific task is a generalized version of crown margin gap estimation. The results suggest that the vibration of the dental tool may be the salient haptic characteristic perceived by the dentist. Our previous experiments indicate that this vibration occurs when the probe releases potential energy after moving across the gap. A Fourier power spectrum of the vibration indicates that the vibration energy is in the maximally sensitive range of the Pacinian corpuscle, an organ which senses fingertip skin vibration. This paper discusses follow-up experiments designed to verify that including the vibration makes the size of the crown margin gap more salient while damping the vibration makes the size of crown margin gap more difficult to estimate. Defining the essential characteristics of the haptic signal is essential for redesigning, implementing and assessing the next generation of our dental surgical simulator.

INTRODUCTION

Haptics is the science concerned with perception through the tactile sense, the sense of touch. We define a haptic signal as a distribution of time-varying pressures across the skin (typically the fingertips) that may be perceived by the haptic sensory organs. Haptic signals can convey task-critical information. We presume that a haptic stimulus produces a characteristic pattern of pressures across the fingertip which a person perceives, recognizes, and relies on for making haptic judgments. Precisely what signal features the person recognizes and relies upon for a given task is generally not known, but might include amplitude, frequency, and pressure. Probably the critical task-specific information is encoded in some specific combination of these features triggered by the perceiver's interaction with the task object. Identifying the most salient characteristics of a haptic signal for a particular task, the haptic signature, can provide many benefits for the designer of a haptic simulator. These benefits include the capability to: a) quantitatively and objectively assess a simulator's realism by comparing the signal produced with the theoretically desired signal, b) design training programs based on quantitative criteria of judgment difficulty, and c) focus design improvements on specific differences between the ideal and actual signal.

In previous work (Thomas, Johnson, Dow and Stanford, 2001; Johnson, Thomas, Stanford and Dow, 2001) we developed the Iowa Dental Surgical Simulator, a force feedback device designed to replicate the sensation a dentist perceives when probing teeth for carious lesions, commonly known as cavities. As part of this work, we developed the Iowa Probe (Wagner, Radtke, Thomas, Goel, Stanford and Wilder, 2000), an electronic sheath that measures transverse forces exerted on a dental tool *in vivo*. More recently, we have focused on simulating the clinical task of estimating crown margin gaps.

When a dentist applies a crown to a tooth, the fit of the crown must be assessed to ensure good bonding with the crown adhesive (Figure 1). To determine the quality of fit, a dentist probes the junction between the crown and the tooth with a pointed instrument, often a shepherd's hook explorer or similar instrument. Because a crown extends below the gum line, the dentist can not see the junction. To perform the examination, the dentist slides the tip of the tool between the gum line and the crown surface and drags the sharp tip across the boundary between the tooth and the gum. The probe will often "catch" at the juncture between the two surfaces. The dentist evaluates the sensation of the catch to estimate the size of the gap between the tooth and the crown. If the gap is too large (greater than 100 micrometers), the fit of the crown is determined to be clinically unacceptable.

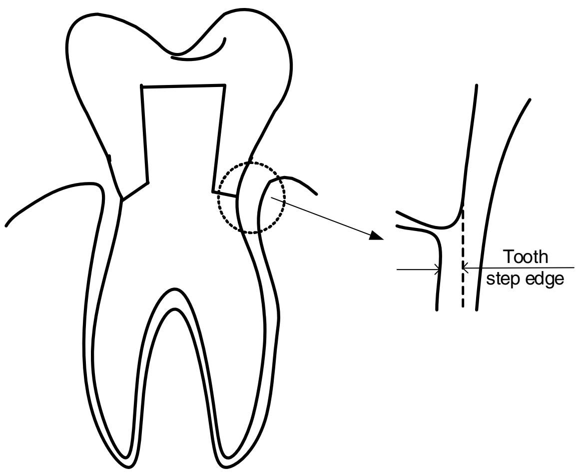

Figure 1: Diagram of a prepared tooth with a dental crown, surrounded by gum tissue. The crown is precisely manufactured to match the geometry of the prepared tooth. If the gap between the tooth and the crown is too large, the adhesive will fail prematurely.

