HUMAN FINGERPAD UNDER INDENTATION I: STATIC AND DYNAMIC FORCE RESPONSE

Rogeve J. Gulati
Mandayam A. Srinivasan

Department of Mechanical Engineering and
Research Laboratory of Electronics
Massachusetts Institute of Technology
Cambridge, Massachusetts

INTRODUCTION

Fingerpad mechanics plays an important role in both the perception of object properties and control of contact conditions during manual exploration and manipulation. The fingerpad can be defined as the palmar side of the distal phalanx, characterized macroscopically by a relatively thick epidermis, epidermal and dermal papillary ridges which give rise to the fingerprints, and a cushion of adipose tissues supported by the bone (Quilliam, 1978; Thomine, 1981). At the microscopic level, the fingerpad skin is rich in sensory nerve endings that convey a tactile "image" to the central nervous system. These mechanoreceptors respond electrophysiologically to stress/strain fields produced by loads at the skin contact interface and the associated fingertip deformations (Srinivasan and Dandekar, 1992). During manipulation of objects, the anatomical features and mechanical behavior of the fingerpad influence contact conditions such as contact area and occurrence of slip. Therefore, for a deeper understanding of tactile perception and manual control, it would be useful to characterize the biomechanical behavior of the fingerpad, particularly its force response to indentation. Based upon preliminary observations that the passive fingerpad exhibits viscoelastic behavior, a set of static and dynamic indentation stimuli were designed for delivery with varied indentor shapes to the passive fingerpad, *in vivo*. The resulting force response was recorded and analyzed for notable features.

METHODS

A computer-controlled high-precision robot ("tactile stimulator") was employed to perform indentation experiments upon the right (dominant) index fingerpads of 5 subjects varying in sex, age and size. Similar to an earlier investigation of compressibility (Srinivasan, *et. al.* 1992), three indentors--a point, a 6.35 mm diameter circular rod and a 25 mm diameter flat plate--were chosen to investigate the effect of contact region on the force response. The subjects were asked to maintain a hand posture such that the index finger was angled at 60° with respect to the path of indentation (see Fig. 1). This angle corresponded to the typical fingerpad orientation during tactual exploration. Additionally, the finger was glued at the nail to a rigid support and the proximal joints comfortably strapped to prevent fingertip motion during indentation.

FIGURE 1

Indentations were delivered along a single axis normal to the skin surface. Velocities, depths and frequencies of ramp+hold+sinusoid stimulation were varied (Fig. 2). Ramp velocity of the stimuli ranged from 1 to 32 mm/sec. Depth was incremented at 0.5 mm up to 3.0 mm (resolution of 20 μm). Sinusoidal frequencies increased from 0.125 hz to 16 hz at amplitudes of 0.25 and 0.5 mm. Force response was measured using a strain gage sensor accurate to 10 mN and digitized at 500 samples/sec. In all cases, initial contact of the indentor with the skin was determined visually by the experimenter along an indentation axis through the center of the nail. The tissues were then preconditioned by at least 10 separate cycles of dynamic loading. Sufficient time was allowed between experimental indentations for the fingerpad to reform to its original (preconditioned) shape. Each stimulus was delivered three times consecutively to check for repeatability of the response. And for each of three experimental sessions for a subject, a set of 50 ramp+hold and sinusoidal stimuli were given with a single indentor.

RESULTS

The indentation experiments verified that the force response of the fingerpad is repeatable and revealed a nonlinear dependence of the force response to depth, velocity, frequency and contact area of indentation. For the subject whose data was "average" among the five, the mean inputs and force responses to three repetitions of two different stimuli with the circular indentor are shown in Fig. 2.

