TWO DIMENSIONAL FINITE ELEMENT MODELING TO IDENTIFY PHYSIOLOGICAL BASES FOR TACTILE GAP DISCRIMINATION

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Tactile edge and gap detection are fundamental to performing manual tasks. Because slowly adapting type I (SA-I) mechanoreceptors encode details pertinent to edge localization, understanding low-level encoding is critical to understanding edge perception. Solid mechanics models may help us understand how mechanoreceptors in the skin encode applied surface indentation into neural signals representing edges. Finite element models test whether an indenter separated by a gap creates unique stress/strain distributions in models based upon orientation to fingerprint lines. Results indicate that a gap axis parallel to ridge lines elicits a more pronounced signal than a gap axis perpendicular to ridge lines. The differences may be due to underlying intermediate ridge microstructure. The percentage differences for three derived stress metrics range from 30-87% greater when the indenter's gap axis parallels the ridges. This initial effort demonstrates that underlying skin microstructure may aid tactile perception of stimulus orientation.

INTRODUCTION

Tactile edge and gap detection are fundamental to performing manual tasks. Understanding the limits at which people can discriminate between and detect stimuli could aid in the safe, optimization of information transfer at the tactile interface in tasks such as surgery, robotic interaction, and driver alerts. For example, the degree of impaired spatial acuity is important parameter to understand when surgical gloves are introduced (Gibson & Craig, 2002).

The perception of edges is highly dependent on how mechanoreceptors in the skin convert applied surface indentation into neural signals, used at the central nervous system to form judgments. Low-level mechanisms enhance spatial contrast independent of cognitive functions. Phillips and Johnson have shown that edge detecting SA-I (slowly adapting type I) receptors embed details about the presence and location of edges (J.R. Phillips & K.O. Johnson, 1981). The SA-I mechanoreceptors are most sensitive to static deformation – particularly edges, corners, and curvature (Johnson, 2001). The principal physical transducer of the SA-I class is the Merkel cell complex, which includes 5-10 Merkel cells (disks) grouped in a tree-like structure. Merkel cell complexes lie on the tips of the epidermal part of the intermediate ridges at the epidermal-dermal junction, Figure 1 (Quilliam, 1978). The intermediate ridges should not be confused with the papillary ridges (a.k.a. fingerprint lines). However, the center of each papillary ridge protuberance lies directly above the center of each intermediate ridge (Bolanowski & Pawson, 2003). Modeling these low-level physiological mechanisms may be essential to understanding cognitive-level tactile perception.

Skin mechanics affects the relationship between applied surface deformation and the stress that receptors interpret as coded, neural signals that represent edge stimuli. Current solid mechanics models correlate a stress measure to neural signal recordings with some accuracy (Dandekar, Raju, & Srinivasan, 2003; Maeno, Kobayashi, & Yamazaki, 1998; J. R. Phillips & K. O. Johnson, 1981). However, with respect to edge detection, the models' accuracy is limited. This may be due to a simplification of anatomical structures essential to focusing stress toward SA-I receptors (Gerling & Thomas, 2005). The addition of the intermediate ridge microstructure opposite the exterior fingerprint lines may better correlate stress/strain distributions to known electrophysiological responses, especially with edge and gap detection.

Wheat and Goodwin have studied the tactile discrimination of gaps when an indenter's orientation is changed by 90° with respect to the fingerprint lines (Wheat & Goodwin, 2000), Figures 1 and 2. In their study, the goal was to determine the acuity of gaps presented at the fingertip surface as a function of the stimulus orientation. They report electrophysiological responses of SA-I afferents with respect to stimulus orientation. Their findings indicate that a gap axis parallel to the skin ridges is easier to discriminate when the indenter's gap axis is positioned perpendicular to the skin ridges.

Our simulation experiments use finite element models in attempt to predict differences in signal acuity based upon stimulus gap orientation. We correlate sampled stress beneath the modeled skin's surface in response to applied indentation to the electrophysiological recordings for the gap orientation experiment. Two, 2D finite element models are used to differentiate the orientation of two indenter gap axes presented both parallel and perpendicular to the fingerprint lines.

