A Finite Element Model of Tactile Flow for Softness Perception

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***Abstract*— Touch is an extremely dynamic sense. To take into account this aspect, it has been hypothesized that there are mechanisms in the brain that specialize in processing dynamic tactile stimuli, in a way not too dissimilar from what happens for optical flow in dynamic vision. The concept of tactile flow, related to the rate of expansion of isostrain volumes in the human fingerpad, was used to explain some perceptual illusions as well as mechanisms of human softness perception. In this paper we describe a computational model of tactile flow, and apply it to a finite element model of interaction between deformable bodies. The shape and material properties of the bodies are modeled from those of a human fingertip interacting with specimens with different softness properties. Results show that the rate of expansion of isostrain volumes can be used to discriminate different materials in terms of their softness characteristics.**

I. INTRODUCTION

When a fingertip (or other tactually endowed part of the body) enters in contact with an object, a complex mechanical interaction occurs, which generates tactile stimuli for the various mechanoreceptors. However, even if tactile information is extremely rich in content and purposes, it might be the case that not all its richness is actually necessary to discriminate softness of different materials. It is thus possible to argue for lower-dimensional projections of the tactual information manifold, which may provide conceptual models of how softness information can be obtained from raw sensor data. These models should be the input for a tractable yet meaningful analysis, hence driving the design of more effective softness displays.

From a cutaneous point of view, contact pressure and displacement on the fingertip surface generate a distribution of stress and strain tensors in the dishomogeneous, anelastic material whose accurate modelling is very difficult. Considering softness discrimination, a possible reduction of dynamic, force-varying tactile information operated by nervous system can be described by the *tactile flow* paradigm [1], [2], which extends Horn and Schunk's equation [3] for image brightness to three-dimensional strain tensor distributions. Tactile flow equation suggests that, in dynamic conditions, a large part of contact sensing on the finger pad can be described by the flow of strain energy density (SED), or, equivalently, the closely related Equivalent Strain of Von Mises (SVM), since Merkel-SA1 afferents, which seem to have a relevant role in the dynamic form in tactile scanning, were proved to be selectively sensitive to these scalar quantities [4].

However, only the flow components that are tangent to the isointensity curve itself (i.e. components perpendicular to the intensity gradient) can be determined, as it results from the constraint equation. This intrinsic ambiguity (the same exhibited also by optic flow) can generate hypotheses on some tactile illusions, which were also psychophysically demonstrated [2]. These illusions can be interpreted in terms of information loss due to projections into a lower dimensional space w.r.t. the plenhaptic function, as it was discussed in [5]. Moreover, the integral version of tactile flow equation can be used to explain the *Contact Area Spread Rate (CASR)* [6] experimental observation, which affirms that a considerable part of tactile ability in object softness discrimination is retained in the relationship between the contact area growth over an indenting probe (e.g. the finger pad which presses the object) and the indenting force itself. Such a paradigm was used to inform the design of tactile displays for softness rendering [6], [7], [8], [9], [10].

Despite the fact that many psychophysical evidences support the tactile flow model, a thorough numerical validation still lacks. In this paper we present a finite element model, inspired by [11] and [12], which simulates the interaction between a fingerpad and a surface. Two materials with different softness properties are considered for the surface. Results show that the rate of expansion of isostrain volumes can be used to discriminate different materials in terms of their softness characteristics.

A. The Tactile Flow Paradigm

Tactile flow paradigm [1] can be regarded as the tactual 3-dimensional counterpart of the 2-dimensional optic flow model [3] for processing dynamic tactile stimuli, which would gather information about softness discrimination, shape recognition and relative motion between fingertip and explored object.

Let $\mathscr{E}(\xi,P)$ denote the SVM at a point ξ within the volume V occupied by the deformed object of reference, under a given resultant force P (this relates to a specific finger pad/object pair, which is henceforth assumed to be given). Consider now the locus of points within the volume V which have the same SVM value. For instance, we will use $\Sigma_i = \{\xi \in V | \mathscr{E}(\xi,P) = \mathscr{E}_i\}$ to refer to the iso-SVM surface whose points have SVM equal to $\mathscr{E}_i$. Assume that, from this condition, the resultant force P is changed to a new

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value $P+\Delta P$: as a consequence, the SVM will change at points within V. If for instance the force is slightly increased in magnitude, it can be expected that the SVM for points previously belonging to Σ_i will also increase.

