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Tactile Illusion Caused by Tangential Skin Srain and Analysis In Terms of Skin Deformation

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Abstract. We describe a new tactile illusion of surface geometry that can be easily produced with simple materials. When the fingertip skin is strained by loading it in traction along a narrow band surrounded by two fixed traction surfaces, the sensation of a raised surface is typically experienced. This and other analogous cases are discussed in terms of tissue deformation created at a short distance inside the skin where the target mechanoreceptors are presumably located. A finite element analysis allowed us to propose that the basis of this illusion is connected with the observation that normal loading and tangential loading can create similar strain distribution, thereby creating an instance of an ambiguous stimulus. In the discussion we relate this stimulus to several other ambiguous tactile stimuli.

Key words: tactile illusions, tactile perception, tangential skin stretch, ambiguous stimuli

1 Introduction

Not a small part of the tactile perception mechanisms remains mysterious. A most interesting question is the manner in which the attributes of objects and surfaces generate cues that eventually give rise to perception. Studies have shown that many aspects of the physics of an object contribute to tactile perception. To name a few, surface roughness, thermal properties, and compliance all contribute to the unified subjective experience of an object [1, 2]. Humans experience the world outside using these properties. Surface flatness, and deviation from it, could one of these attributes since the tactile sense excels at detecting such deviations as local features of high curvature [3], or shapes of low curvature [4].

The perception of the geometric attributes of surfaces makes it possible to grasp and manipulate objects, to appreciate the finish of surfaces, or even to read Braille. Several studies have shown that the experience of flatness can be modified when the fingerpad is actively stimulated using certain geometric patterns or vibration [5, 6]. Other studies indicate that deforming the skin laterally

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can produce the sensation of objects indenting the skin due to the inherently ambiguous nature of mechanical stimulation [7], a phenomenon that has been applied to the development of high-performance tactile transducers [8, 9].

In this paper, we describe a new stimulus that produces the sensation of a narrow band being raised or lowered relatively to the side regions although all the surfaces remain geometrically flush. This effect is caused by applying a shearing load to the skin via the central band or via the neighboring surfaces. Interestingly, this illusion is also effective in quasi-static conditions. The effect could presumably be explained by mechanical factors, neurophysiological factors at the periphery and centrally, as well as by higher level perceptual mechanisms.

Here, we focus on mechanical factors which, once understood, could provide a basis on which a more complete account of why the conscious experience of flatness is modified by this stimulation. To this end, a detailed finite element analysis of a three-layered skin model loaded as described was conducted. The results indicate that, indeed, this loading pattern of traction creates at a short distance inside the skin, where the targeted mechanoreceptors would be located, a strain distribution that resembles the distribution caused by a geometrically raised or indented narrow band, thereby creating an ambiguous stimulus.

2 Description Of The Stimulus

A schematic of the stimulus is shown in Fig. 1a. The stimulus consists of two parts. The central plate has a narrow band extending from it. The other plate has a matching slot. Combining the two plates together results in a flat plate.

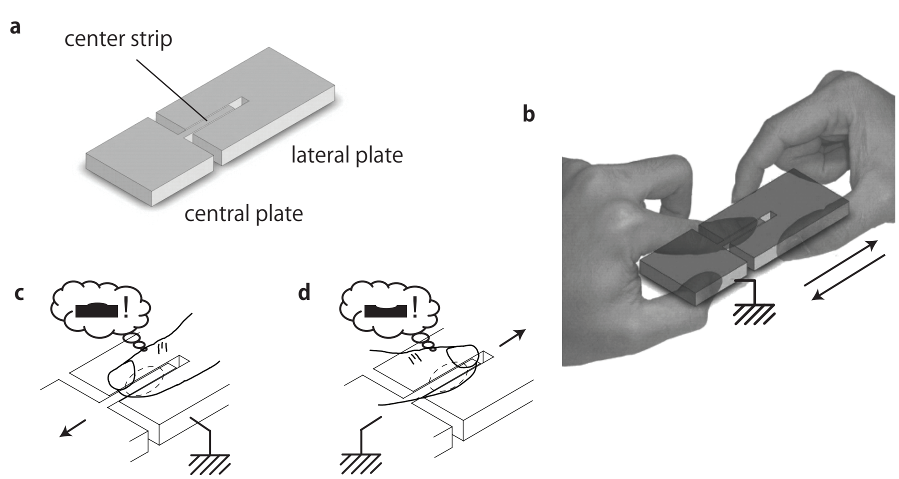

Fig. 1. Schematic of the stimulus. **a**, drawing of the stimulus. **b**, one hand manipulates the plate, the other gounds it. The index finger is stimulated. **c**,**d**, a raised, respectively recessed, surface is experienced.

