Modeling the Human Touch:
A FEM Model of the Human Hand Fingertips for Haptic Application

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Abstract:
Performance of tactile sensation, which plays an important role in artificial skin, fingers for Robotics, and wearable haptic device is affected by fingertip deformation characteristics produced when touching objects.
In particular, tactile performance of human fingertips is strictly associated with activity of the nerve endings and sensitivity of the soft tissue within the fingertip to the static and dynamic skin indentation.
In this study, a Finite Element model, based on the physiological structure of the fingertip, has been developed to simulate the interaction between fingertip and a flat plate while in contact. The fingertip is assumed to be composed of skin layers, comprising both epidermis and dermis, subcutaneous tissue, nail and arterial bone. All of them are threated as nonlinear and inhomogeneous materials.
Results show that the soft tissues of fingertips are very sensitive to stimuli; stress and deformations are depending on the characteristic of the touched flat plate. The present study represents an effort to develop a predictive model to be used in the design and optimization process of new cutaneous haptic interfaces.

Keywords: Finite Element Method (FEM), contact interaction, tactile sensation, Hyperelastic, fingertip.

1. Introduction

Sensation of touch, pressure, temperature and vibration are included in the tactile senses; the sense of touch is fundamental to exploit the world.
Humans use their fingertips as first approach when touching an object. Haptics technology aims at recreating the sense of touch by applying forces, vibrations, or motions to the user. To develop this type of technology it is extremely important to understand how the human skin, and in particular the hand fingers, reacts, in terms of tactile sensation and sensory thresholds, while in contact with a specific surface. This problem is particularly important in wearable haptics devices, in which, for the sake of wearability, often underactuated and undersensed mechanical solutions are exploited [3]. An example of this type of device is shown in Fig. 1.

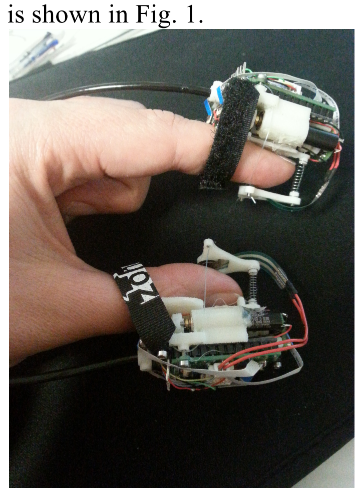

Figure 1. Example of wearable haptic devices for the tactile stimuli of the index and thumb fingertips, [3].

In [4] the authors underline how human brain is stimulated by electrical impulses activated by tactile receptors beneath the skin that respond to deformation of the skin, when the fingertips come in contact with any surfaces.
Nerve impulses frequencies, which are the main characteristics of the transmitted signals, are mainly associated with the stress and strain [5].

The human fingertip has a very complex structure and mechanics.

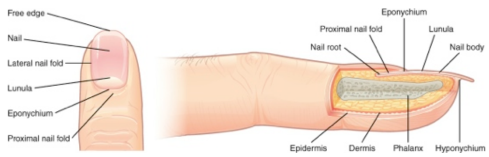

Figure 2. Detailed physiological structure of the human fingertip [1].

From a macroscopically point of view, the human fingertip is composed of epidermis, dermis, subcutaneous tissue, nail and bone. Each of them has specific peculiarities; the epidermis, e.g. the most external fingertip layer, consist of protective horny structures. The dermis layer is in contact with the epidermis and contains various mechanoreceptors, as detailed reported in [6]. The subcutaneous tissue is mainly composed of lipocytes fat. Tactile sensation is strictly dependent on strain and stress transmission, which are enormously influenced by the skin and subcutaneous layers. For these reasons, it is really important to well know all the biomechanical properties of each fingertip layer.

In order to simulate the contact interaction between the fingertip and a known object, many studies have been conducted in literature.

Different fingertip models have been previously proposed; in [7,8] the authors developed fingertips represented by an incompressible fluid (subcutaneous tissue) enclosed by an elastic membrane (skin). Due to the considerations of uniform tension in the membrane and uniform fluid pressure, these models are not able to analyze variations in the stress and strain within the tissue, and thus, they cannot predict the mechanical stimuli of the mechanoreceptors within the skin.