From another point of view, the surface Σ_i can be considered as it moves, under the new load conditions, to points that are farther away from the center of the contact region. To describe how an iso-SVM surface moves across the volume V, a simple differential equation for the conservation of SVM, analogous to optic flow equation in the form, is produced

$$\frac{d\mathscr{E}(\xi,P)}{dP}=0 \tag{1}$$

and, by expanding the total derivative,

$$\frac{\partial\mathscr{E}}{\partial\xi}\frac{\partial\xi}{\partial P}+\frac{\partial\mathscr{E}}{\partial P}=0 \tag{2}$$

or

$$\nabla\mathscr{E}\,\vec{\phi}=-\frac{\partial\mathscr{E}}{\partial P} \tag{3}$$

Here, $\nabla\mathscr{E}=\frac{\partial\mathscr{E}}{\partial\xi}$ is the spatial gradient of $\mathscr{E}$, i.e. a vector normal to the surface in ξ, and $\frac{\partial\mathscr{E}}{\partial P}$ is the differential change in SVM which is obtained by measuring it at point ξ before and after applying the infinitesimal load change dP. Finally, the vector $\vec{\phi}(\xi)=\frac{\partial\xi}{\partial P}$ denotes the infinitesimal motion of a surface element in Σ_i, and will be referred to as the flow of SVM in the finger pad associated to the load change. Time-varying excitation of SVM-sensitive mechanoreceptors embedded in V is thus directly related to the SVM flow through their location, which might in turn be related to the perception of the spatial direction in which stimuli evolve. Notice that, analogously to optic flow equation, tactile flow equation exhibits an intrinsic ambiguity since it defines the 3-dimensional flow vector $\vec{\phi}$ only up to a 2-dimensional subspace (the tangent space to Σ at ξ)[1].

As it was suggested in [1], the rate of expansion of iso-SVM surfaces can be related to the rate of the expansion of contact area under increasing load. Therefore tactile flow computational model can be associated to the experimental paradigm of the Contact Area Spread Rate (CASR) [6].

II. MATERIALS AND METHODS

A CAD model of the fingertip was built, to simulate the shape and structure of a human distal phalanx. The stratification was conducted similarly to what was done in [11] and [12]. A cylindrical body with a rounded tip (radius 6 mm) was used to simulate the bone; around this body shells were added to simulate subcutaneous, dermis and epidermis layers. A separate shell portion was also placed on the upper epidermis to simulate the nail. The finger was then placed in an initial configuration of tangency to a plate, with the bone axis inclined by 15 degrees respect to the plate plane. Fig. 1 shows the geometry, while Table I reports details on the dimensions.

[1]This ambiguity can provide an explanation for perceptual illusions psychophysically observed in tactile domain [2]

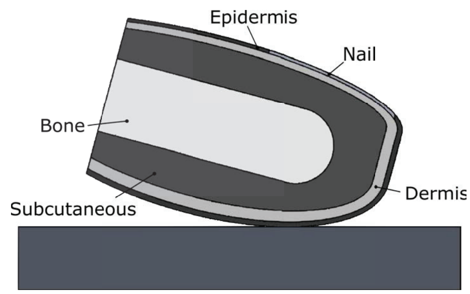


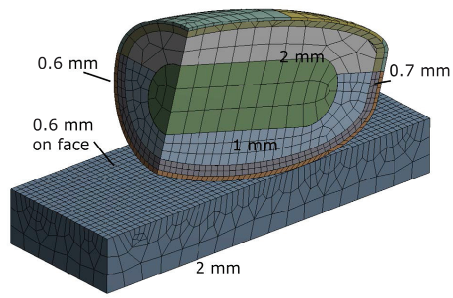
Fig. 1: Finger model geometry.

