Estimation of Finger Pad Deformation based on Skin Deformation Transferred to the Radial Side

Yoichiro Matsuura, Shogo Okamoto, and Yoji Yamada ⋆

Abstract. *Techniques to measure the deformation of finger pad when rubbing material surfaces are important for the analysis of textural sensations and development of tactile texture displays. However, such measurements are difficult because when the finger pad is in contact with the material surfaces, it is not exposed for measurement. We developed a technique to estimate finger pad shear deformation by using the skin deformation transferred to the side of the fingertip. Good agreement was shown between measured finger pad accelerations and those estimated by our method. The skin deformation of the finger side can be effectively used to estimate that of the finger pad with an average accuracy of 0.93.*

Keywords: Accelerometer, Transfer function, Skin impedance

1 Introduction

Texture sensations are evoked during mechanical interaction between finger pads and material surfaces. Hence, measurement of finger pad deformation or shear force during rubbing motion is important for the analysis of tactile sensations and development of tactile texture displays. For example, as a representative display technique, the vibrotactile texture display presents the sense of materials by controlling the spectrum or frequency components of vibratory stimuli imparted to the finger pad [1]. Most of these techniques are based on the measurement of skin vibration or shear deformation of the finger pad during rubbing motion. However, such measurement during active touch is difficult and methods of direct measurement are limited.

The most successful measurement of finger pad slipping on materials appears to be recording with a camera through transparent materials [2], which is not applicable to general materials. Thus, many researchers have attempted or developed indirect measurements of finger pads. For example, Wiertlewski et al. measured the interaction forces between a fixed finger pad and materials moved laterally against the finger pad [3]. The shear displacement of a finger pad can be determined from such force measurements, given that the finger pad's mechanical impedance is well specified. The neighboring skin parts reflect the mechanical deformation of the finger pad. Bensmaïa et al. analyzed fingertip vibration during tactile exploration of materials using a Hall effect transducer and magnet [4]. They also attempted to measure the displacement of the

⋆ Department of Mechanical Science and Engineering, the Graduate School of Engineering, Nagoya University. Nagoya, Japan. This study is in part supported by KAKENHI Shitsukan (25135717).

skin near the contact surface using a laser velocity sensor [5]. To estimate the load applied to the finger pad, Nakatani et al. measured the radial deformation of the fingertip that results from the Poisson effect when the finger pad is pressed [6]. Tanaka et al. measured the skin vibration propagated to the radial side of the fingertip during exploration of materials using the differential output of two accelerometers [7]. As demonstrated by these studies, it is effective to focus on the skin area close to the finger pad that transfers mechanical deformation to adjacent tissues. Accelerometers are suitable for measuring the fast and fine deformation of skin owing to their excellent frequency response [8]. In a completely different approach, some researchers embedded sensors in pseudo fingers to investigate the internal physics [9, 10].

As described above, early studies were not adequate for measuring fast and fine finger pad deformation, or measured related quantities that are indirectly linked to finger pad deformation. In some studies, the attenuation of skin propagation was not considered. In this study, we have developed a fundamental technique to estimate the shear displacement of a finger pad from the displacement propagated to the radial side of the fingertip. Such a technique will lead to a wearable sensor for finger pad shear deformation caused by active exploration of material surfaces.

2 Operating Principle: Transfer Function Between the Side of the Fingertip and Finger Pad

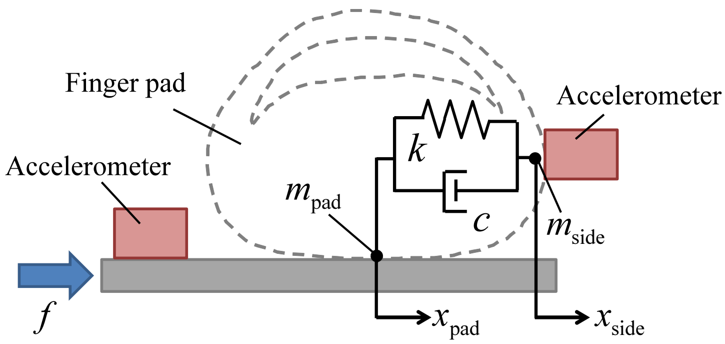


Fig. 1. Spring-mass-damper model of finger skin

As is shown in Fig. 1, deformation of the side of a fingertip accompanies the finger pad's shear deformation. Given the transfer characteristics between these two types of deformation, it is possible to estimate the shear deformation of the finger pad from the deformation of the side of the fingertip. With the physical model of the finger pad as shown in Fig. 1, the equations of motion of the finger pad and radial side point massess are:

