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PRELIMINARY FINGERTIP PRESSURE AREA DISTRIBUTION VIA EXPERIMENTAL TEST AND NUMERICAL MODEL

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Abstract – The fingertip deformation represents the basic mechanical action that shapes human haptic perception. In this work, we present an experimental set up to provide, as proof of the concept, a characterization of human fingertip mechanical properties, in terms of contact area and pressure distribution. Such measures are then correlated with the output of a 3D Finite Element (FE) Model of fingertip developed in order to validate our numerical approach for further investigations.

Keywords: Biomechanics, pressure sensors, pressure distribution, contact area, finite element model.

1. INTRODUCTION

The investigation of the mechanisms of human tactile perception represents a fundamental topic in haptics (i.e. the science and the technology of touch). Indeed, if the comprehension of the underpinning human perceptual mechanisms is clearly the main goal of most of the neuroscientific studies, it may also lead to a correct development of tactile devices and haptic systems, as they are intended to convey controllable and effective stimuli. What is noticeable is that the mandatory step to properly develop such investigation is the clear understanding of mechanical properties of soft tissues and, more specifically, the tissues of the main "organ of touch", i.e., human hand and its fingers. Indeed, tactile stimuli are mainly mechanical as well as the inputs eliciting the response of tactile receptors [1]. In literature, many accurate methods are presented for in vivo mechanical measurements (see e.g. [2], [3] and [4]) and different acquisition systems are used, such as digital camera-based systems to measure skin deformation [5], Magnetic Resonance (MR) images taken before and during compressional loading of the finger tissue [6] or non-intrusive suction instruments [7], among the others. These mechanical properties are then extensively used to develop Finite Element (FE) models of human finger, which represent one of the most useful tools adopted by the research community to investigate some properties that are hardly measurable (such as internal strain distribution). Many numerical models have been built, which differ for dimensionality, accuracy and mechanical response to different tasks (see e.g. [3], [4], [8] and [9], among the most significant). However, despite individual differences among them, they all need to be first validated, or, in other words, to be tested in terms of the correct matching of numerical results with experimental data for a large variety of mechanical conditions and parameters (such as velocity, different interaction surfaces and indenters, etc.). Among these fingertip mechanical properties, the investigation of pressure distribution between the finger and soft materials is still a challenging task [10] [11]. In the biomedical field, currently the use of sensors is widely adopted, wherever there are high pressure values and wide contact area: palm, plantar and car seat pressure distribution sensors (e.g. by Novel, Tekscan and Sensitronics) are exploited for grasping, walking and seating forces investigation. The success of the aforementioned sensors is based on their low stiffness and high sensitivity w.r.t the measured pressure. On the contrary, when there are low loads, more specifically, when fingertip is in contact with soft material, sensors stiffness should be comparable with the highest compliance of the system. In particular, for fingertip deformation, it is reasonable to assume as compliance limit the value of 0.1 mNm [12] [13], which is comparable with fingertip and common paper stiffness. To achieve this goal, we used a film sensor (in paperboard material), whose stiffness was 0.05 mNm [12] [13]. This sensor can adapt itself to the high deformation that occurs during the contact between two soft materials, such as fingerpad and compliant deformable objects. For this reason, in this work, we show a proof of concept of a novel method to measure pressure distribution especially for fingertip interaction, based on the integration of experimental data and numerical model. The paper is organized in two parts: the first one focuses on the measurement of contact area and pressure area (i.e. the area where pressure value is above sensor threshold) and contact forces trough the aforementioned experimental measurements; the second one deals with the validation of the numerical model of the fingertip. To achieve this goal, first we have designed and built a test rig, which enables to compress human fingerpad with a flat surface. The indentation parameters such as velocity or finger orientation were controlled. Two experimental tests were carried out: one for measuring the contact area trough high resolution camera and related forces, while the other one for measuring the pressure area with the aforementioned pressure sensor film. Finally, based on literature parameters and geometrical observations, we built a FE model of human fingerpad. Outputs from the numerical model in a simulation mimicking the procedure for data acquisition and the experimental measures were compared and hence FE model validated. Once validated the model, results of the simulation can be used to numerically determine pressure distribution, with a resolution higher than the one used for experimental measures. Results, although preliminary, encouraged us to further investigate the here described methodology, which we have presented as a proof of concept.

