Analysis and Design of a Tactile Sensor Detecting Strain Distribution Inside an Elastic Finger

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Abstract

Humans obtain complex information using different tactile receptors in the skin of the finger. Artificial tactile sensors capable of detecting complex information can be realized by imitating certain characteristics of the human finger, such as the geometry of the finger and the location of the tactile receptors. In the present paper, we analyzed the strain distribution that occurs inside an elastic finger having a curved surface when the finger is in contact with an object. Detection of the shear strain distribution pattern was found to be important. In addition, a strain distribution sensor was developed, in which strain gages bonded on thin plates are arranged at uniform intervals inside the curved surface of an elastic finger made of silicone rubber. The geometry of the elastic finger was designed by calculating the contact condition between the finger and objects with/without tangential load using FE (Finite Element) analysis. The fundamental characteristics of the strain distribution sensor were confirmed.

1. Introduction

The human finger has tactile receptors capable of obtaining complex information about objects. Moreover, acting in concert, the fingers allow an object to be lifted using adequate grasping force and without slippage, even when the weight and frictional coefficient of the object are unknown. In addition, receptors in the skin of the fingers allow the stiffness and internal geometry of an elastic object to be estimated. The texture and shape of an object can be determined by moving the fingers along the surface of the object as well. Artificial sensors capable of detecting such complex information are needed in order to develop dexterous robots and remote manipulators for use in s wide variety of applications.

Many studies have been performed concerning the tactile sensation of human beings [1]-[5]. Johansson [1] showed that partial slippage between the fingers and an object is important for grasping the object with the fingers. Srinivasan [2] clarified the relationship between shear strain energy near the tactile receptors and nerve signals. Ricker [3] showed that shear deformation is important for reconstructing the geometry of an object in contact with a cylindrical finger. Maeno [5] showed that the shear strain distribution pattern inside an elastic finger indicates the stick/slip condition at the finger surface during precision gripping. From the above studies, it can be concluded that both the curved surface of the finger and the shear strain distribution inside the finger are important for detecting complex information about the object. In the present study, we propose a sensor capable of detecting the strain distribution inside an elastic finger having a curved surface. First, contact between the elastic finger and the object is calculated using finite element (FE) analysis. We show that changes in the stick/slip condition at the surface of the elastic finger when lifting an object can be estimated by the shear strain distribution pattern. In addition, the shear strain distribution pattern can be used to determine the internal structure of the object in contact with the finger. Therefore, a sensor is constructed for detecting the strain distribution, and strain gages are incorporated in an elastic finger made of silicone rubber. The importance of the shear strain distribution is confirmed by measuring the fundamental characteristics of the sensor in contact with objects having various friction coefficients and weights.

2. Finite element analysis

Contact between an elastic finger having a curved surface and an object is analyzed using the finite element method (FEM) to show that complex information about the object in contact with the elastic finger is indicated by the shear strain distribution inside the elastic finger.

2.1 Method of contact analysis

There are many commercialized FE codes capable of solving the contact between two elastic bodies. However, normal/tangential reaction force and stick/slip at the contact interface can not usually be calculated accurately using these codes due to the error caused by convergent calculation. Therefore, we propose a method of analyzing

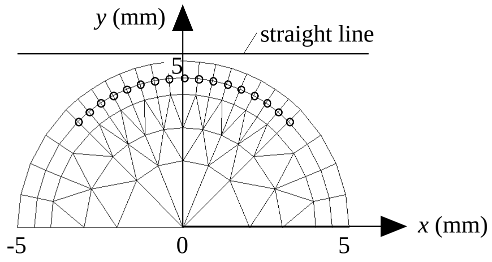


Fig. 1 Finite element model of half cylinder

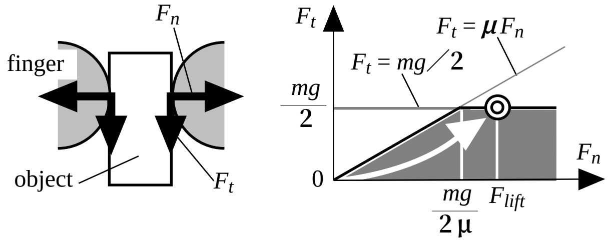


Fig. 2 Relationship between normal force (grip force) F_n and tangential force (friction force) F_t