$$m_{\mathrm{pad}}\ddot{x}_{\mathrm{pad}}(t) = k(x_{\mathrm{side}}(t) - x_{\mathrm{pad}}(t)) + c(\dot{x}_{\mathrm{side}}(t) - \dot{x}_{\mathrm{pad}}(t)) + f(t) \tag{1}$$

$$m_{\mathrm{side}}\ddot{x}_{\mathrm{side}}(t) = -k(x_{\mathrm{side}}(t) - x_{\mathrm{pad}}(t)) - c(\dot{x}_{\mathrm{side}}(t) - \dot{x}_{\mathrm{pad}}(t)) \tag{2}$$

where m_{pad} and m_{side} are the point masses of the finger pad and radial side, respectively; $x_{\text{pad}}(t)$ and $x_{\text{side}}(t)$ are the respective displacements of the finger pad and radial side; and $f(t)$is the force that causes the displacement of the finger pad. The transfer function for which the input and output respectively are the displacements $x_{\text{pad}}(t)$ and $x_{\text{side}}(t)$ of the two point masses, is expressed by:

$$G(s) = \alpha \frac{(cs+k)}{m_{\text{side}}s^2 + cs + k} \tag{3}$$

where α is a constant value to indicate the transfer ratio between the two skin deformations, which is naturally smaller than 1.0. We use the inverse of this transfer function to estimate $x_{\text{pad}}(t)$ from $x_{\text{side}}(t)$. Note that the use of $G(s)^{-1}$ for high frequency bands is limited because $G(s)$ is a proper function. Eventually, these processes are similar to the specification of lump mechanical properties of the finger tip, which has been attempted by many research groups thus far (e.g. [11]).

3 Specification of Transfer Characteristics of the Fingertip

3.1 Measurement of the Skin Acceleration

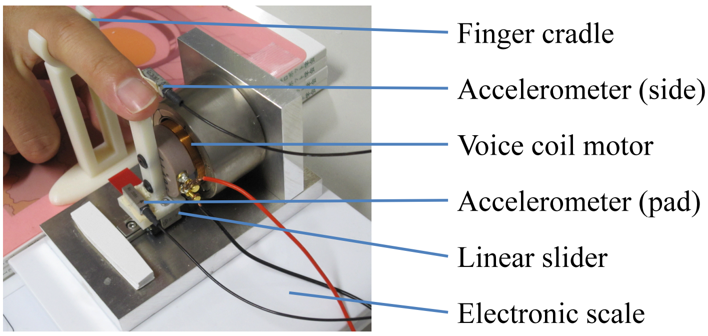


Fig. 2. Experimental apparatus for measuring acceleration of a fingertip

Fig. 2 shows an apparatus that generates and measures the acceleration of skin deformation. One accelerometer (2302B, Showa Sokki Co. Ltd., Japan, single degree of freedom) was taped to the radial side of the fingertip, and another was mounted on the vibration generator to which the finger pad was bonded. The vibration was produced by a voice coil motor and its motion was restrained along a low-frictional linear slider. The accelerometers recorded $\ddot{x}_{\text{side}}(t)$ and $\ddot{x}_{\text{pad}}(t)$, respectively, along the direction of vibration at 5 kHz. During the measurement, the proximal interphalangeal joint was fixed to the base through a clip. The contact force between the finger pad and vibration generator, or pressing force of the finger, was maintained at approximately 1 N by monitoring an electronic scale. Sinusoidal vibratory stimuli, swept across the frequency range of

10–500 Hz, were applied to the finger pad. This trial was repeated 10 times for each of the 5 male voluntary participants in their 20's.

3.2 Frequency Response Characteristics of the Finger Pad

Gain characteristics of the fingertip skin obtained from the five participants are shown in Fig. 3 with a dotted line. These values were computed using the equation $G(f) = 20\log_{10}(\ddot{x}_{\text{side}}(f)/\ddot{x}_{\text{pad}}(f))$, where f is the frequency. For this computation, the average gains of all of the trials were used for each individual. The peak of the gain characteristic was found in the frequency band of approximately 100–300 Hz. This value is similar to those reported in the literature referenced above [7, 12].