2. MATERIALS AND METHODS

The experimental test consists of indenting the fingertip, using a linear actuator, with a flat surface and to measure the size of the fingertip area, fingertip deformation and pressure distribution. Contact area measurements were carried out in two different ways: i) the contact area is obtained through high resolution video-camera, ii) the area of the pressure distribution is obtained from pressure distribution on the pressure sensors. We have used both types of results for the validation of a 3D Finite Element (FE) model of human fingertip. To achieve the experimental measures, we built the experimental Test Rig shown in Fig.1.

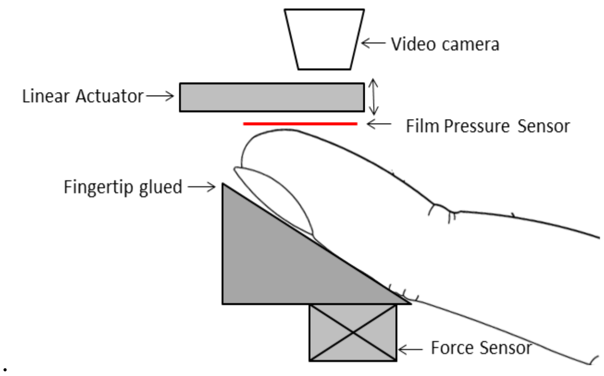

Fig. 1. Measurement Apparatus for Experimental Tests.

2.1. Test Rig

The test rig is a one degree of freedom (dof) device that permits to move a flat surface towards the fingertip to indent it. The displacement is provided by a linear DC actuator (Faulhaber LM2070-040-01 plus MCLM3003 controller) with 9.2N of constant force, max acceleration of 94 m/s^2, 200 µm of accuracy and 60 µm of repeatability. The contact area is recorded through a video-camera (Sony HDRCX505VE 12MP) with 1500 x 1120 effective pixels per video frame and 50fps. The direction of the movement is guaranteed by slider (Standa 7T125Z-10) that has an angular deviation ≤ 200 µrad. The forces and torques are recorded through a 6 dofs force/torque sensor (ATI 6dof Nano17) with 0.00625 N force resolution and 0.03125 Nmm for torque. The force sensor is rigidly connected to the flat surface (indenter), which is moved against the finger. In order to correctly position the fingertip and control its orientation, a micro goniometer (Standa 7G174-30) with reading resolution of 0.1deg was chosen. The sensor pressure, showed in red in Fig. 1, of Pressurex - microGreen (Sensor Products Inc. PMG1), has 10-400 kPa pressure range and 45 µm spatial resolution with 17% accuracy. The flat surface, which will contact with the fingerpad, is in Plexiglass.

3. EXPERIMENTAL TEST PROCEDURE

The experimental tests consist in positioning the fingertip in the finger-holder and moving the flat surface toward the fingerpad, as shown in Fig.2. The subject right forefinger was fixed to the finger-holder on the top of the nail and oriented at 15 deg w.r.t. the flat surface. The fingerpad was free of callus and subject gave her informed consent to the experimental test. Three different displacement levels were considered (1, 2, 3 mm) and only one velocity (2 mm/s), as a preliminary test case. Some results of the images captured by video-camera are displayed in Fig.3, where four snapshots show the different contact areas per each indentation displacement (0, 1, 2, 3 mm). The area was manually measured from the video-camera images, based on a luminosity binarization thresholds algorithm.

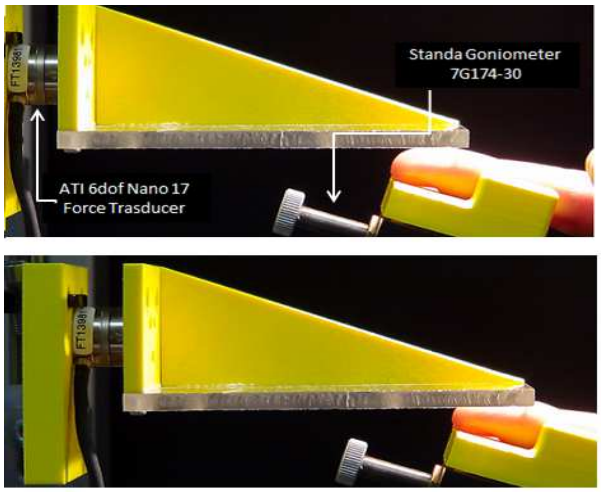

Fig. 2. Flat surface displacement and fingertip indentation.