In [9,10], the authors developed fingertip models comprising homogeneous, isotropic and incompressible elastic media.

Nevertheless, all the aforementioned models are of two-dimensional (2D) type. A 3D model is analyzed in [11]; the authors developed a multi-layered fingertip model composed of dermis, epidermis, subcutaneous tissue, nail and arterial bone. The soft tissue (i.e. inner skin layer and subcutaneous tissues) were assumed to be nonlinearly elastic and viscoelastic, while the nail, bone and outer skin layer were considered to be composed by an elastic material. FE models demonstrate excellent prediction of response of soft tissues to loading. Nevertheless, to the best of our knowledge, little attention has been paid so far to the deformation dependence within fingertip soft tissue on tactile sensation.

Using a similar model as in [11], in this study a multi-layered structural 3D FE fingertip model is developed to analyze the deformation distribution characteristics within fingertip soft tissues. Moreover, the contact interaction between the developed fingertip model and a flat plate is analyzed.

The remaining part of the paper is organized as follow. Section 2 contains a detailed argumentation of the proposed FE model. Results of simulations are reported in Section 3. In Section 4 some conclusions are drawn and future direction of research are outlined.

2. Methods: Finite Element Model

As specified in [12], the anatomy of the tissues within a fingertip is a multilayered structure. It includes dermis, epidermis, subcutaneous, arterial bone and nail. The dimensions of the fingertip are assumed to be as an index finger of a typical male subject [2].

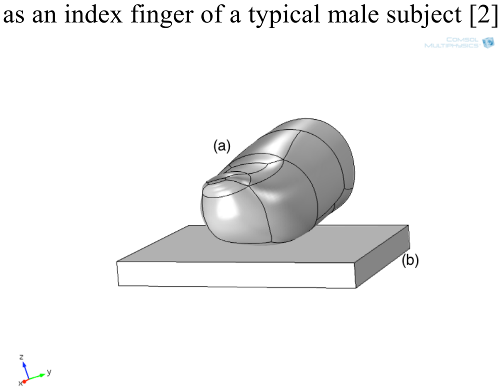

Figure 3. Front size view of the 3D fingertip model (a) in contact with a flat surface (b).

The skin, including dermis epidermis, and the subcutaneous tissues are assumed to be hyperelastic (nonlinearly elastic) and linearly viscoelastic. The nail and the bone are considered as linearly elastic materials.

The fingertip cross-sections and the bone are considered elliptical and the tissue thickness is assumed to be asymmetric with respect to the bone. The flat plate is assumed to be part of the aluminum materials with Young's modulus of 69 GPa, Poisson coefficient of 0.33 and density of 2700 Kg/m^3. Other constants of the fingertip structure are reported in Table 1.

	Young module [MPa]	Poisson ratio
Dermis	0.08	0.48
Epidermis	0.136	0.48
Subcutaneous	0.034	0.48
Bone	17000	0.3
Nail	170	0.3

Table 1. Constants of the developed fingertip model [13].

The finite element software package COMSOL Multiphysics was used for the analysis.

As a first stage, the simulations were conducted by statically pre-compressing the fingertip. Different prescribed displacements were applied to the plate toward the fingertip, The back cross-section of the finger was fixed in both horizontal and vertical direction, as well as the center of the fingernail.

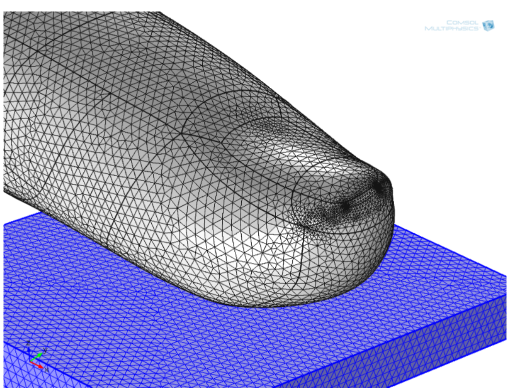

Figure 4. FE model of the fingertip in contact with the flat surface.