3.3 Curve Fitting of the Transfer Function

Table 1. Identified parameters of transfer function

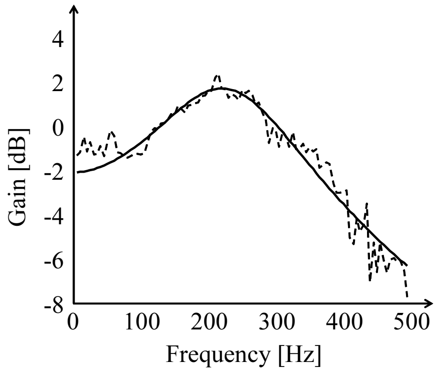
Participant	α	m_{side} kg	k N/m	c N·s/m	R^2
A	0.783	1.97×10^{-4}	5.17×10^{2}	0.288	0.937
B	0.818	1.76×10^{-4}	4.87×10^{2}	0.284	0.924
C	0.842	3.83×10^{-4}	7.09×10^{2}	0.731	0.946
D	0.805	5.38×10^{-4}	8.49×10^{2}	0.612	0.952
E	0.900	5.01×10^{-4}	6.85×10^{2}	0.845	0.924

We fitted transfer functions of (3) to the gain curves of each participant in order to identify the physical parameters m_{side}, k, c, and constant α. Transfer functions obtained from the gain curves are shown in Fig. 3 with a solid line. Identified values and R^2 values for the curve fits are listed in Table. 1.

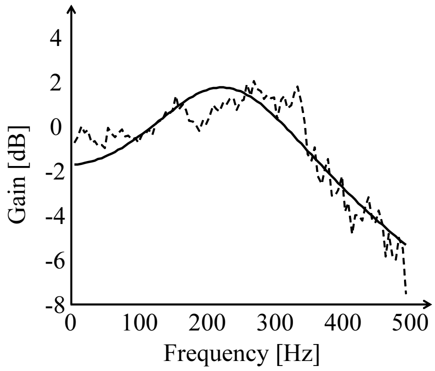
We cannot compare these parameters to those found in other studies because our dynamic model of the finger pad is different from those used by other researchers. However, computed values found in our study are not significantly different from those of other researches under similar conditions. Nakazawa et al. reported mean values of stiffness and damping coefficient of 4.80×10^2 N/m and 2.10 N·s/m, respectively, for the middle finger [13]. Wiertlewski et al. reported a point mass of 1.27×10^{-4} kg, stiffness of 9.13×10^2 N/m, and damping coefficient of 1.327 N· s/m as mean values.

4 Estimation of Finger Pad Deformation from that of the Side of the Fingertip

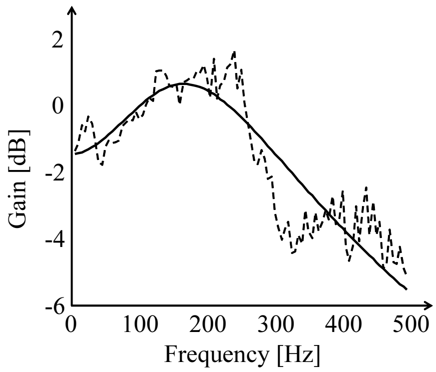
We validated the method for estimating the acceleration of finger pad deformation from that of the side of the fingertip using leave-one-out cross-validation. We computed how well the transfer function performed on the basis of the results of 9 of the 10 trials in Sec. 3.1 to estimate the output of the trial that was excluded. The computed mean and standard deviation of the goodness of estimation are shown in Tab. 2. The mean of the goodness of estimation was higher than 0.92, which is a high value for each participant.