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The plates must have the same thickness, and the clearance should be tight so that the upper surface feels flush when stationary. The width of the central band is preferably 3.0 mm. This width was determined from the study of a related effect, the “fishbone illusion” [5], which provided the inspiration for this report. The plates were made of Delrin® plastic, but other materials could be used. Sandpaper is glued on the upper surfaces to enhance tangential traction. Variants of this stimulus can also be prepared with PostIt® notes as for the “ridge/trough illusion” [10], or cardboard of a cereal box, for instance. For those variants, glue or absence of it is used to vary adhesion. In the present instance, the side regions or the central band are actively moved by an external agent while the sensing finger remains passive.

To experience the illusion, place the two combined pieces of the stimulus on a flat surface. Then, hold down the sides of one piece with the thumb and middle finger of one hand, and touch the center of the stimulus with the index finger of the same hand as shown in Fig. 1b. Hold the other piece with the other hand and manually move it back and forth along the band direction (i.e. one piece is moved and the other is fixed). An assistant can be called upon to apply the load. The illusion may be experienced whether or not the moved section slips on the finger, albeit with different intensity. In any event, the plates should not move vertically. Then, attend to the surface geometry under the index fingerpad, and evaluate whether it feels raised, indented, or flat during movement. Now, switch roles of the two hands (or switch two plates) and evaluate it again. In either case, the sensing index finger is stationary with respect to the fixed plate.

The apparatus and method above gave the authors illusory shape sensations. Although the touched surface is geometrically flat, when one plate of the two plates is moved, the central strip part felt higher or lower than the lateral regions. The sensation of the surface no longer being flat is strong that it is easy to decide which case creates the sensation of a raised band or of an indented band. The central band feels raised when it is moved and indented when the lateral regions are moved, see Fig. 1c,d.

3 Beginning Of An Explanation

What causes this illusion?, and why do these cases result in the sensation of a raised or indented central band? An intuitive answer to the first question can easily be imagined. The flat surface geometry of the two plates is the same, but the skin deformation is nonuniform and highly characterized, due to the traction pattern created by the moving plate. The moving part pulls the skin in one direction while the stationary part holds the skin. The skin stretch caused by the moving plate produces much more strain than the skin compression on the flat surface at rest does. The uneven strain distribution in the finger pad tissue may resemble that caused by a raised or depressed band. The association between skin stretch and shape sensations has already been noted [9, 11].

As for the second question, one can easily imagine that a geometrically raised band will cause more stimulation in the central region than in the sides. The

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same is true when pulling the central band sideways. A mirror situation occurs when pressing the finger on a depressed band or when pulling the side regions tangentially. While this sounds reasonable, it provides motivation for a more in-depth analysis.

Could it be that, inside the skin tissue regions where the mechanoreceptors are located, the strain distribution caused by a geometrically raised or indented band is similar to the distribution caused by partial surface traction of our stimulus? If it is true, then the sensation should be similar, i.e., one cannot distinguish the geometic surface caused by the normal load and the tangential traction.

In order to pursue this explanation, a finite element analysis can be used to assess the strain distribution in the skin quantitatively. Although the results of such simulation should be treated with the greatest caution, they can provide valuable insight. Such models, to be reliable, particularly to predict the behavior of living tissues, even more so at a small scale, should be extensively validated by measurements, which is exceedingly difficult to do in our case.

Several other possibilities for analysis exist. One approach would be to record the response of peripheral nerves. From the neural response of multiple fibers, it would be possible — in principle — to evaluate the similarity of the ensemble neural response to different physical stimuli. However, as discussed by Goodwin *et al.* [12], current technology does not allow us to measure a large number of multiple neuron responses simultaneously.

