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In Vivo Compressibility of the Human Fingertip

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Abstract

During manual exploration or manipulation of objects by humans, the mechanical properties of the fingerpads play a dominant role in governing the sensing of tactile information as well as the control of manipulation. To determine the *in vivo* compressibility of human fingertips, static indentation experiments were performed using a specially designed apparatus. Volume changes of the fingertips were measured at various depths of indentation by a sharp probe. The results show that the fingertip is almost incompressible for a point indentor, with the highest change in volume (about 1%) occurring at the largest depth of indentation (4 mm). This data is being used in the development of reliable mechanistic models of the fingertip to gain a deeper understanding of the biomechanical bases of tactile sense.

Introduction

We constantly grasp, press, squeeze, or stroke objects with our fingerpads. We use physical contact with objects to explore their geometrical properties such as surface texture and shape, as well as material properties such as compliance. While manipulating the objects, say, moving them from one location to another using a pinch grasp, contact conditions give us information about the weight of the object, whether the object is slipping, and if so, whether the control action of increased grasp force has terminated the slip. Yet, we know very little about the nature of the contact between the fingerpad and various objects that differ in their physical properties, or the kind of spatio-temporal contact information that is gathered by our tactile sensors. We know even less about how this information is processed by the central nervous system, and is used in controlling the contact conditions with the help of the motor system.

One of the major factors that govern the quality of tactile information about the object as well as the effect of motor action on the object is the mechanics of contact between the fingerpad and the object. In order to gain a deeper understanding of this interaction, development of reliable mechanistic models of the human fingertip is necessary (Srinivasan and Dandekar, 1992). This requires the specification of its external and internal geometry, as well as the material properties of the constituent soft tissues. For a first analysis, we can view the fingertip as a block of material and focus only on its external geometry and bulk material properties. In the mathematical representation of the material properties, it is important to know if the fingertip is incompressible, since it leads to simpler constitutive equations. In the tests for compressibility of the human skin *in vitro* (North and Gibson, 1978; Vossoughi and Vaishnav, 1979) the ratio of the bulk to shear modulus was found to be about 10^3. In impedance tests *in vivo* (Von Gierke, *et al*, 1952), this ratio was of the order of 10^6, thus confirming its incompressibility (for a review, see Lanir, 1987).

In this study, we focused on the experimental determination of *in vivo* compressibility of the human fingertip. We designed an apparatus and performed experiments to measure the change in volume of the fingertip under static indentations by a probe. We also developed a technique for casting three dimensional copies of the undeformed fingertip so as to measure its initial volume and, in the future, to determine its external geometry. The results will help us develop reliable finite element models of the human fingertip to study the role of its mechanical behavior in manual exploration and manipulation.

Apparatus

The apparatus was designed to allow a subject's fingerpad to be indented by a probe to a known depth, and to enable the corresponding change in volume to be measured. The basic technique was to enclose the fingertip in an incompressible fluid such that the change in the fingertip volume was indicated by a change in the fluid level. There were several design constraints: (1) Experiments should be non-invasive and *in vivo*; (2) There should be no evident leak in the system; (3) Apparatus must be sensitive enough to measure very small volume changes of the fingerpad; (4) Dynamic real-time measurements to track the fluid level changes over a period of seconds to minutes should be possible;

(5) Subject's arm and finger should be constrained to prevent motion and tremors during the experiment; and (6) Apparatus should accommodate a range of subjects.