The objective of the simulation was to calculate the estimated forces within the applied displacement, so to be compared to the results in [13-14]. Moreover, Von Mises stress distribution within soft tissue of the fingertip is analyzed.

3. Results

Using the proposed fingertip model (Fig. 2), the reaction force of the fingertip was determined for different plate prescribed displacements.

The normal contact force/displacement curve is shown in Fig. 5. The force is normalized with respect to the force at the maximum displacement (set to 2.0 mm).

Ten simulation samples were conducted, with a step decreasing of 0.2 mm. The results are compared with the experimental data in [13] and simulations in [14]. The contact force distribution points coming from the developed model lies between the two curves of reference data, except for a couple of values.

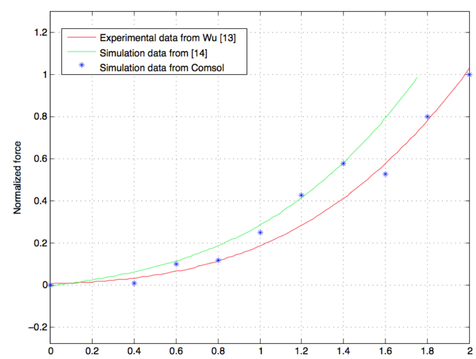

Figure 5. Relationship between force and displacement of the contact interaction between fingertip and flap plate.

In Fig. 6 and 7, there are depicted a front size caption of the total displacement and Von Mises stress, respectively, when a prescribed plate displacement of 2.0 mm is applied.

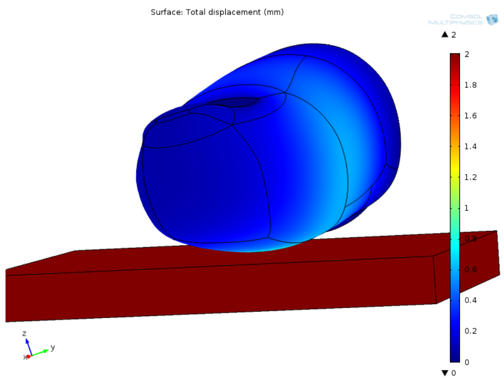

Figure 6. Caption of the total displacement when a prescribed plate displacement of 0.2 mm is applied.

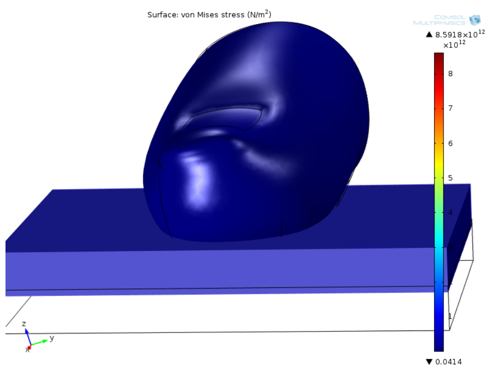

Figure 7. Caption of the Von Mises stress when a prescribed plate displacement of 0.2 mm is applied.

In Fig. 8 the cross-section centered in the contact interaction is analyzed. It is shown that the pressure clearly causes an evident dermis and epidermis displacement. Subcutaneous geometry is obviously less affected, instead.
Fig. 9 shows a quite high Von Mises concentration in the contact interaction point.

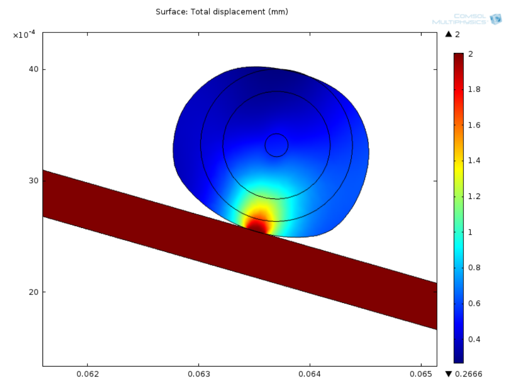

Figure 8. Cross-section caption of the total displacement when a prescribed plate displacement of 0.2 mm is applied.