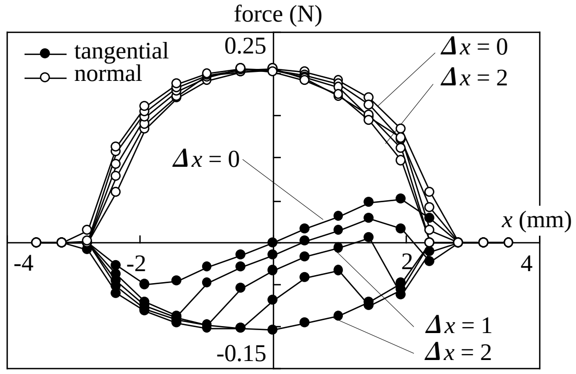


Fig. 3 Normal and tangential force distributions

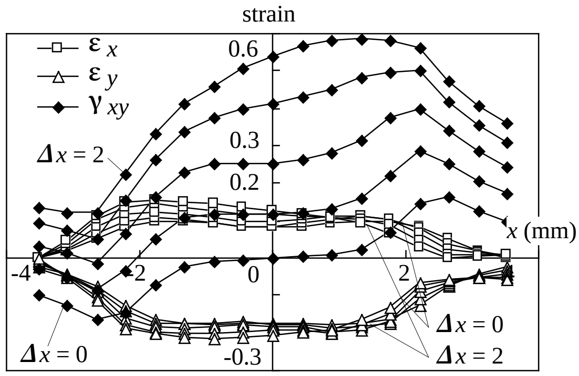


Fig. 4 Strain distribution inside FE model

the time-dependent contact problem, including stick/slip in the tangential direction, at the surface of two bodies. Discrete time and space are defined in a simulation.

The following conditions must be satisfied for the nodes at the surface of the example finger shown in Fig. 1:

non-contact nodes:	$w_n < w_{object}$,	$F_n = 0$
contact nodes:	$w_n = w_{object}$,	$F_n \geqq 0$
sticking nodes:	$w_t = w_t'$,	$\mid F_t \mid \leqq \mid \mu F_n \mid$
slipping nodes:	$\mid F_t \mid = \mid \mu F_n \mid$	

where, w_n and w_t are the locations in the normal and tangential directions, F_n and F_t are the nodal forces in the normal and tangential directions, respectively, w_{object} is the normal location of the object, and μ is the friction coefficient. The prime represents values in previous time frame. The contact problem for a specific time is solved by repeating the calculation while changing the contact conditions until the above-mentioned conditions are satisfied. When these conditions have been satisfied, we move to the next time frame. The FE code MARC is used in the present study.

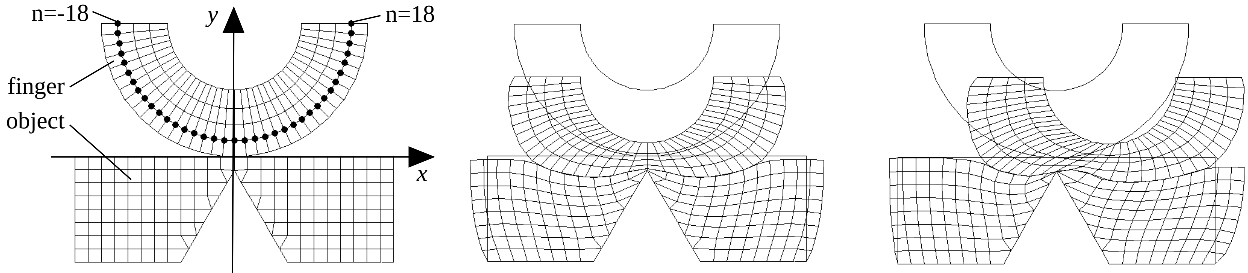
2.2 Control of grasping force

Figure 2 shows the relationship between the normal force (grip force) F_n and the tangential force (friction force) F_t when an object is lifted by the fingers. The normal and tangential forces increase simultaneously through the route shown by the white arrow in the figure until they reach the point at which the object is lifted, represented by the "◎" symbol. The problem of lifting an object without applying excessive force or producing a complete slip can be replaced by the problem in which the route and the reaching point of the forces must be found.

How can the route and the reaching point be found? This information was obtained by detecting vibration due to the complete slip of the object or by detecting the friction coefficient between object and sensor from past research [4],[5]. Human beings, however, can grasp and lift objects without detecting the friction coefficient or a complete slip. Analyzing the contact between a human finger model and a plane object, we found that detection of the shear stress/strain distribution is important for tactile sensation [6]. In the present study, we analyzed the contact between a finger having a cylindrical surface and a plate in order to demonstrate that the above result can be applied to an artificial sensor.