In keeping with these constraints, the apparatus shown in Figure 1 was constructed. A clear 1 inch diameter plastic tube, closed at one end, served as the main chamber for the fluid and the finger. Its open end diameter was reduced by a smooth thick layer of epoxy so that the metacarpopharangeal joint of the subjects' fingers fit snugly at the opening. Plastic tubing was bonded with water-resistant epoxy at two places as shown to serve as water inlet and outlet, and needle valves controlled the water flow. A graduated cylinder with 1/100 ml graduations was mounted vertically to allow the volume changes to be observed. On one side, part of a syringe was mounted horizontally and its plunger was replaced by a 0.25 inch diameter aluminum indentor with a conical tip. An o-ring between the rod and syringe tube provided a seal against leak, while still allowing motion of the plunger. Dial gauge calipers were mounted on the stationary syringe tube and the aluminum indentor. This enabled the indentation depth to be read accurately to 0.02 mm. On the open end of the main tube, a latex fingercot used to encase the subject's fingertip (distal phalanx) was stretched over the lip of the tube and sealed with an o-ring. A small nub was bonded inside the main tube such that the subject could rest his/her fingernail against it during the indentations. In some cases, the end of the finger cot was glued to the nub to prevent motion of the finger. Secure wrist and arm braces were used to minimize any motion of the finger during indentations, since the apparatus was sensitive enough to pick up fingertip motions equivalent to 1/100 ml change in volume. A video camera was kept focused on the graduated cylinder to record the water level changes on video tape.

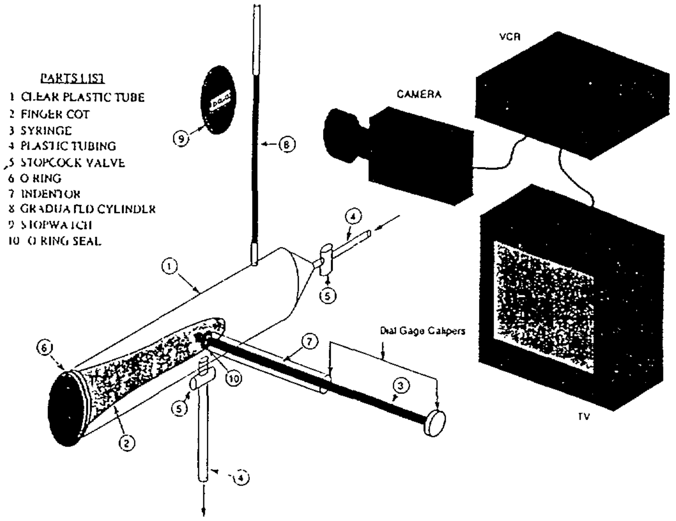

Figure 1: *Schematic of the experimental setup. The subject's fingertip was inserted into the fingercot, and the main tube 1 was filled with water prior to the indentations. Water inlet and outlet are represented by 4, with the arrows showing the water flow path. Each mm of indentation caused a volume input of 3/100 ml into the main tube, equal to the inner volume of 1mm length of the syringe tube.*