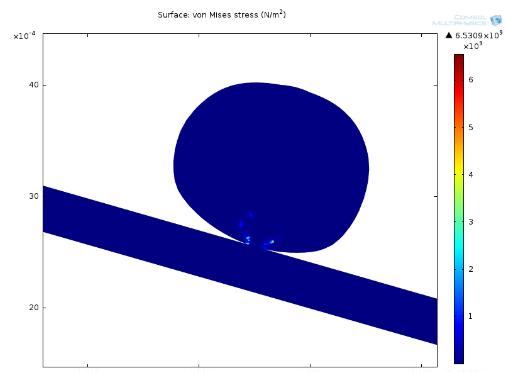

Figure 9. Cross-section caption of the Von Mises stress when a prescribed plate displacement of 0.2 mm is applied.

4. Discussion and Conclusion

In this paper a FE model of the human fingertip has been developed. The model reproduces the mechanical structure of the fingertip. In this work we analyzed the static stress and strain distributions when the fingertip is touching a flat surface.
The obtained results shown that the developed model is able to predict with an acceptable degree of reliability the contact force, when an object is in contact with the fingertip.
However, predictive model does not perfectly fit the experimental data [13]. This is due to a list of factors; the fingertip geometry could be improved and constant materials need a more

deep investigation. Further research will include much more nonlinearity and inhomogeneity in the material definitions. Moreover, in the future improvements of this work, the dynamic behavior will be analyzed. The final objective of the study will be a predictive model to be used in the design and optimization process of new cutaneous haptic interfaces.

References

[1]. www.cnx.org
[2]. Clemente CD, Anatomy: a regional atlas of the human body, 2nd ed. Baltimore, Munich: Urban and Achwarzengerg (1981).
[3]. D. Prattichizzo, F. Chinello, C. Pacchierotti, M. Malvezzi. Towards wearability in fingertip haptics: a 3-DoF wearable device for cutaneous force feedback. *IEEE Transactions on Haptics*, **6(4)**, 506-516 (2013).
[4]. A. Guyton, Human physiology and mechanism of disease, 3rd ed. Philadelphia: W.B. Saunders Co, (1982).
[5]. M. Srinivasan, R. LaMotte, Tactile discrimination of shape: response of slowly and rapidly adapting mechanoreceptive afferents to a step indented into the monkey fingerpad, *Journal of Neuroscience*, **7**, 1682-1697 (1987).
[6]. H. Gray, Anatomy of the human body, 29th ed Philadelphia: Lea and Febider, (1973).
[7]. M. Srinivasan, Surface deflection of primate fingertip under line load, *Journal of Biomech*, **22**, 343-349 (1989).
[8]. E. Serina, E. Mockensturm, CJ, Mote, D. Rempel, A structural model of the forced compression of the fingertip pulp, *Journal of Biomech*, **31**, 639-646 (1998).
[9]. J. Philips, K. Johnson, Tactile spatial resolution. III. A continuum mechanics model of skin predicting mechanoreceptor responses to bars, edges and gratings, *J Neurophysiol*, **46**, 1204-1225 (1981).
[10]. M. Srinivasan, K. Dandekar, An investigation of the mechanics of tactile sense using two-dimensional models of the primate fingertip. *ASME J Biomech Eng*, **118**, 48-55 (1996).
[11]. J.Z. Wu, R.G. Dong, S. Rakheja, A.W. Schopper, W.P. Smutz. A structural fingertip mdel for simulating of the biomechanics of tactile sensation. *Medical Engineering and Phisics*, **26**, 165-175 (2004).
[12]. P.J. Pinel, *Biopsychology,* Allyn and Bacon Publications, London (1990).
[13]. J.Z. Wu, R.G. Dong, W.P. Smutz. Dynamic interaction between a fingerpad and a flat surface: experiments and analysis . *Medical Engineering and Phisics*, **25**, 397-406 (2003).
[14]. J. Jindrich, Z. Yan, B. Thodore. Non-linear viscoelasic models predict fingertip pulp force-displacement characteristics during voluntary tapping, *J Biomech*, **36**, 497-503 (2003).

10. Acknowledgements

The research leading to these results has received funding from the European Union Seventh Frame–work Programme FP7/2007-2013 under grant agreement n. 601165 of the project “WEARHAP - WEARable HAPtics for humans and robots”.