	Geometry details
Bone	6 mm radius
Subcutaneous	2.5 mm thick
Dermis	0.93 mm thick
Epidermis	0.41 mm thick

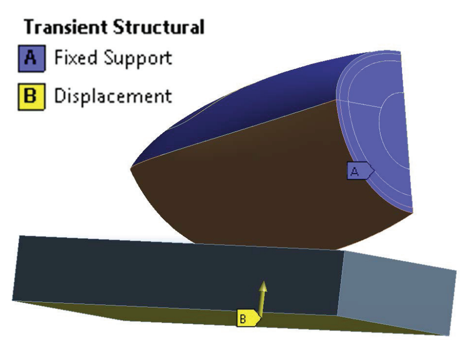
TABLE I: Finger model dimensions.

Skin Layer	**C10**	**C01**	**C20**	**C11**	**C02**	**D1**
Dermis	2430	5420	239000	262000	74700	13.3
Subcutaneous	300	671	29800	32700	9330	106.5

TABLE II: Material properties for the Mooney-Rivlin model materials.



(a) Mesh.



(b) Load conditions.

Fig. 2: Finger model mesh, constraints and imposed displacement.

Materials were taken from [11] and [12]. In particular, bone, epidermis and nail were modeled as linear materials, with Young's modulus equal to 17, 2.00 and 170 MPa respectively and Poisson's ratio equal to 0.3 for all. Dermis and subcutaneous tissue were modeled as Mooney-Rivlin hyperelastic materials (Table II). For what concerns the plate, two different materials were used corresponding to two different contact conditions: structural steel (E = 200 GPa, $\nu = 0.3$) and soft silicone (E = 180 KPa, $\nu = 0.48$).

The geometry and material properties were loaded on ANSYS Workbench to construct a finite element model (FEM). The symmetry of the model was taken advantage of in order to reduce the number of elements. Different element sizes were used for the different layers, refining the mesh for the layers closer to the contact with the plate and keeping a coarse structure from farther layers: figure 2(a) shows the details on the element size.

All contacts were modeled as bonded contacts, except for the contact between the finger and the plate which was modeled as a frictional contact with a 0.2 friction coefficient. A fixed support constraint was applied on the upper epidermis layer and on the rear sectioned face, and a displacement of 0.2 mm/s over 12 seconds (2.4 mm overall) was imposed to the lower face of the plate, as shown in figure 2(b). This displacement velocity is the same which was used in [13] for the quasi-static load condition.

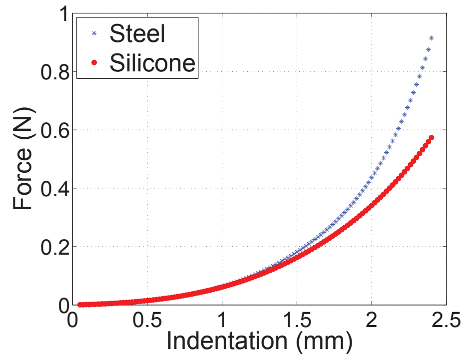
III. Results

Figure 3 shows the results for what concerns force interaction between the finger and the plate, i.e. the force applied on the fingerpad. Both force-indentation and force-area plots are considered. It is worth noting that the force-indentation curve for steel (Figure 3(a)) is comparable to the result shown in Figure 2-a of [13], while the curve for contact with the silicone shows lower forces, as one would expect. Also, the force-area curve for silicone shows a higher CASR respect to the force-area curve for steel, which is coherent with [6]. While this is by no means a thorough validation of the model, these results are reasonable and give indication that the model is reliable.

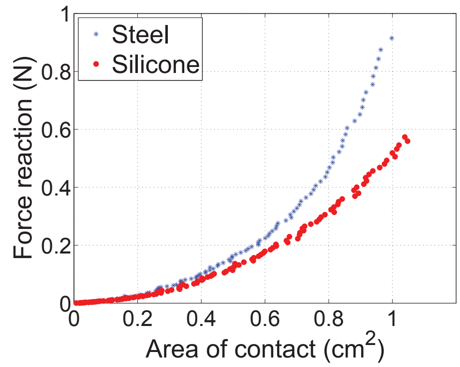
	Force (N)	Steel ind. (mm)	Silicone ind. (mm)
A	0.11	1.24	1.28
B	0.50	2.08	2.30

TABLE III: Conditions for isostrain analysis.