Figure 1 shows a plain strain FE model of a simple half-cylindrical finger used to analyze the fundamental contact condition, including partial incipient slip, when the tangential load is changed by generating various forced displacements of the plate in the *x*- and *y*-directions. The FE model consists of 96 nodes and 108 elements. The elastic modulus of the finger is 1 MPa. Plane strain elements are used. Nonlinearity due to large deformation is neglected.

Figure 3 shows a normal and tangential contact force distribution at the surface of the cylindrical finger (see Fig. 1) for the following boundary conditions. First, a forced displacement of the plate in the *y*-direction of -1



(a) FE model (b) Deformation when Δx=10 mm (c) Deformation when Δx=Δy=10 mm

Fig. 5 FE model for contact between finger and object

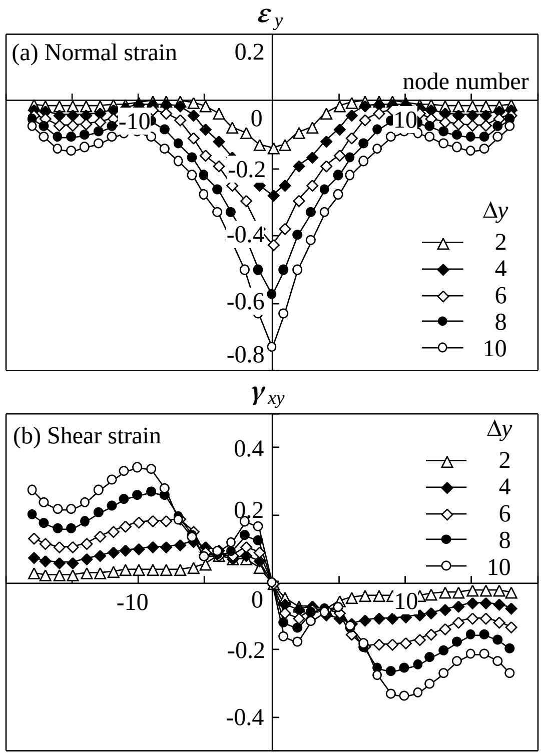


Fig. 6 Strain distribution when plate is moved in y-direction

mm is generated. Next, a forced displacement Δx of the plate is generated in the *x*-direction. The friction coefficient μ is 0.5. When Δx is zero, the sum of the tangential force F_t is zero and all of the contact nodes stick. When Δx increases, the normal force does not change noticeably. In contrast, the tangential force F_t starts changing from both edges of the contact area and reaches the dynamic friction force in the contact area. Accordingly, the partial incipient slip regions at both edges of the contact area increase. Finally, when Δx is 2 mm, the F_t of all of the contact nodes reaches $-\mu F_n$ because all the contact nodes slip.

Figure 4 shows the normal and shear strain inside the elastic finger at the nodes shown as circles in Fig. 1. The shear strain γ_{xy} changes as a function of the change in the tangential contact force, whereas normal strains ε_x and ε_y do not change noticeably. Therefore, the stick/slip condition can be estimated by detecting changes in the shear strain distribution pattern inside the cylindrical elastic finger. When the stick/slip condition is known, the grasping and lifting force can be controlled without producing a complete slip. Furthermore, detection of the friction coefficient between the finger and object is not necessary.

2.3 Detection of the internal structure of the object

Medical doctors are able to feel lumps or hardened tissue in the breast during examinations for breast cancer simply by applying pressure to the patient's skin. They detect differences in hardness or firmness using tactile sensors beneath the skin of the fingers. We believe that they are also detecting the shear strain distribution. In this section, we show that the internal structure of the object in contact with the sensor can also be detected using the shear strain distribution inside the elastic finger.

We analyze the contact between a finger having a curved surface and an elastic object having variable internal hardness. Figure 5 shows the model and results of the FE analysis. Figure 5 (a) shows the FE model of the elastic finger and elastic object. Nodes at the bottom of the elastic object are constrained in the *x*- and *y*-directions. This model represents a triangular hard material placed inside a soft material. The FE model consists of 382 nodes and 310 plane strain elements. The elastic modulus of the finger is 3 MPa. Contact is analyzed as described in the previous section. The strain distribution was calculated for two movements: movement of the elastic finger in the negative *y*-direction for 10 mm and simultaneous movement in the *x*- and negative *y*-directions for 10 mm.