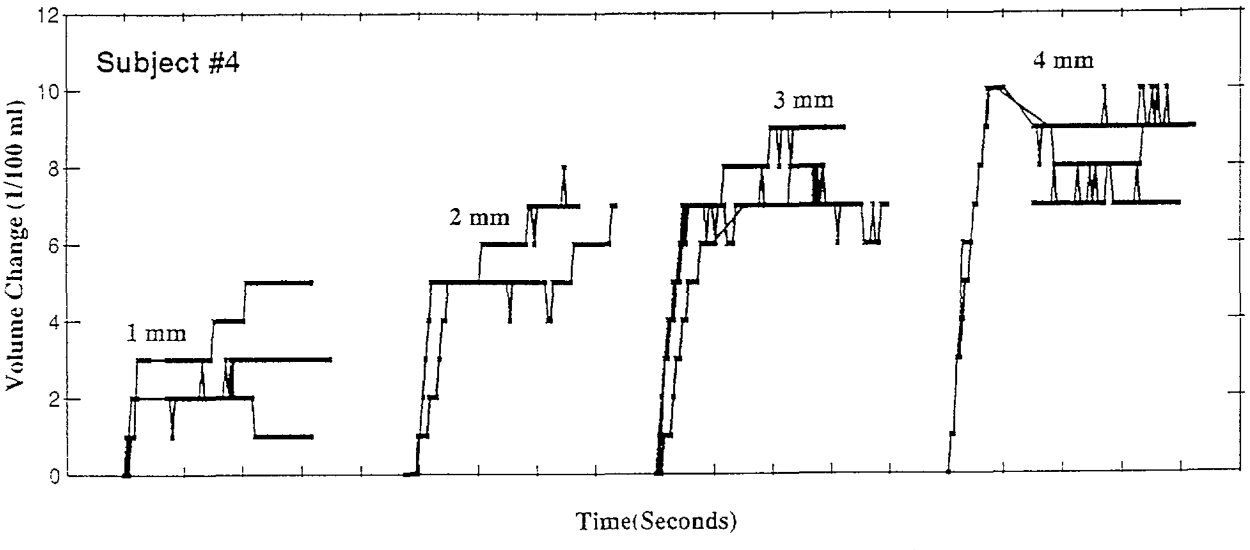

Figure 2: *The change in volume of the water column in the graduated cylinder is shown as a function of time. The data is for one subject, and includes pre-indentation, indentation ramp, and post-ramp measurements for 3 repetitions each, of 1, 2, 3, and 4, mm indentation depths. The time at the beginning of the ramps for each indentation depth is arbitrary and the resolution of the measurements is 1/100 ml. If the fingertip was perfectly incompressible, the change in the volume of water would have been a constant 3/100 ml per mm of indentation depth. Each interval between ticks on the time axis represents 4 seconds.*