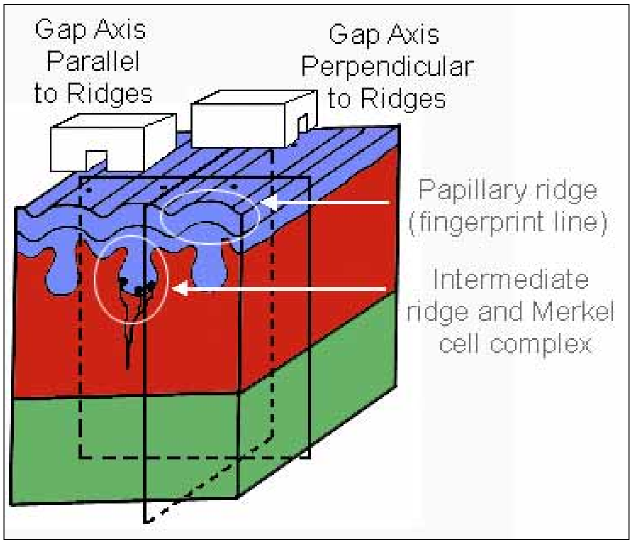

Figure 1. Fingerpad anatomy, adapted from (Quilliam, 1975). Section of skin showing the papillary and intermediate ridges, along with the location of the Merkel cell complex on the tips of the intermediate ridges. The two planes are perpendicular to the ridge lines and parallel to one ridge line.

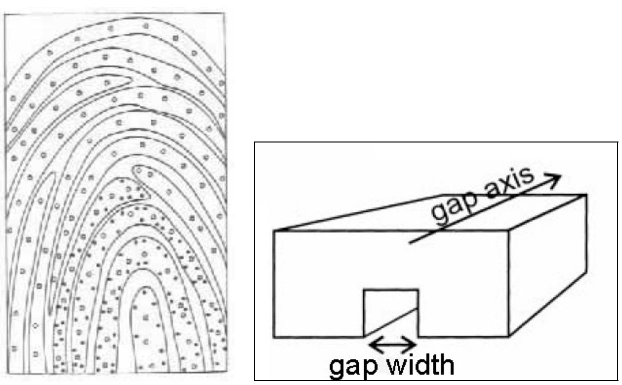

Figure 2. (left) overview image to present exterior fingerprint whorls, where dots represent locations of the Merkel cell complex, from (Quilliam, 1975); (right) 3D representation of indenter, adapted from (Wheat & Goodwin, 2000).

HYPOTHESIS

This work hypothesizes that an applied stimulus oriented with a gap axis parallel to the ridge lines will elicit a stress/strain response with a more pronounced signal than the response when the gap axis is perpendicular to the ridge lines. This result may be a consequence of skin microstructural mechanisms that focus applied stress like a lens toward Merkel cell receptors beneath, which lie at the ridge tips (Gerling & Thomas, 2005). Such a lensing mechanism may be especially adept at accentuating stress at edge boundaries, especially when the indenter is perpendicular to the ridges, because stress may highly contrast between adjacent ridge tips.

Three derived measures will assess the performance characteristics of the stress distributions: edge slope, peak-to-valley difference, and horizontal location of maximum stress. The <u>edge slope</u> is the average of the two slope increases between the point of maximum stress and the point to either side in the stress distribution. This measure defines the stress contrast between adjacent measurements near the indenter's edge. The <u>peak-to-valley difference</u> is the maximum stress value at the peak minus the minimum stress value at the valley. This defines the range of response. The <u>horizontal location of maximum stress</u> is the lateral (x-value) location that represents the sampled point with maximum stress. This defines the precision with which the edge is localized.

The between-model comparison evaluates a model's response to the indenter relative to second model's response to that indenter. Our three, specific experimental hypotheses are:

1) Edge Slope: the GA-Parallel-Ridges model will demonstrate a greater <u>edge slope</u> compared to the GA-Perpendicular-Ridges model
2) Peak-to-Valley Difference: the GA-Parallel-Ridges model will demonstrate a greater <u>peak-to-valley difference</u> than the GA-Perpendicular-Ridges model;
3) The <u>horizontal location of maximum stress</u> will be found in the same lateral sampling location for both models.

