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Artificial Finger Skin having Ridges and Distributed Tactile Sensors used for Grasp Force Control

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Abstract

An artificial elastic finger skin for robot fingers is developed for controlling grasp force when weight and frictional coefficient of the grasped object is unknown. The elastic finger skin has ridges at the surface to divide the stick/slip area. It also has a pair of tactile sensors embedded per one ridge same as finger of human. Surface of the whole finger is curved so that reaction force distribute. A Finite Element (FE) model of the elastic finger skin is made to conduct a dynamic contact analysis using a FE method in order to design the elastic finger skin in detail. Then the elastic finger skin is made. As a result, it is confirmed by calculation and experiment that the incipient slippage of the ridge that occurs near the edge of contact area is detected. It is useful for controlling grasping force when the weight and friction coefficient between the elastic finger skin and grasping object are unknown.

1. Introduction

Epidermal ridges are located at the surface of fingers of human. Papillae are arranged in two lines underneath the ridge. FA I and FA II tactile receptors are also arranged in two lines underneath the ridge. Maeno *et al.* [1] showed by finite element (FE) analysis that this structure is for enlarge the sensitivity of the tactile receptors. It is also shown that the structure of epidermal ridges is in relation to the partial insipient slippage between the fingers and object. This structure also seems to be useful for tactile receptors to detect signals for controlling an adequate force to grip and lift an object without slippage.

On the other hand, a use of a robot hand to grip and lift an object is one of the most important problems in the field of robotics. Several methods have been presented. One method is to pay attention to the detection of partial incipient slippage between the finger and object. This method is thought to be similar to what humans do [2][3]. The partial incipient slippage refers to the contact condition between the robot fingers and grasping object in which a part of contact area slips while the other part sticks. This method was proposed first by Trembley *et al.* [4]. They detected the partial incipient slippage of a finger skin by sensing micro vibrations, which are caused by an expansion of the slip regions within the contact area when a tangential force increases. The micro vibrations are detected by two accelerometers near the skin. However, entire slippage easily occurs immediately after the micro vibrations occur. This is because the location of the partial incipient slippage is not specified and so the tiny partial incipient slippage cannot be detected when it locally occurs near the edge of the contact area. The stick/slip distribution between the finger and object should be measured to control grasping and lifting force precisely. De Rossi *et al.* [5] made a device covered with silicone rubber and having distributed PVDF films as tactile sensors underneath the silicone rubber. The distributed tactile sensors can selectively be sensitive to shear and normal stress components. A neural network, whose inputs are outputs from the tactile sensors, provides a global sliding coefficient as an output. The partial incipient slippage between the device and objects are investigated. However, accuracy for detecting the global sliding slippage is not high enough, because the location of partial incipient slippage was not specified because the device has a flat surface. Maeno *et al.* [6] showed that the shear strain distribution pattern inside a curved elastic finger indicates the stick/slip distribution at the finger surface during the precision grip. The partial incipient slippage always occurs near the edge of contact area by use of the curved finger. They also proposed a sensor detecting the strain distribution pattern inside the elastic finger having curved surface instead of using the detected value itself [7][8]. The strain distribution pattern is measured by strain gages embedded in the elastic finger. They showed a method for controlling the grasping force by use of proposed elastic robot finger as well. However, an object should be lifted by a certain speed. If the weight of object is changed while lifting the object, the object cannot be kept on grasping. Other methods in which the slippage is detected have also been presented. Yamada *et al*. [9] showed a slip sensor that has elastic ridges at the surface and is capable of isolating a stick-slip vibration due to an entire slippage between the sensor and grasping object. The sensor can detect the entire slippage and control the grasping force quickly and correctly to avoid dropping an object. However, the method is not adequate because the position of the object slightly changes due to the entire slippage.

In this study, an artificial elastic finger skin that has a unique geometry imitating a configuration of ridges and FA I receptors of finger of human is designed and manufactured by combining the method proposed by Maeno *et al*. [8] and Yamada *et al*. [9]. Then it is shown that it can detect the incipient slippage of the ridges near the edge of contact area. A design of the elastic finger skin is described in chapter 2. A model and results of FE analyses are shown in chapter 3. Experiment to confirm the analysis is conducted in chapter 4. The conclusions of this study are described in chapter 5.

2. Design of artificial finger skin

2.1 What to mimic finger of human

The artificial finger skin can be designed by imitating the characteristics of finger of human because human can grasp an object by voluntary speed of finger without producing entire slippage, even when the weight and friction coefficient between the finger and the object are unknown. The characteristics we paid attention to are as follows: First, the finger of human consists of flexible material and has a curved surface. Then a partial incipient slippage easily occurs near the edge of contact area between the finger and the object. Normal reaction force at the center of the contact area is larger than that near the edge of the contact area. However tangential reaction force is almost equal throughout the contact area. Therefore, the center of contact area generally "sticks".