We recently discovered that a shepherd's hook explorer, a commonly used dental instrument, has a natural vibration located in the frequency range of 250-350Hz. Vibrations of this frequency stimulate Pacinian Corpuscles, one of several haptic receptors in the fingertip. This observation led us to the hypothesis that vibration is a salient haptic feature of crown margin gap estimation, because the size of the gap (when modeled as a step edge) correlates with the amount of energy released as a exponentially decaying, 250-350Hz, tool handle vibration.

Force profiles recorded by the Iowa Probe suggest that vibration energy is related to the size of the crown margin gap. The following paper presents the evidence supporting this conclusion along with a predictive mathematical model of the amount of vibration energy that will result for a particular step edge. The results suggest that the stimulus information is present in the task and could be useful to the dentist during crown margin gap estimation. Future research will determine whether dentists use this information to estimate crown margin gaps.

We propose two tests that will demonstrate the utility of the characteristic vibration in the estimation of crown margin gaps. The first test will damp the vibration energy to test whether the dentists can accurately estimate margin gaps when the vibration is removed. The second test will add the vibration in a force feedback simulator and demonstrate that when the characteristic vibration is present, dentists can estimate the size of crown margin gaps more accurately than when the vibration is removed.

A MODEL OF THE VIBRATION ENERGY

In order to measure the amount of vibration energy expended after the probe crosses a simple step edge, an apparatus was constructed to constrain the motion of the probe along a rod. The sharp end of the probe moved perpendicular to the surface of a stimulus block machined with either a 25, 50, 75 or 100 micrometer step edge. The rod fixture allowed the tip to freely rotate directly toward and away from the block surface. Weights and pulleys were arranged to control the force on tip into the block and the force pulling the tip across the surface along a line perpendicular to the step edge (Figure 2). This apparatus allowed repeatable measurements of the probe tip response when the same pattern of force stimulation was applied.

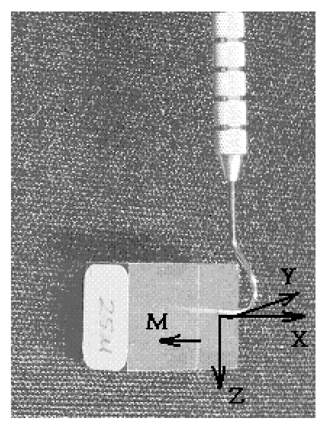

Figure 2: Illustration of the relative position of shepherd's hook explorer and the block. The probe motion is in the direction of the arrow labeled "M." The rod fixture attaches at the probe handle, above this figure.

Figure 3 presents a sample output from the probe. The vertical axis represents the force in Newtons recorded by the strain gauges in the X-direction on the block. The horizontal axis is time in milliseconds. At approximately 38 ms, the probe contacted the step edge. Shortly thereafter, it passed over the edge and started a damped resonance. The resonance was primarily in the

X-axis (parallel to the direction of travel), but a sympathetic resonance occurred in the Y-axis direction, parallel to the surface normal.

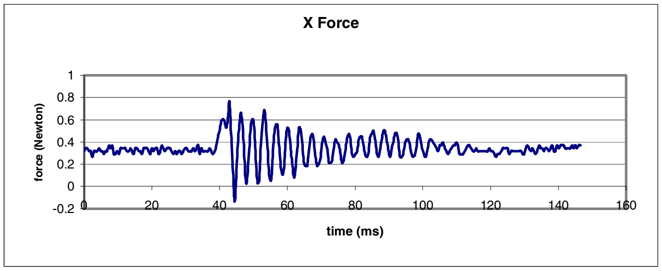

Figure 3: Forces on the dental probe as it crosses the step edge on a steel block.

The set of force profiles from the step edge experiments were analyzed using a Fourier transform. The profiles collected in the initial laboratory studies were broken into 2 portions representing the preliminary loading phase and the vibration phase. Figure 4 displays a sample of the Fourier transform of the loading phase for both the X and Y probe axes. The peaks on the left of the spectrum indicate that more than 64% the signal's energy is in the low frequency band (0-100 Hz). Figure 5 displays the Fourier transform during the vibration phase, during which approximately 86% of the signal's energy is in the high frequency band (250-350 Hz).