Another complementary approach is to adopt a psychophysical method. Measuring human behavior to a stimulus can help us discover the input-output relation of the human tactile system. This is useful to model the relationship between physical stimuli and perception but would not contribute directly to clarifying the underlying mechanisms of the illusion. It would give little insight regarding the mechanics of the strain distribution mentioned in the previous section.

With all its limitations, we must resort to a finite element analysis. Several studies related to the tactile response using finite element methods have been reported. These studies using 2D models [13, 14] and 3D models [15] provide some insight regarding the relation of mechanical stimulation with mechanical deformation, and even with neural responses. In most physiology textbooks, tactile perception of surface geometry is thought to result from normal pressure. But here, normal pressure is uniform; a 2D-section model would not be sufficient for analysis. In our study, the analysis of the strain tensor field in tissue volume caused by tangential load requires a 3D model. In the following section, a finite element model of skin deformation patterns in question is described.

4 Finite Element Analysis

Figure 2 shows the 3D finite element model used in our simulation.The model is a rectangular solid shape ($10 \times 20 \times 6.75$ mm in width, length and height). This solid is divided into three material regions having a uniform Young's modulus in each. These regions simulate the epidermis, the dermis, and the subcutaneous

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tissues. The thicknesses are 1.0, 0.75, and 5.0 mm respectively, and the Young's moduli are 0.136, 0.08, and 0.034 MPa, respectively. These data are taken from Maeno *et al.* [14]. The number of tetrahedrons in the mesh is 8 637.

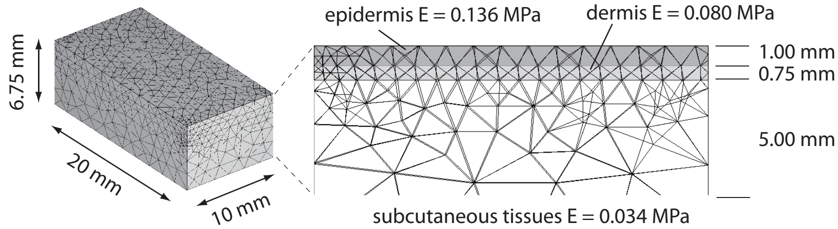


Fig. 2. Three-dimensional finite element model used in the simulation.

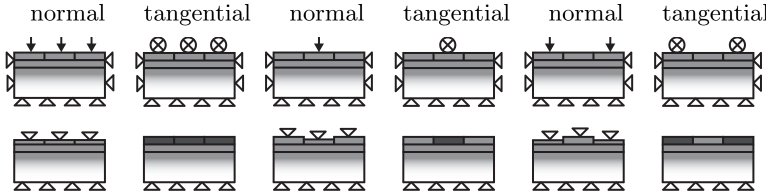
The simulation was carried out in two steps with a view to tune the parameters to realistic values. In a first step, standard loads of 1 N were applied to the six conditions shown in Table 1, top row. In these condition the block is clamped on all sides but the upper surface and the loads are applied at the upper surface. The first and second conditions correspond to the case of a simple normal and tangential loads. The third and fourth conditions are designed to evaluate the putative similarity of mechanical deformation between the normal and tangential load applied in the central area. The fifth and sixth conditions are mirror cases.

In a second step, the displacements observed in the first simulation were applied as boundary conditions in a second simulation. This time, however, the subcutaneous tissues were not clamped to replicate more closely the natural condition, except for the bottom surface to represent the bone anchor. This gave another set of six conditions listed in Table 1, bottom row.

The strain of each component is calculated in the region between the epidermis and the dermis, where the mechanoreceptor cells are located [16].

Table 1. Six loading and displacement conditions examined in the analyses.

1: uniform normal	2: uniform tangential	3: central normal	4: central tangential	5: lateral normal	6: lateral tangential



To analyze the data generated by the finite element model, we made the assumption that the receptor cells respond to the maximum strain, which is not

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specific to a particular direction. Moreover, the choice of coordinates selected to perform the simulation is arbitrary and is selected for convenience. Evaluating the results in terms of principal strains eliminates the dependence of the results on this choice.