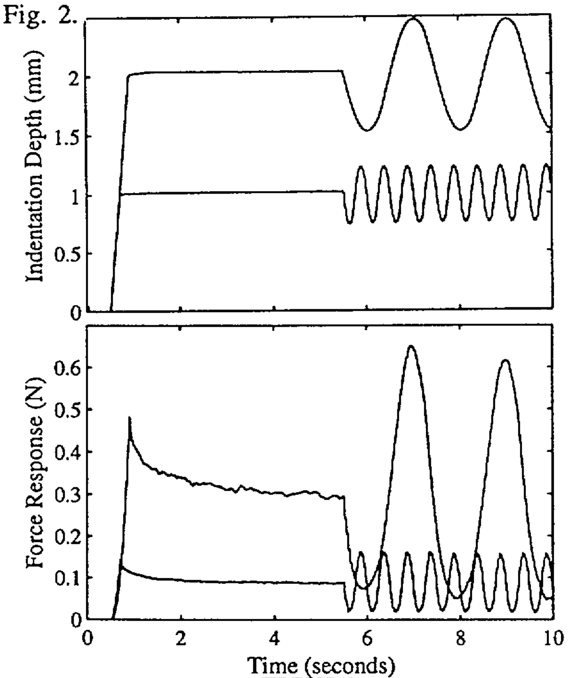

FIGURE 2

Mean static force responses as functions of indentation depth are plotted in Fig. 3 for the three indentors.

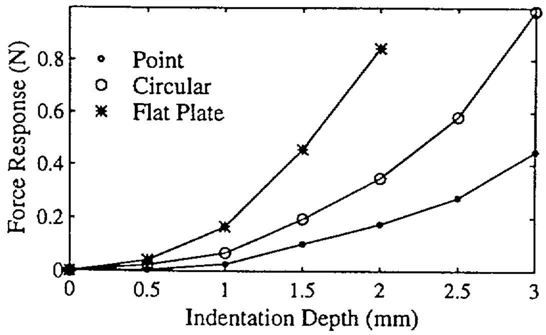

FIGURE 3

Fig. 4 displays steady state and dynamic force data for the same subject with the circular indentor at 3 frequencies. The hysteresis curves demonstrate an increase in mean impedance and energy loss with frequency. Fourier analysis of the data for sinusoidal stimuli indicated a phase shift of less than 10° between input and output at the stimulus (fundamental) frequency.

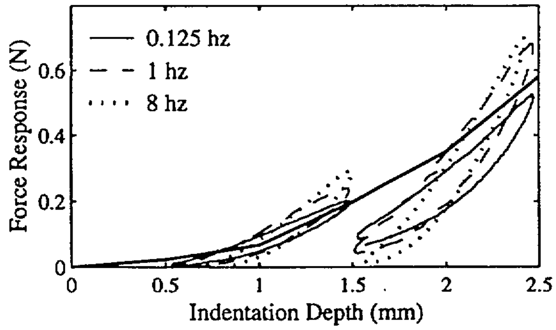

FIGURE 4

Fig. 5 shows average impedance (i.e. average slope of the hysteresis) for one subject with all three indentors stimulated with 0.5 mm amplitude sinusoids at eight input frequencies.

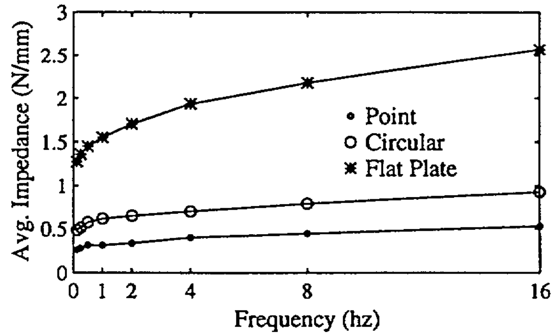

FIGURE 5

CONCLUSIONS

Analysis of the acquired data has clearly shown that the fingerpad exhibits nonlinear and viscoelastic mechanical behavior. The experiments have identified relative magnitudes of the force response to various indentations and the dependence on static and dynamic aspects of the stimuli. A successful model based on the experimental data from all 5 subjects will be useful in gaining a deeper understanding of tactile perception and manual control and will help in the design of intelligent prostheses and force-reflecting interfaces for human-machine interactions.

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REFERENCES

Quilliam, T.A. "The structure of fingerprint skin." *Active Touch*. Ed. G. Gordon, Oxford: Pergamon, **1978**.

Srinivasan, M.A. and Dandekar, K. "Role of fingertip geometry in transmission of tactile mechanical signals." *Advances in Bioengineering*, 22: 59-72, **1992**.

Srinivasan, M.A., Gulati, R.J., and Dandekar, K. "In vivo compressibility of the human fingertip." *Advances in Bioengineering*. 22:573-576, **1992**.

Thomine, J.M. "The skin of the hand." *The Hand*. Vol. 1, Ed. R. Tubiana, W.B. Saunders & Co., **1981**.