Figure 6 shows the normal and tangential strain distributions for the movement of the finger in the negative *y*-direction. Node numbers represent the black circles shown in Fig. 5 (a). The distribution pattern of the normal strain ε_y does not change noticeably, and only the magnitude is changed. The distribution pattern of the shear strain γ_{xy} changes slightly.

Figure 7 shows the normal and tangential strain distributions for the movement of the finger in the *x*- and negative *y*-direction. The distribution pattern of the normal

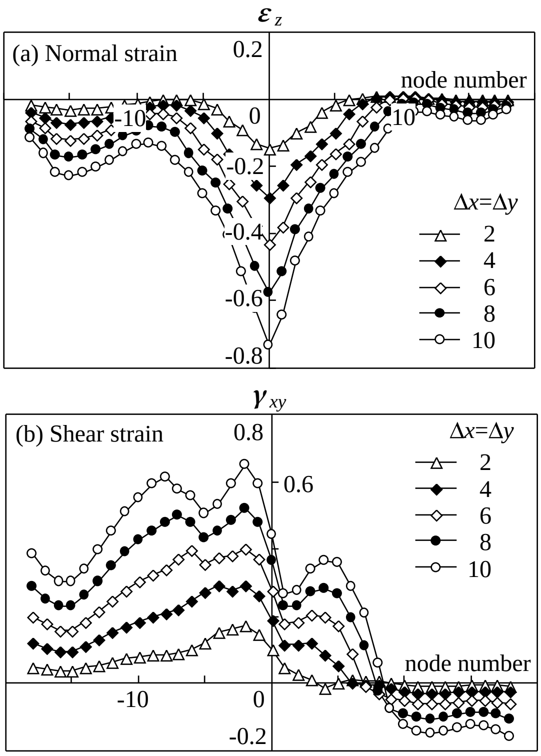


Fig. 7 Strain distribution when plate is moved in x- and y-directions

Fig. 8 Diagram of finger-shaped sensor

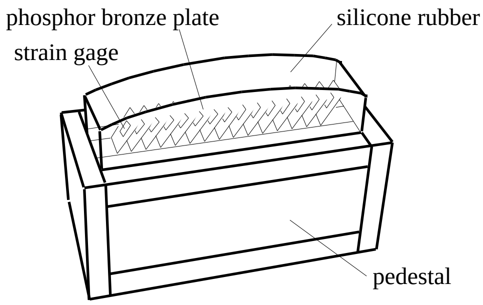


Fig. 9 Top view of finger-shaped sensor

Fig. 10 FE model of sensor

strain ε_y does not change noticeably. In contrast, that of the shear strain γ_{xy} changes according to the movement of the finger. Therefore, the internal geometry of the object can be estimated using the change in the shear strain distribution detected in the cylindrical elastic finger. Tangential movement has the effect of magnifying the change in the shear strain distribution pattern. This corresponds to the fact that people move their fingers in the tangential direction to detect the internal geometry of an object.

In addition, the strain distributions for several elastic objects having various internal geometries are calculated. In each case, the shear strain distribution pattern reveals the internal geometry of the object. Therefore, detection of the shear strain distribution pattern can also be used to estimate the internal geometry of an object.

3. Development of the strain distribution sensor

In the previous section, we showed that detection of the shear strain distribution inside the cylindrical elastic finger is essential in tactile sensing for controlling the grasping force and detecting the internal geometry of an object. However, creating a sensor capable of detecting the shear strain distribution inside a homogeneous elastic body is difficult. Therefore, the structure of an elastic finger is proposed in which a number of sensors are incorporated for detecting the normal strain. In addition, the fundamental characteristics of the proposed sensor are measured.