The results of the two simulations are seen in Figs. 3 and 4. The principal strain distribution in the tissue is different between conditions 1 and 2 (Fig. 3 and 4, left). On the other hand, the region where the surface load applied has a positive value in the center for both conditions 3 and 4 (Figs. 3 and 4, center). Similarly, for conditions 5 and 6 (Figs. 3 and 4, right), the central area has only a small strain value (almost zero) and the lateral areas have a positive value. The maximum shear strain is also calculated based on the components of principal strain by using the relationship between principal strain and principal shear strain [17]. The results are similar to the top row of Figs. 3 or 4, and therefore the plot is not shown here. This indicates that a similar pattern of strain and shear strain is applied in the area where the receptor cells would be located.

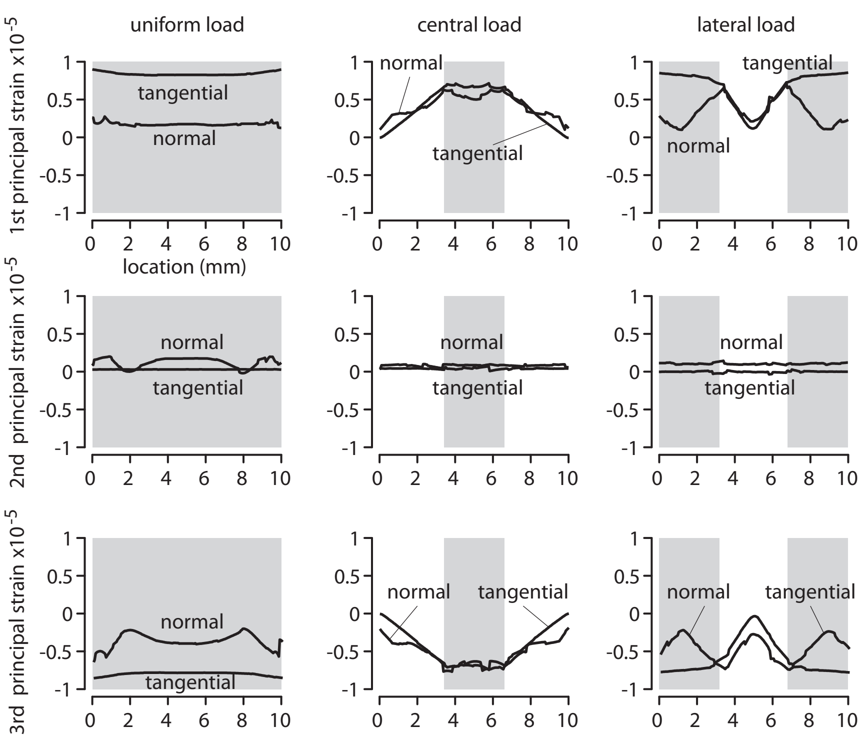

Fig. 3. Plot of the principal strain for each experimental condition when loading the skin. Uniform surface load (left), surface load in the central area (center) and in the lateral area (right) are shown. Areas shaded in grey indicate the regions where the load is applied.