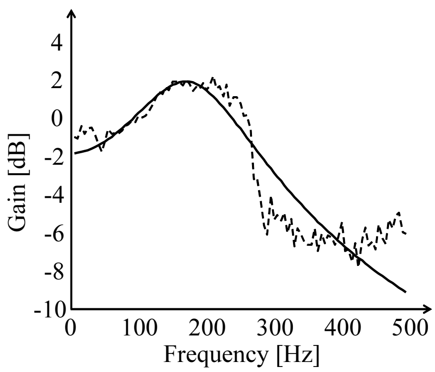
(a) Participant A



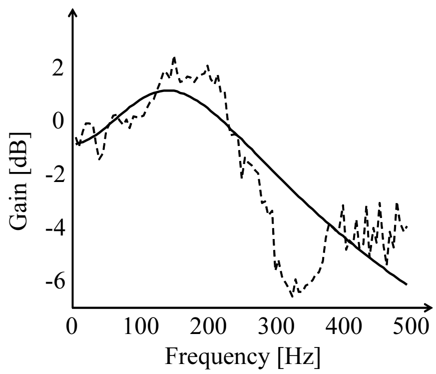
(b) Participant B



(c) Participant C



(d) Participant D



(e) Participant E

Fig. 3. Observed and fitted gain curves. Dotted and solid curves are observed and fitted characteristics, respectively.

Table 2. Result of leave-one-out cross-validation

Participant	Mean $R^2 \pm$ std. dev.
A	$0.938 \pm 2.14 \times 10^{-6}$
B	$0.924 \pm 2.52 \times 10^{-5}$
C	$0.946 \pm 8.09 \times 10^{-6}$
D	$0.952 \pm 1.93 \times 10^{-8}$
E	$0.925 \pm 4.47 \times 10^{-7}$

5 Conclusion

We developed a technique for estimating the finger pad shear deformation from the deformation of the radial side of the fingertip due to mechanical strain that propagates from the finger pad. Practically, this technique leads to a small, accelerometer-based wearable sensor that provides highly accurate estimation of finger pad shear deformation during rubbing motion. We specified the transfer function of skin deformation between the finger pad and radial side of the fingertip and examined the accuracy of estimation by cross-validation. As a result, we found that our approach could estimate the finger pad shear deformation with an average accuracy of 0.93. In the future, we will further sophisticate the experimental equipment and data analysis, and its mechanical properties such as the mass of the accelerometer should thoroughly be considered for specification of the impedance of the finger tip.

References

1. Konyo, M., Tadokoro, S., Takamori, T., Oguro, K.: Artificial tactile feel display using soft gel actuators. IEEE International Conference on Robotics and Automation (2000) 3416–3421
2. Levesque, V., Hayward, V.: Experimental evidence of lateral skin strain during tactile exploration. Eurohaptics **July** (2003) 261–275
3. Wiertlewski, M., Losada, J., Hayward, V.: The spatial spectrum of tangential skin displacement can encode tactual texture. IEEE Transactions on Robotics **27**(3) (2011) 461–472
4. Bensmaïa, S., Hollins, M.: Pacinian representations of fine surface texture. Perception and Psychophysics **67**(5) (2005) 842–854
5. Webera, A.I., Saala, H.P., Lieberb, J.D., Chenga, J.W., Manfredia, L.R., Dammann III, J.F., Bensmaïa, S.J.: Spatial and temporal codes mediate the tactile perception of natural textures. PNAS **110**(42) (2013) 17107–17112
6. Nakatani, M., Shiojima, K., Kinoshita, S., Kawasoe, T., Koketsu, K., Wada, J.: Wearable contact force sensor system based on fingerpad deformation. IEEE World Haptics Conference (2011) 323–328
7. Tanaka, Y., Horita, Y., Sano, A.: Finger-mounted skin vibration sensor for active touch. Eurohaptics (2012) 169–174
8. Okamoto, S., Wiertlewski, M., Hayward, V.: Anticipatory vibrotactile cueing facilitates grip force adjustment. IEEE World Haptics Conference (2013) 525–530
9. Tomimoto, M.: The frictional pattern of tactile sensations in anthropomorphic fingertip. Tribology International **44** (2011) 1340–1347
10. Mukaibo, Y., Shirado, H., Konyo, M., Maeno, T.: Development of a texture sensor emulating the tissue structure and perceptual mechanism of human fingers. IEEE International Conference on Robotics and Automation (2005) 2565–2570

11. Wang, Q., Hayward, V.: In vivo biomechanics of the fingerpad skin under local tangential traction. Journal of Biomechanics **40**(4) (2007) 851–860
12. Lundstrom, R.: Local vibrations-mechanical impedance of the human hand ' s glabrous skin. Biomechanics **17**(2) (1984) 137–144
13. Nakazawa, N., Ikeura, R., Inooka, H.: Characteristics of human fingertips in the shearing direction. Biological Cybernetics **82**(3) (2000) 207–214