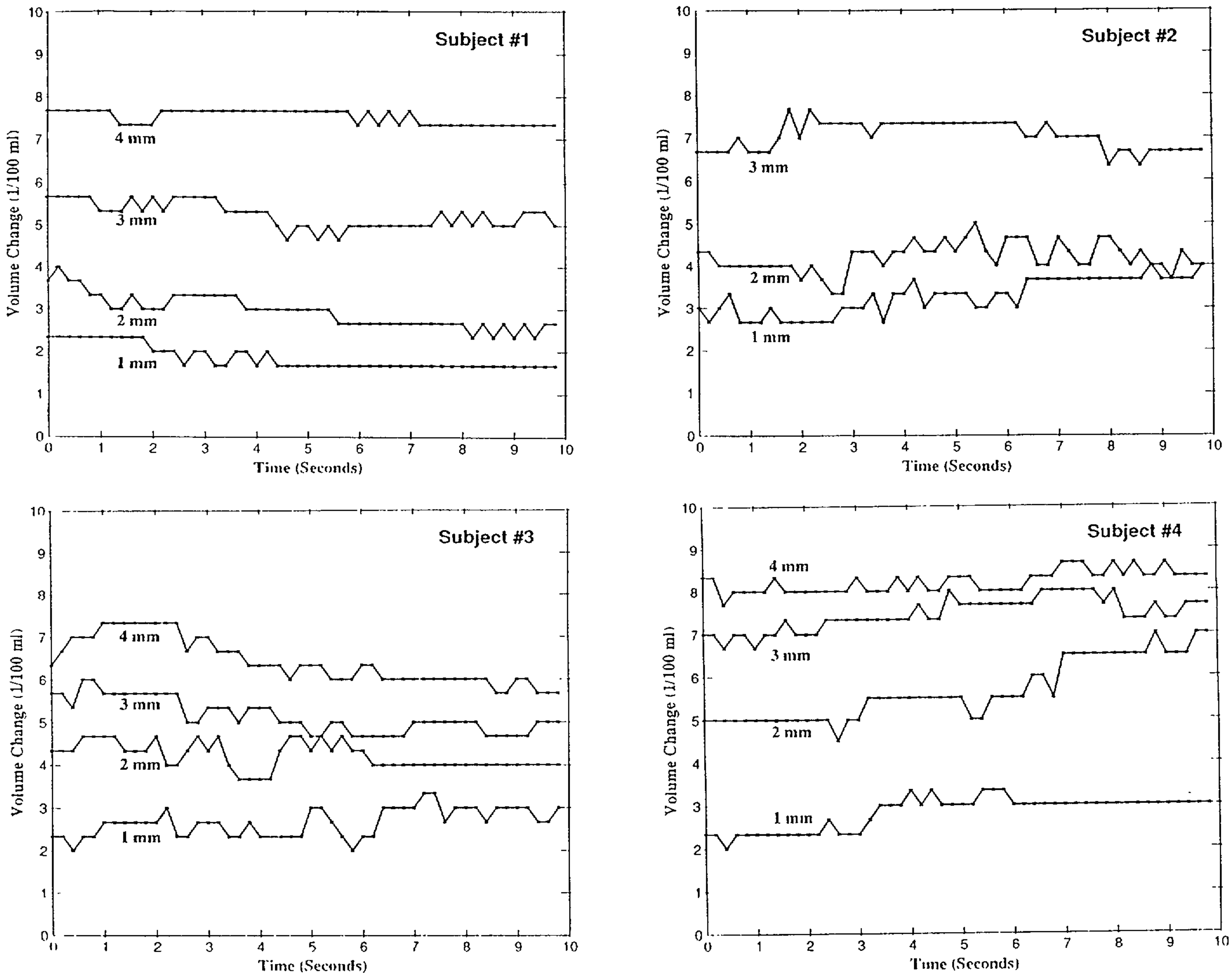

Figure 3: *The mean change in the volume of water during the steady indentation phase is shown as a function of time. The data for all the four subjects is shown. Each trace represents the mean of three repetitions for the indicated depth of indentation.*

Experimental Procedure

The general procedure involved indenting the fingertip of the subject to a known depth, recording on the video the water level changes in the graduated cylinder, and pulling back the indentor to allow the fingertip to reform before the next indentation. As described below, the preparations included checking the system for leaks, setting up the video recording, and getting the subjects' hands suitably restrained to minimize any motions of the fingertip.

The apparatus was checked for leaks initially as well as periodically during the experiments. The main tube was capped off and filled slowly with water so as to remove any air bubbles from the system through the graduated cylinder. By making sure that the water level in the cylinder remained the same for about 5 minutes, the possibility of leaks in the system was eliminated. The resolution of the system was checked by measuring the smallest indentor motion that caused an observable water level change in the cylinder. However, the main limitation on the resolution was the fineness of the graduations in the cylinder, which were 1/100 ml each. The calibration of the system involved moving the indentor by 1 mm so that the corresponding volume of 3/100 ml (equal to syringe inner volume per mm. length) was introduced into the main chamber, and making sure that the cylinder water level rose by 3 divisions

The subjects were comfortably seated, with their forearms strapped to a support at several locations. A rigid brace was used to prevent wrist motions. Each subject's forefinger was inserted into a fresh fingercot, and a dot of 5 minute epoxy was placed on the fingercot at the fingernail region. The fingertip was inserted into the main tube whose opening snugly fit the metacarpophalangeal joint. The end of the fingercot was stretched over the lip of the tube and sealed with an o-ring. After the subject pressed his/her fingernail against the nub for 5 minutes so that the epoxy bonded the cot to the nub, the main tube was filled with water.

	Original	Volume Reduction for each Indentation Depth							
	Volume	1 ml		2 ml		3 ml		4 ml	
	ml	in *ml*	in %	in *ml*	in %	in *ml*	in %	in *ml*	in %
Subject 1	3.7	0.0146	0.319	0.0304	0.846	0.0375	1.044	0.0422	1.243
Subject 2	4.5	-0.0026	-0.070	0.0181	0.488	0.0196	0.532	—	—
Subject 3	3.6	0 0034	0.076	0.0179	0.399	0.0386	0.859	0.0558	1.241
Subject 4	4.4	0.0019	0.042	0.0034	0.077	0.0155	0.353	0.0378	0.861
Average			0.091		0.453		0.697		1.115

Table 1: *Summary of the fingertip compressibility data for all the subjects at all depths of indentation.*

Again air bubbles were eliminated and we made sure there were no leaks.