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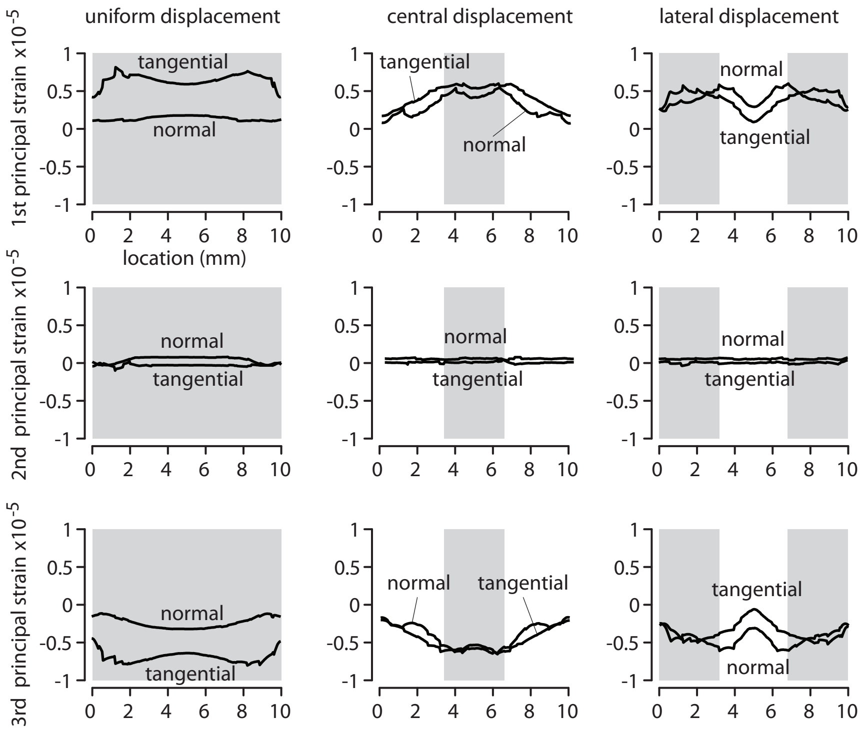

Fig. 4. Same layout as in Fig. 3. Here the skin is displaced instead of being loaded.

5 General discussion

The results presented in the previous section show that we might be in the presence of an interesting phenomenon. They indicate that the illusion could be explained by the patterns of the resultant principal strains in the skin tissue. From the finite element analysis, it can be speculated that:

1. At least for certain components the strain between normal surface load and tangential surface load are comparable.
2. If the tactile stimulus can be interpreted in multiple ways, i.e., the stimulus is ambiguous, and if there are only two possible solutions, i.e., relative elevation of the central band with respect to the sides, the stimulus may be associated with the prior assumptions that cause the brain to confuse the shear load with the normal load.

To appreciate the surface geometry of contact, presumably, the only possible cue given by the physical stimulus is the deformation of the skin tissue. Recently, Wang and Hayward [7] suggested that mechanoreceptors are likely to respond to strain caused by the deformation in the tissues in which they are embedded. They

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also exhibited another possible instance of different load condition where tactile stimulus yields similar strain fields at a short distance inside the skin tissue, using the results of Kikuuwe *et al.* [18]. These results indicate that different deformation conditions can be perceptually equivalent when the strain fields are similar. In other words, if a pair of resultant strain fields from two different physical stimuli would be indistinguishable for the sensory system, they are also perceptually indistinguishable. This may explain the phenomenon in part.

It is probably the case that the peripheral input from our physical stimuli is similar to that from other stimuli, but is not exactly the same. Inexact replication might confuse the nervous system. This is seen in Fig. 3 and 4, in which a pair of principal strain components are similar to each other but not exactly the same. However, even in this case, the sensory nervous system is forced to determine it as one of the two possibilities: the central strip is raised or recessed; and use this prior constraint to solve the problem. This follows from the observation that *most* adjacent regions of common surfaces that give non-uniform stimulation are not at the same height. If the ensemble neural responses are monotonically related to the strain distribution, then the elevation of the central strip may be determined from the relative activity of adjacent regions, yielding an experience of height variation.

In the simulation we only evaluated the magnitude of the principal strains. Whether the mechanoreceptors respond to preferred directions or not is an open question. In fact, when the strain magnitude is large, it is quite likely that receptors respond to all components of normal and shear strains. With this taken into consideration, the magnitude of the maximum component of the principal strain would determine the intensity of the response. The phenomenon that we found supports this view.

We found yet another instance where tactile stimuli can be as ambiguous as visual stimuli can be. The central nervous system must make the best possible judgement given available sensory input, analogously to what is observed in the visual domain and which is at the origin of many illusions, such as the Necker cube, the Mach card illusion, the hollow mask illusion and so on.

The ability of human tactile perception to overcome the lack of sensory information also indicates the necessity to develop design criteria for tactile sensors and displays. Robotic researchers concerned with the design of artificial tactile sensors already noticed the ambiguous nature of the tactile input mediated by elastic materials [19–22]. Efforts devoted to making artificial tactile sensors could prove fruitful for helping us comprehend the human tactile mechanisms.

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