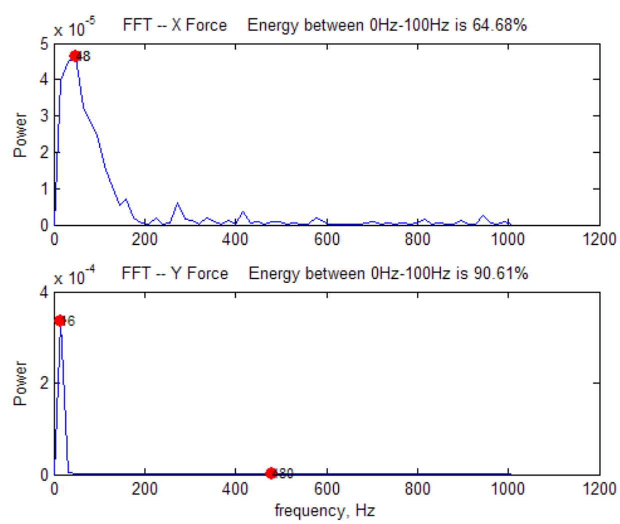

Figure 4: Fourier transform of the forces experienced during the loading phase.

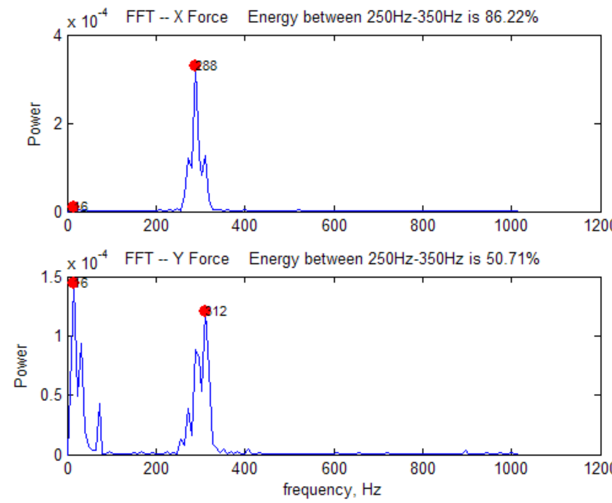

Figure 5: Fourier transform of the forces experienced during the vibratory phase after crossing the step edge.

It appears that the shepherd's hook explorer effectively acts like a spring and transforms potential energy stored in its deflection at the step edge into a vibration at its natural resonant frequency of approximately 250 Hz. The most likely sensor to be stimulated is the Pacinian corpuses, cells in hairless skin responsible for the detection of most high frequency vibration (Burdea, 1996; Klatzky, Lederman, Hamilton, Grindley, & Swendsen, 2003). These cells are most sensitive to vibrations with frequencies near 250Hz (Kontarinis & Howe, 1995).

A mathematical model based on this idea leads to the following expression for the energy produced by the vibratory energy:

$$E_v = C_v * 0.5 * F_{px}^2 / k = C_v * 0.5 * \left(\frac{\sin\alpha + \mu\cos\alpha}{\cos\alpha - \mu\sin\alpha} \right)^2 * F_{py}^2 / k \qquad (1)$$

where Cv is the percentage of potential energy transformed into vibrating energy, k is the spring constant, measured to be 9.81E3 N/m, F_{py} is the downward force on the probe (into the block surface), μ is the coefficient of friction, and α is the critical angle at which the spherical probe tip will slide over the step edge. Alpha is given by the following expression:

$$\alpha = \cos^{-1}\left(\frac{R - H}{R} \right) \qquad (2)$$

where R is the radius of the probe tip and H is the height of the step edge. For the shepherd's hook explorer in our laboratory experiments, R = 125 μm, and C_v = 20% (as determined by a nonlinear regression of the experimental data to equation 1). The total energy in the vibration was in the range of 10-20μJ over 16ms, which represents 625-1250μW of power. This is well above the detection threshold of 0.08μW of power delivered to the fingertip at this frequency (Khanna & Sherrick, 1981).