METHOD

The indenter is applied to the surfaces of two different finite element models of idealized, fingerpad skin. The independent variable is the 2D slice orientation (GA-Parallel-Ridges and GA-Perpendicular-Ridges). Each model considered a 2D slice from the skin section in Figure 1. The GA-Parallel-Ridges model considered a slice where the indenter's gap axis is parallel to the ridge direction, thus showing ridges in its profile. The GA-Perpendicular-Ridges model considered a slice where the indenter's gap axis is perpendicular to ridge direction, thus showing no ridges in its profile. Both models share the same material properties and nearly the same interior layering dimensions. The intermediate ridge profile is the only between-models variation. The 0.5 mm u-bar (channel) indenter is applied to each model's surface. The dependent variable is von Mises stress. Upon surface indentation, von Mises stress is measured in the GA-Parallel-Ridges model at the tips of the intermediate ridges (a depth of 0.75 mm) at a lateral sampling interval of 0.185 mm. In the GA-Perpendicular-Ridges model, stress is measured at a similar depth and horizontal increment. Two stress distribution plots are generated (two models × one indenter), Figure 3.

Finite Element Model

Both models are linear elastic, 2D finite element (FE) models. The models include interior layers and material properties similar to Maeno's fingertip plane section (Maeno et al., 1998). They include three skin layers: epidermis, dermis, and subcutaneous fat. The intermediate ridge structure of the GA-Parallel-Ridges model describes the epidermal-dermal junction with a sinusoid, Figure 1. The material properties include a Young's Modulus of 1.36×10^5 Pa for the epidermis, 8.0×10^4 Pa for the dermis, 3.4×10^4 Pa for the subcutaneous fat with a Poisson's Ratio of 0.48 for each layer (Fung, 1993; Maeno et al., 1998).

The MSC/PATRAN 2004 software was used to generate each mesh. Both meshes utilize four node, bilinear plane strain quadrilateral elements, type CPE4. Each model follows the plane strain assumption (J. R. Phillips & K. O. Johnson, 1981). The entire mesh for each model contains between 40,000 and 60,000 elements and nodes. The two meshes differ because the GA-Perpendicular-Ridges model is without the sinusoid ridge structure, but mesh density is nearly equal. Both models are composed of twenty primitives to both left and right of the center primitive, for a total of forty-one per model. Fixed boundary conditions constrain each model's left, right, and bottom edges. The twenty primitives create a skin-like buffer between the center primitive and the fixed boundaries. By implementing this buffer, the side boundary conditions do not impact stress propagation upon surface indention.

Indentation Procedure and Measurement Extraction

The finite element software ABAQUS Standard, version 6.4 is used to analyze each mesh's response to an applied indenter. The indentation stimuli is a channel indenter (two indenters, each 0.5 mm wide, with a 1.0 mm gap between their inside edges). The indention is implemented by displacing the appropriate center nodes by 0.5 mm (Dandekar et al., 2003; J. R. Phillips & K. O. Johnson, 1981; Srinivasan & Dandekar, 1996).

The main dependent variable is von Mises stress, equation 1.1, where σ_{xx}, σ_{yy}, σ_{zz} represent normal stresses and σ_{xy}, σ_{yz}, σ_{zx} represent shear stresses. Von Mises stress has been used to compare stress distributions (Maeno et al., 1998).

$$\sigma_{vm} = \frac{1}{\sqrt{2}}\sqrt{\begin{matrix}(\sigma_{xx}-\sigma_{yy})^2+(\sigma_{yy}-\sigma_{zz})^2+ \\ (\sigma_{zz}-\sigma_{xx})^2+6(\sigma_{xy}^2+\sigma_{yz}^2+\sigma_{zx}^2)\end{matrix}} \qquad (0.1)$$

Von Mises stress is measured in selected elements based on their position in the undeformed surface in a manner similar to previous studies (Dandekar et al., 2003; Maeno et al., 1998; Srinivasan & Dandekar, 1996; Wu, Dong, Rakheja, Schopper, & Smutz, 2004). Because the elements are so small and the stress changes so quickly at ridge tips in the GA-Parallel-Ridges model, von Mises stress samples are averaged for 18 small elements at a depth of 0.75 mm on the epidermal side of the tip of the intermediate ridge. For the GA-Perpendicular-Ridges model, the elements are larger and the stress change is more gradual in the critical region, so only one measurement is taken from a single element. The 18 averaged elements in the GA-Parallel-Ridges model create a sample area approximately equal to one sample from the GA-Perpendicular-Ridges model. Comparatively smaller elements at the sinusoidal ridge tips permit reasonably square elements. In both models, such samples were taken at lateral increments of one primitive (every 0.185 mm). Therefore, 29 total data points emerge from 14 measurements to the left of the center primitive, 14 measurements to the right, and one from the center primitive itself.