The indentor tip was placed such that the subject reported just barely detectable contact with it, and the video recording of the water level along with time display in a stop watch commenced. After the subject was instructed to remain passive, and be absolutely still for the next 30 seconds, the fingerpad was indented by 1 mm, as measured by the dial gauge calipers. The indentation ramp time was kept approximately constant at about 2 seconds for all indentations, and after 30 seconds the indentor was withdrawn to its initial position. The subject was allowed to relax for approximately 2 minutes, while the fingertip regained its undeformed shape. This procedure was repeated three times at each depth of indentation equal to 1, 2, 3, and 4 mm. Two male and two female subjects were tested.

The undeformed volume of each of the subjects' fingertips was measured by casting a negative mold of the fingertips using a fast setting elastic impression material. By accurately measuring the water needed to fill the mold up to the level of the distal finger joint, the volume of the fingertip as a whole was determined. Transcribing of the video data, i.e., the water- level in the cylinder and the associated time on the stop watch, was done off-line with frame-by-frame playback. The data was sampled at 0.2 sec. and intervals just before the indentation ramp as well as for 10 seconds duration after the end of the ramp.

Results

The full data collected for one subject before indentation, during the ramp, and under steady indentation is shown in Fig. 2. The velocity of indentation for the three repetitions at each indentation depth, as well as for each of the depths is approximately constant. During steady indentation at a particular depth there are variations of the order of 1/100 ml among the data points. These may be due to a combination of pulse, very small tremors and other uncontrolled motions of the fingertip. As the depth of indentation increases, the change in the volume of water is also shown to increase. If the fingertip was perfectly incompressible, the change in the volume of water would have been 3/100 ml per mm of indentation, equal to the volume of water displaced by the plunger in the syringe. The data in Fig. 2 shows that the reduction in the volume of the fingertip increases as the depth of indentation increases, but is of the order of only a few hundredths of a ml, even at the indentation depth of 4 mm.

In order to minimize errors due to uncontrolled small motions (due to pulse, tremor, etc) which randomly increase or decrease the water volume, we averaged the measurements for the three repetitions at each depth of indentation. The data for all the subjects is shown in Fig. 3. The variations within each trace is only of the order of 1/100 ml, which is the resolution of the apparatus. Among the 15 traces shown, (subject 2 moved during 4 mm indentation, and that data was rejected), equal number of traces tend to move up, down, or remain steady over the 10 sec period shown. Since the change in water volume is plotted here, if the traces move up it means that the finger is regaining its undeformed volume ; if the traces move down, then the finger is getting further compressed over time. No clear trend for either of these cases is supported by the data.

For each subject, the undeformed volume of the fingertips and the volume change at each depth of indentation is summarized in Table 1. Any change in the volume of the fingercot is assumed to be negligible, since it is made of an almost incompressible material, and being thin, has as a very small initial volume relative to that of the fingertip. For the point indentor, the percent volume change for each subject as well as for the average for all the subjects show that they increase with the indentation depth, but are very small (about 1% at an indentation depth of 4 mm). The next question as to whether this change in volume is due to the outflow of fluids such as blood, tissue compression, or both, requires further research.

Acknowledgements

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References

[1] Lanir, Y., "Skin Mechanics", *Handbook of Bioengineering*, eds: Skalak, R. and Chien, S., McGraw-Hill, pp. 11.1-11.25, 1987.

[2] North, J. F. and Gibson, F., "Volume compressibility of human abdominal skin", *J. Biomechanics*, Vol. 11, pp. 203-207, 1978.

[3] Srinivasan, M. A. and Dandekar, K., " Role of fingertip geometry in the transmission of tactile mechanical signals". Proceedings of the Bioengineering division, ASME winter annual meeting, 1992.

[4] von Gierke, H. E., Oestreicher, H. L., Franke, E. K., Parrack, H. O , and von Wittem, W. W., "Physics of vibration in living tissues", *J. Appl. Physiol*, Vol. 4, pp.886-900, 1952.

[5] Vossoughi, J., and Vaishnav, R N., "A comment", *J Biomechanics*, Vol. 12, pp. 481, 1979.