3.1. Contact Area Values and Force

The indentation tests were carried out measuring the contact area and the force at fixed displacement intervals (1 mm, 2 mm, 3 mm) at the velocity of 2 mm/s. The contact area is the area recorded when the fingertip skin is completely stick to the Plexiglass surface. The area values are reported in Table 1 where the mean area and relative standard deviation are indicated. Results are obtained upon three tests per each displacement intervals. The force values recorded during these tests are reported in Table 2, together with their peak force values.

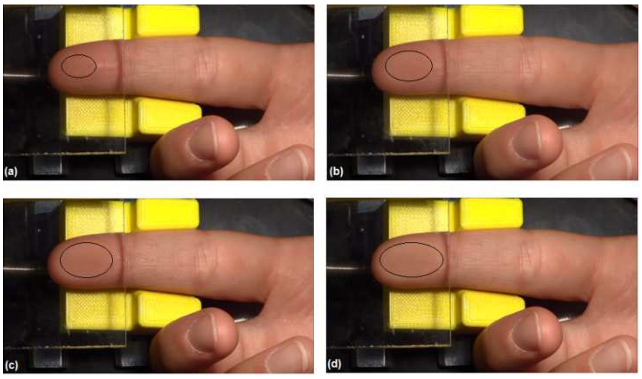

Fig. 3. Contact area with different indentation: a) 0 mm, b) 1 mm, c) 2 mm d) 3 mm.

Table 1. Contact areas values of the indentation with related average and standard deviation.

Experimental Area Values [mm^2]			
Indentation	1 mm	2 mm	3 mm
Test 1	92.82	148.8	147.2
Test 2	70.07	117.8	129.6
Test 3	99.19	106.6	121.6
Average	87.36	124.4	132.8
STD (%)	12.34	21.86	13.10

Table 2. Contact force values of the indentation with related average and standard deviation.

Experimental Force Values [N]			
Indentation	1 mm	2 mm	3 mm
Test 1	0.80	1.01	1.72
Test 2	0.75	1.05	1.76
Test 3	0.78	1.02	1.64
Average	0.78	1.03	1.71
STD (%)	3.2	2.0	3.6

3.2. Pressure Distribution Area Values

The experimental test with the pressure sensor focuses on pressure area and pressure distribution approximation. The sensor is made by a film of microscopic pigmented particles adhered to the donor substrate, which are attracted to the chemically surface-treated receiver sheet. The full scale is sufficient for our application. However, the threshold (10kPa), the resolution (15kPa) and the accuracy (17%) we cannot expect an output with more than two levels of pressure (lower and greater than 10kPa), since the maximum expected value is around 25-30kPa [14]. The area with a pressure above the threshold is named "pressure area". The film is inserted between the fingerpad and the flat moving surface for each measurement. Some preliminary results are shown in Fig.4. Given that the sensor measures the final pressure distribution, only step-wise displacement can be used. We chose 1 mm, 2 mm, 3 mm and we performed three measures each. Results are shown in Table 3. Given its resolution, the sensor enables to measure pressure distribution as a proof-of-concept for the acquisition method.

Table 3. Pressure area values of the indentation with related average and standard deviation.

Pressure Area Values [mm^2]			
Indentation	1 mm	2 mm	3 mm
Test 1	40.32	87.8	104.1
Test 2	37.80	77.0	82.0
Test 3	49.06	61.6	79.7
Average	42.39	75.46	88.6
STD (%)	13.9	17.4	15.2

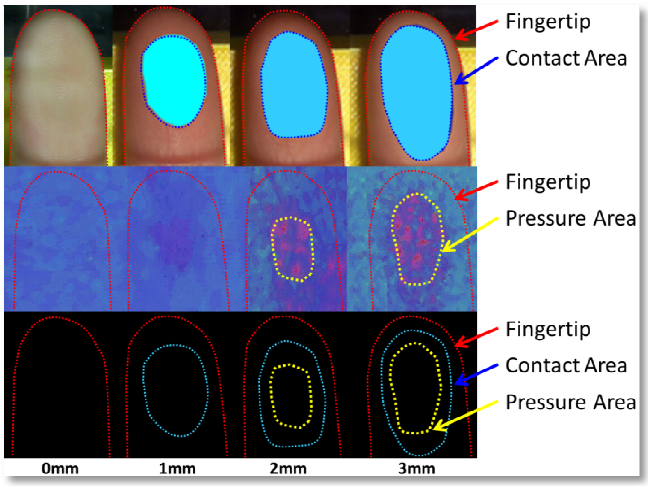

Fig. 4. (top) Contact area (dotted cyan line) measured through high resolution camera. (middle) Pressure area (dotted yellow line) measured with film pressure sensor. (bottom) Comparison between contact and pressure area. From left to right : 0 mm, 1 mm, 2 mm, 3 mm indentation.