RESULTS

Models indicate that an applied stimulus oriented where the gap axis is parallel to the ridge lines enhances performance over a model where the gap axis is perpendicular to the ridge lines, similar to the findings of Wheat and Goodwin.

Edge Slope

Figure 3 indicates that the GA-Parallel-Ridges model has a tighter peak stress distribution than the GA-Perpendicular-Ridges model. The edge slope is 87% larger for the GA-Parallel-Ridges model than the GA-Perpendicular-Ridges model.

Peak-to-Valley Difference

As shown in Figure 3, the peak-to-valley difference is larger for the GA-Parallel-Ridges model than the GA-Perpendicular-Ridges model. The peak-to-valley percentage difference is 30% larger for the GA-Parallel-Ridges model than the GA-Perpendicular-Ridges model.

Horizontal Location of Maximum Stress

However, the GA-Perpendicular-Ridges model shifts the horizontal location of maximum stress outside by one lateral measurement, compared to no shift for the GA-Parallel-Ridges model, Figure 3.

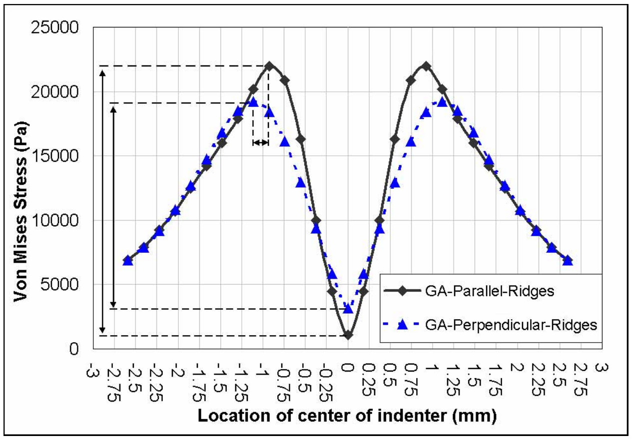

Figure 3: Between-models plot.

DISCUSSION

Although other explanations for edge enhancement are possible, indentions with a gap axis orientated parallel to the ridges may enhance edge acuity. The GA-Parallel-Ridges model provides much more sensitivity and precision than that demonstrated by the GA-Perpendicular-Ridges model.

The GA-Parallel-Ridges model is more sensitive. Its peak-to-valley difference is 30% greater than the GA-Perpendicular-Ridges model. Its peaks and valleys exceed the equivalent high (peak) and low (valley) bounds of the GA-Perpendicular-Ridges model.

The GA-Parallel-Ridges model also increases edge localization precision, by sharpening the contrast near the indenter's edge. The GA-Parallel-Ridges model demonstrates an 87% greater edge slope difference. Additionally, the horizontal location of maximum stress for the GA-Perpendicular-Ridges model is found outside the indenter's edge by one lateral measurement location.

It appears that the intermediate ridges significantly affect point-to-point stress contrast, given the large edge slope differences between the models. This may be one key to edge detection ability and reason why indenter orientation matters.

There are other potential explanations for edge enhancement, including that the GA-Perpendicular-Ridges model takes sampling points from within a stiffer material than does the GA-Parallel-Ridges model. However, these issues of sampling location with respect to material property also deserve investigation.

CONCLUSION

Learning how to predict an edge's detectabiltiy and characteristics (location, height, area, and gradient) are fundamental to understanding the sense of touch. The combination of physiological modeling with sensory perception may be a promising direction in attempt to better understand sensory perception.

Predictive solid mechanics models could help human factors researchers concerned with how well people can discriminate between and understand stimuli. Such understanding could aid in the design of appropriate stimuli or gloves for tasks such as surgery, robotic interaction, and driver alerts. By safely optimizing the information transfer at the tactile interface via predictive models, we can more productively develop stimuli, as opposed to current trial and error experimentation. The models would also give more precise rules of thumb than collected data from simple two-point discrimination and grating stimuli experiments. Such predictive models could also create stimulus devices and training programs for incrementally advancing expert performance with very dense tactile displays.

In addition to improving tactile interfaces and training expert performance, understanding the mechanotransduction underlying this work is also of practical interest for neural prosthesis, aiding people whose sense of touch is deteriorating, and improving man-machine interfaces.

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