We can then take the analysis a step further, and consider the evolution of SVM in the finger for the two different contacts. Figure 4 shows the strain distribution in the fingerpad at the final time. Strain is higher for the contact with steel, which is the expected result; however, we are interested in evaluating the rate of expansion of the isostrain volumes. In order to do that, we consider two contact forces P_A and $P_B > P_A$, and for various strain values and for both contact conditions we calculate $\frac{\Delta V}{\Delta P} = \frac{V_B - V_A}{P_B - P_A}$ (see table III for more details). Figure 5 show the result of this operation: in



(a) Force-Indentation curve.



(b) Force-Area curve.

Fig. 3: Force reaction on the plate.

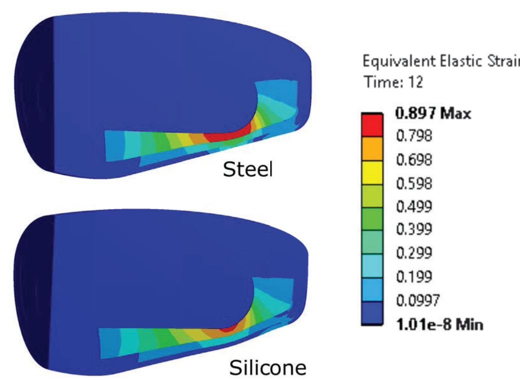
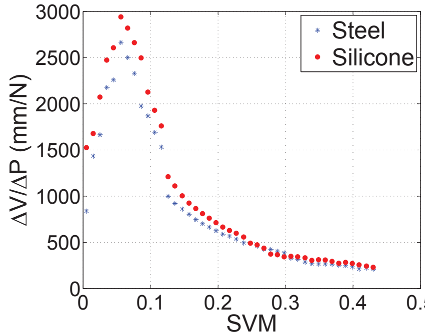


Fig. 4: Finger strain under the two conditions.

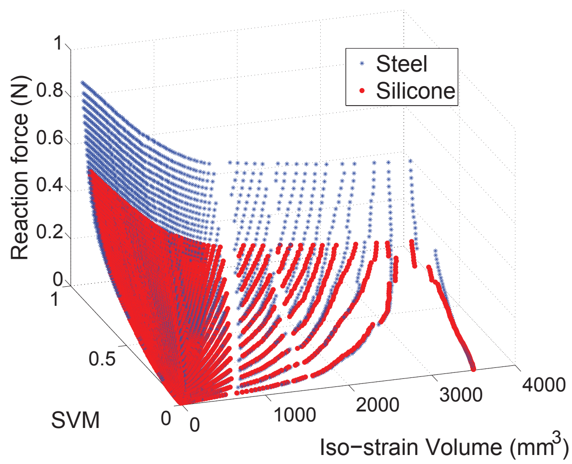
particular, from Figure 5(a) it can be seen that the isostrain volume changes more for the softer material: in other words, it is possible to discriminate between a harder and a softer material by looking at $\frac{\Delta V}{\Delta P}$. Figure 5(b) shows a complete 3D representation of SVM, isostrain volumes and force reactions.

IV. Conclusions

In this work we described a finite element model of a human finger pressing on a plate, for which we considered two different materials. An evaluation of the quality of the model was carried with considerations on the force-indentation and force-area, which lead to reasonable results



(a) Isostrain volume variation.



(b) 3D plot of SVM, isostrain volumes and forces for both materials.

Fig. 5: Strain analysis.

respect to existing literature on this topic. The model was then employed to perform an analysis of the rate of expansion of the isostrain volumes for the two different materials considered: this analysis showed indication that this ratio can be used to discriminate between two materials with different softness. Future work will focus on improving the finger model by making it more realistic (e.g., using a real bone geometry instead of a simple cylinder), and on validating the model in a more quantitative and thorough manner. We also plan to use this model to continue the investigation of the tactile flow paradigm.

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