EXPERIMENT 1: DAMPING THE VIBRATION ON A REAL DENTAL INSTRUMENT

The first proposed experiment will compare the effect of two tightly fitting plastic sheaths with same weights but different stiffness mounted on identical dental probes. The soft plastic sheath will damp the probe's vibration but the hard sheath will not. The effectiveness of the damping of each sheath will be measured with a pressure sensor mounted between the sheath and holding clamps while a controlled vibration is induced in the tip by moving it a fixed distance and releasing it. Our hypothesis is that there will be a statistically significant decrease in the performance of the dentists when estimating the height a sample step edge when the vibration is damped with the soft sheath.

Method

Ten participants including both practicing dentists and advanced students will be recruited from the College of Dentistry. Each participant will estimate the height of a step edges on four steel blocks (Figure 6) with: an unsheathed probe, a probe covered with the hard sheath, and a probe covered with a soft sheath. Three repetitions of the experiment will be performed with each participant, balancing the presentation of the different probes and randomizing the blocks within each experimental set. The participant's estimate of the height of each edge will be recorded. An F-test on the estimate errors followed by Tukey's family rate confidence interval will be used to determine whether the participants estimated the size of the step edge less accurately when the vibration was damped with the soft sheath. We do not expect that the unsheathed and the hard-sheathed probe will produce statistically different estimate errors.

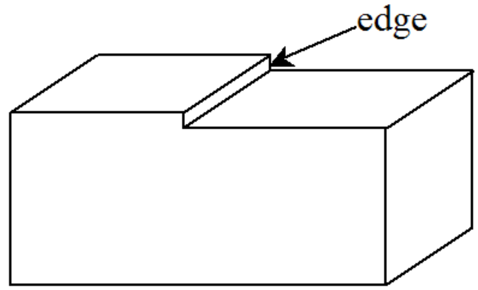

Figure 6. A series of 10 steel blocks with step edges of 10 to 100 μm in increments of 10 μm will simulate the geometry of the edge between a crown and a tooth. The size of the edge is exaggerated in the drawing.

EXPERIMENT 2: SIMULATING THE VIBRATION ON A HAPTIC FEEDBACK DEVICE

The second experiment will use our revised haptic simulator. The revised dental simulator will produce the 250 Hz vibration based on equation 1 when the virtual probe crosses the simulated step edge. We expect that the haptic rendering realism will be improved when vibration information is added. Consequently, we expect that dentists will be able to more effectively estimate the height of a series of virtual models of the steel blocks when the vibration is added. There are, of course, other technical limitations of the Phantom Device that may limit its ability to reproduce veridical haptic signals and these may limit the ability of the dentists to perform the task. For example, although the simulator's end effector has six-degree of freedom, only three position degrees are actuated. Consequently, the device does not produce torques that may be important to the signal realism. This limitation restricts the simulator's ability to accurately reproduce the force profile encountered in the normal clinical setting. Such technical limitations always limit the ability of a simulator to exactly reproduce natural sensations, which is one reason why identifying the critical features of a simulation is so important to our research.

Method

A software program will be written for the Phantom device based on the three dimensional geometry of each of the ten steel blocks. The simulator will be programmed to provide feedback equivalent to moving a point across the surface of this geometry, using the haptic feedback algorithms provided with the device (the Ghost software). In a second condition, a vibration with the frequency and intensity predicted by the analytic model will be added to the force response from the simulator. This will induce a vibration in the handle when the point is moved across the step edge.

Dentists and students from the same subject pool as experiment one will be recruited for the study. The experimental method will be similar to experiment one, except that rather than changing the probes and sheathes, the experiment will compare the vibration and no vibration conditions. In addition to asking the participants to estimate the height of each step edge, they will also be asked to rate the subjective realism of the display. The results are expected to indicate that when the vibration is not present, the participants will be less effective in judging the heights of the step edges. We also expect that they will rate the subjective realism higher when the vibration is present.

CONCLUSIONS

Together the experiments are expected to demonstrate that vibration is a critical component of the haptic signal used by a dentist to estimate the height of crown margin gaps. This study is important because it will prove, perhaps for the first time, the specific, quantifiable utility of the vibration component in a haptic experiment. It will also demonstrate that the vibration can be effectively added to existing commercial haptic simulators. Perhaps most importantly, rather than building the simulator to pass a subjective test of realism, it will demonstrate that haptic simulators can be developed based on a quantitative analysis of the information content of the signals present.

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