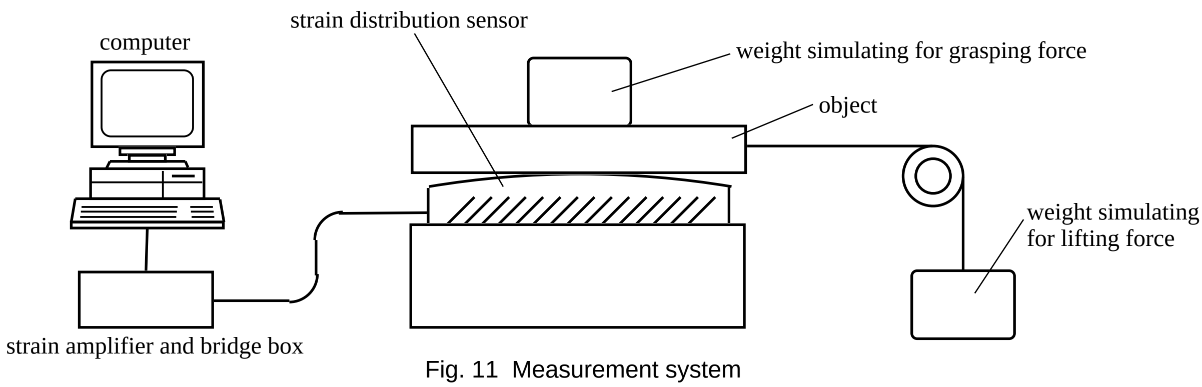


Fig. 11 Measurement system

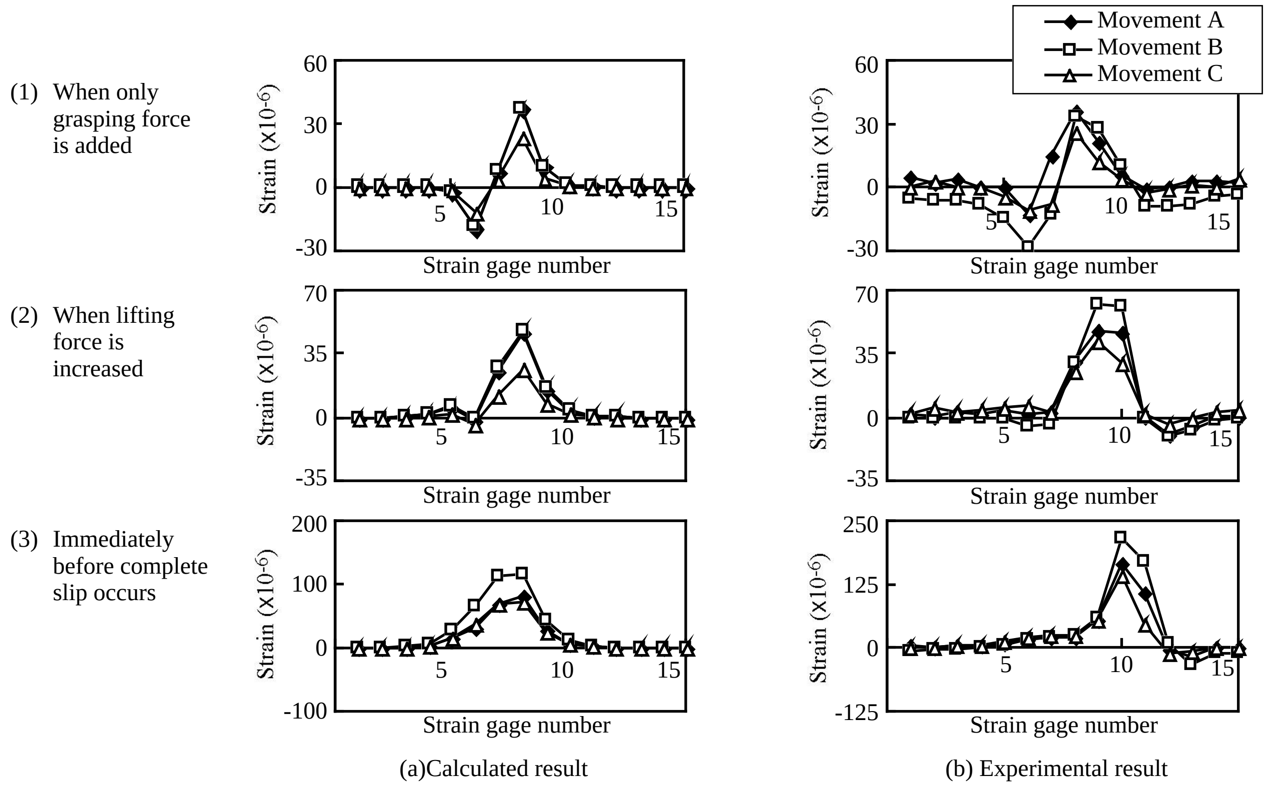


Fig. 12 Calculated and measured strain distributions

Table 1 Relationship between Δy_{max} , Δx_{slip} and μ

	Δy_{max} (mm)	Δx_{slip} (mm)	μ
Movement A	0.021	0.036	0.8
Movement B	0.021	0.064	1.4
Movement C	0.012	0.036	1.4

3.1 Design of the sensor

The proposed elastic finger design is shown in Figs. 8 and 9. Fifteen phosphor bronze plates having a thickness of 0.1 mm are incorporated at an angle of 45 degrees from the *x*-axis in an elastic body of silicone rubber. Strain gages are bonded to the phosphor bronze plates.