4. NUMERICAL MODEL

The numerical model is a fully parametrized Finite Element (FE) Model that replicates the fingertip shape of the right-handed subject (female, age 28), who carried out the experimental tests. Fingertip was free of callus.

4.1. Geometry and Material

The geometry of the fingertip is determined by the physical one of the tested fingertip. The FE model, built in ANSYS [15], has 7736 solid brick 8 nod elements, with 21714 dofs as shown in Fig.5. The fingertip materials used in the model were the same of Wu et al. [3] and Gerling et al. [9] with epidermis, nail and bone as linear materials and Young's Modulus of 2 MPa and 17 MPa for the bone. The dermis and subcutaneous tissues were modeled with Mooney-Rivlin formulation for nonlinear materials, but without the viscosity properties [9]. The fingertip is indented by an inclined plane of 15 deg w.r.t. finger longitudinal axis. The displacement of the plan is perpendicular to the plane axis, as in the test rig. The constraints are set on the nail. The contact is established between the moving plane and the bottom part of the finger.

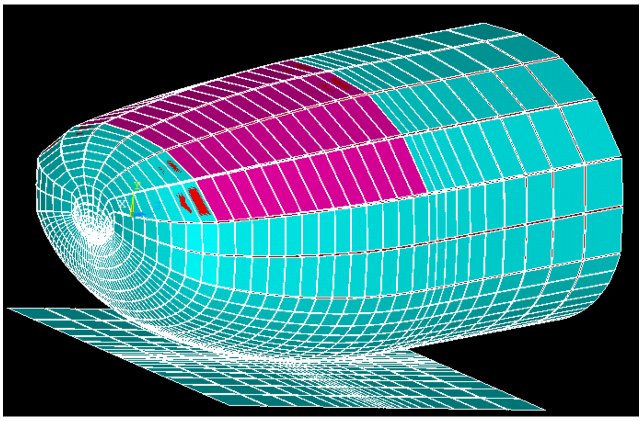

Fig. 5. Human fingerpad Finite Element (FE) Model.

4.2. Numerical Simulation

The simulations were carried out moving the flat surface against the fingertip as in the experimental tests. We used a quasi static analysis. Some results are shown in Fig.6. It is possible to notice the increase of the indentation and the contact area. The contours display the pressure between the plane and the skin. The contact areas and the pressure areas are measured using a binarization threshold algorithm.

5. VALIDATION AND DISCUSSION

We have compared the numerical output of contact and pressure area with the experimental one, under the same condition of indentation (1 mm, 2 mm, 3 mm). What can be seen from Table 4, the accuracy (average) between the measures is under 20%. This result, although preliminary, represents an encouraging starting point to be further investigated. The same behavior can be observed also for the experimental forces.

Table 4. Contact area values of the indentation : average and standard deviation.

Experimental and Numerical Values Comparison			
Indentation	1 mm	2 mm	3 mm
Experimental Contact Area	87.3±10.5	124±14.7	133±16.8
Numerical Contact Area	78.2	111	129
Accurancy (%)	10.2	10.3	12.1
Experimental Pressure Area	42.4±5.91	75.4±13.2	88.6±13.5
Numerical Pressure Area	53.3	61.4	80.1
Accurancy (%)	16.4	16.2	7.4
Experimental Force [N]	0.78±0.09	1.03±0.09	1.71±0.06
Numerical Force [N]	0.65	1.10	1.90
Accurancy (%)	15.2	12.5	11.1

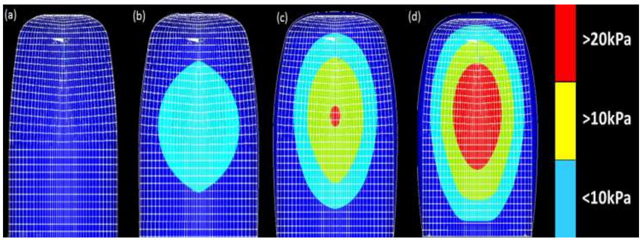

Fig. 6. Pressure distribution numerical results with different indentations: a) 0 mm, b) 1 mm, c) 2 mm, d) 3 mm. The cyan area is comparable to the contact area of the experimental results as well as the yellow area to the pressure area.

6. CONCLUSION

In this paper, we have present a preliminary integrated characterization of the fingertip properties in terms of contact area, pressure distribution and indentation. The experimental results are used to validate a 3D model of the finger. This FE model permits to achieve several pressure distribution levels that, otherwise, would be hard to experimentally measure. Results, although preliminary, are encouraging and motivate us to proceed towards a more accurate, exhaustive and effective mechanical characterization o finger characteristics (e.g. with more subjects), which might be used to drive the development of more realistic numerical model and to investigate the interaction with soft materials, to inform the design of haptic systems or tactile sensors.

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REFERENCES

[1] K. O. Johnson, The roles and functions of cutaneous mechanoreceptors, (2001) Curr. Opin. Neurobiol., vol. 11, no. 4, pp. 455461.
[2] H. Fruhstorfer, U. Abel, C. D. Garthe, and A. Knuttel, (2000) Thickness of stratum corneum of the volar fingertips.
[3] J. Z. Wu, R. G. Dong, S. Rakheja, A. W. Schopper, and W. P. Smutz, (2004), A structural fingertip model for simulating of the biomechanics of tactile sensation, Med. Eng. Phys., vol. 26, no. 2, pp. 165175.
[4] T. Maeno, K. Kobayashi and N. Yamazaki, (1998) Relationship between the Structure of Human Finger Tissue and the Location of Tactile Receptors. Bulletin of JSME International Journal, Vol. 41, No. 1, C, pp. 94-100.
[5] V. Lvesque, (2002) Measurement of Skin Deformation Using Fingerprint Feature Tracking M. Eng. Thesis, McGill University.
[6] A. E. Bowden, R. D. Rabbitt and J. A. Weiss, (1999) Stress and Strain in the Human Distal Phalanx Under Indentation. Proceedings of the First Joint BMES/EMBS Conference Serving Humanity, Advancing Technology Oct 1516, Atlanta, GA, USA.
[7] S. Giavazzi, M. F. Ganatea, M. Trkov, P. utari and T. Rodi, (2010) Inverse determination of viscoelastic properties of human fingertip skin. RMZ Materials and Geo environment, Vol. 57, No. 1, pp. 116.
[8] K. Dandekar, B. I. Raju and M. A. Srinivasan, (2003) 3-D Finite-Element Models of Human and Monkey Fingertips to Investigate the Mechanics of Tactile Sense. Transactions of the ASME. Vol. 125.
[9] G. J. Gerling, I. I. Rivest, D. R. Lesniak, J. R. Scanlon and L. Wan. Validating a Population Model of Tactile Mechanotransduction of Slowly Adapting Type I Afferents at Levels of Skin Mechanics, Single-unit Response and Psychophysics. IEEE Transactions on Haptics.
[10] T. Nakamura, F. Kimura, and A. Yamamoto, (2013) A Photoelastic Tactile Sensor to Measure Contact Pressure Distributions on Object Surfaces. Journal of Robotics and Mechatronics, Vol. 25, No. 2 , pp. 355-363
[11] W. J. Peine, R. D. Howe, Do Humans Sense Finger Deformation Or Distributed Pressure To Detect Lumps In Soft Tissue?, (1998) Proc. ASME Int. Mech. Eng. Congress Expo., Vol DSC-64 pp. 273-278
[12] Shima, K., Tamura, Y., Tsuji, T., Kandori, A., Yokoe, M., Sakoda, S. (2009). Estimation of human finger tapping forces based on a fingerpad-stiffness model.
[13] Bending stiffness of paper and paperboard, T 535 om-96, The Technological Association of the Pulp and Paper Industry.
[14] Pawluk, D. T., Howe, R. D. (1999). Dynamic contact of the human fingerpad against a flat surface. Journal of Biomechanical Engineering, 121, 6, 605-11.
[15] ANSYS Academic Teaching Mechanical, Release 14.5