Although the geometry of the elastic finger differs from that described in the previous section, the normal strain distribution pattern inside the finger is expected to be similar to the shear strain distribution mentioned previously. FE analysis of the deformation and strain of the finger is conducted in order to confirm that the strain distribution obtained by the strain gages bonded to the phosphor bronze plate cantilevers is similar to the shear strain distribution calculated in the previous section. The FE model is shown in Fig. 10.

Contact between the finger and a plane plate was analyzed to confirm that the strain distribution obtained in the strain gages indicates the condition of stick/slip at the contact surface. Stick/slip information is useful for controlling the grasping force, as shown previously in Section 2.2. Figure 12 (a) shows the calculated results.

The strain distribution was calculated for three movements, designated as A, B, and C. Table 1 shows the corresponding displacement of the plate and the friction coefficient for each movement. The normal and tangential displacements of the plate are designated by Δy_{max} and Δx_{slip}, respectively, and μ is the friction coefficient between the plate and the finger. The strain distributions obtained using the strain gages are somewhat different from those obtained in the previous section because the structure of the finger is different. However, the pattern of the distribution is similar. A local maxim and a local minimum occur when the grasping (normal) force is applied (see Figure 12 (a), (1)). The absolute value of the local minimum decreases when the lifting (tangential) force is increased (see Figure 12 (a), (2)). Finally, the local minimum disappears when nearly all of the contact nodes slip (see Figure 12 (a), (3)). Therefore, the normal strain distribution measured at the strain gages functions in the same way as the shear strain distribution functions inside a homogeneous body. Furthermore, the distribution pattern is similar even when the displacement of the plate and the frictional coefficient differ. For all cases, the strain distribution is asymmetric when the tangential force (lifting force) and the slipping area are sufficiently small. In contrast, the strain distribution is almost symmetric and has one peak when the tangential force (lifting force) is too large and the entire contact area slips. Therefore, we can control the lifting and grasping force by monitoring the strain distribution pattern. If the strain distribution pattern approaches the pattern indicating the complete slip, the normal (grasping) force should be increased. While the strain distribution pattern remains similar to that indicating a small partial slip, the tangential (lifting) force can be increased. Thus, adequate lifting and grasping forces can be realized allowing control similar to that of human beings.

3.2 Measurement

The fundamental characteristics of the proposed sensor are measured in order to confirm that the strain distribution patterns are the same as those calculated. Figure 11 shows the measurement system. The displacement of the plate and the friction coefficient between the finger and the plate are applied as shown in Table 1.

Figure 12 (b) shows the measurements obtained for the different movement of the plate and friction coefficient. The magnitude of the strain distribution is different from that obtained in the calculation. This is due to an error in calculation, which occurs due to the aspect ratio of the mesh of the phosphor bronze plate being too large. In addition, error also occurs due to nonlinearity. The nonlinearity of the elasticity of the silicorn rubber and the nonlinearity due to the large deformation are neglected in the calculation. However, notably, the distribution pattern of the strain is similar. Even when the amount of strain differs, the haptic information indicated in the strain distribution pattern can be recognized.

4. Conclusions

First, the shear strain distribution inside the cylindrical finger was shown to play an important role in detecting complex haptic information, such as stick/slip at the surface of an object and the distribution of hardness inside the object. Next, the geometry of a sensor capable of detecting the normal strain on the inclined plate inside the silicone rubber, instead of the shear strain of a homogeneous elastic finger, was proposed. In addition, a cylindrical finger-shaped sensor was created and the fundamental characteristics of the sensor were measured. The strain distribution pattern obtained was found to be similar to the results obtained using FE analysis.

In future studies, the proposed sensor will be used to detect complex haptic information such as stick/slip at the surface of an object and the distribution of stiffness inside an object. A suitable method for pattern recognition should be discussed in future work.

Acknowledgements

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