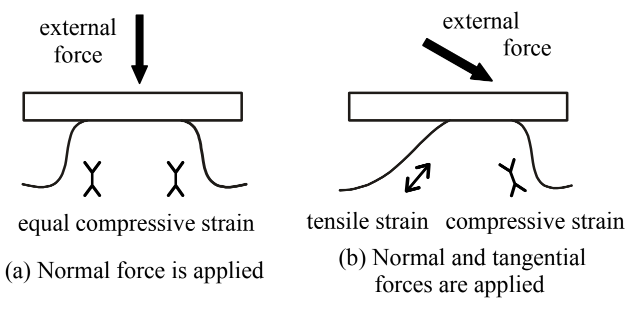


Fig. 1 Distribution of strain inside the ridge

On the other hand, the edge of the contact area easily changes its contact condition from "stick" to "slip". Because of this, the partial incipient slippage occurs near the edge of the contact area. Second, epidermal ridges are distributed at the surface of the finger. When the partial incipient slippage occurs, constraints due to the "stick" condition of the ridges near the edge of the contact area are released. Then, elastic deformation of the ridges is suddenly reduced. Furthermore, speed of movement of the slipping ridge is constant which depend on the natural frequency of the ridge, even when the friction coefficient between the finger and the object and the applied force changes. Third, a pair of FA I receptors are located at the tip of papillae which is arranged in two lines underneath the epidermal ridge. A stress concentration occurs at the location of FA I receptors. A strain distribution inside the ridge is closely related to the deformation of ridges as shown in Fig. 1. Strain at the location of the pair of FA I receptors are equal when only the normal force is applied to the ridge as shown in Fig. 1 (a). On the other hand, the strains differ each other when both the normal and tangential forces are applied to the ridges as shown in Fig. 1 (b). Now, we can conclude that the deformation of the ridge in tangential direction can be detected by subtracting the strains at the two points underneath the ridge. Particularly, when the partial incipient slippage occurs, a velocity of the subtracted value must decreases largely and an acceleration of the subtracted value becomes negative impulse at that time.

It is expected that the incipient slippage of each ridge can be detected by use of the above-mentioned velocity and acceleration of strain underneath the each ridge. Information of the incipient slippage can be used as inputs for controlling the grasping force, even when the weight and friction coefficient of the object and the applied force are unknown.

2.2 Detailed design

The artificial finger skin is designed in detail imitating the above-mentioned characteristics of human finger.

First, a shape of ridges is decided. A FE model of one ridge is made for conducting a dynamic contact analysis using a FE method. The shape of the ridge consists of a combination of several arcs. Friction coefficient is 1.0 in the analysis. Material properties of the model which are similar to those of silicone rubber are as follows: Young's module of artificial finger skin is 4.96 MPa. Poison's ratio is 0.49. Mass density is 1230 kg/m^3. Mechanical material type of finger is isotropy. Then, a flat object is set to be in contact with the model from the top. The flat object is defined as a rigid body. Then, an external force is applied by changing the position of the flat object. Figure 2 shows a distribution of strain inside the ridge when the normal and tangential movements of the flat object are applied. FE program MARC is used. As a result, shear strain underneath the right hand edge of the ridge is large as expected in Fig. 1 (b). Now, we can say

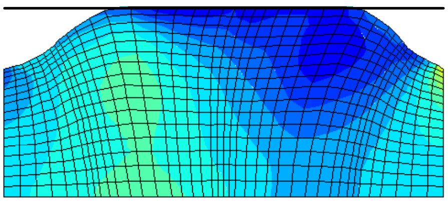


Fig. 2 Distribution of shear strain inside the ridge

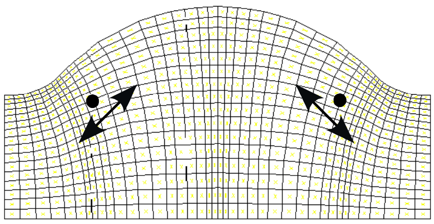


Fig. 3 Points and directions for subtracting the strains

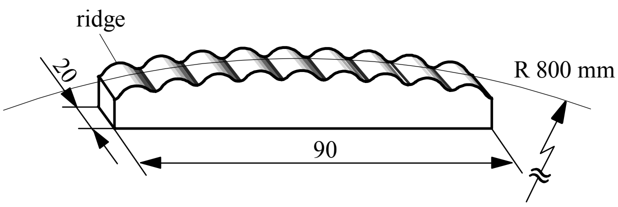


Fig. 4 Top view of designed artificial finger skin

that the shape of the ridge is adequate.

Second, locations and directions to detect the pair of strain inside the ridge are decided. A relationship between the directions of external force and principal strain inside the ridge is analyzed. Results are as follows: Only when the normal force is applied, the direction of principal strain at the location corresponds to that of FA I receptors is almost parallel to the direction of external force. However, when both the normal and tangential forces are applied, the direction of principal strain at the same location is inclined to about 45 degrees. Consequently, a relationship between the tangential deformation of the ridge and the subtracted value of strains can be calculated. So, the location and direction are decided as shown in Fig. 3.

Third, a radius of curvature for the artificial finger skin is decided. If the radius is too large, normal contact force does not distributed and the location of the incipient slippage of the ridges cannot be specified near the edge of contact area. If the radius is too small, contact area is too small and ridges at the edge of the artificial finger skin does not in contact, even when a large normal force is applied. The radius is decided to be 800 mm by considering the above-mentioned condition. Results of FE analysis show that all the ridges are in contact with a flat object when the normal force of about 4 N is applied, so the assumed limit of the weight of the object is about 8 N when the object is grasped by two fingers. Number of ridges is nine so as to detect the partial incipient slippage selectively, even when the contact area changes due to the change in value and direction of normal contact force. Designed artificial finger skin is shown in Fig. 4.

3. Numerical analysis

3.1 FE model of artificial finger skin

A FE model of the designed entire artificial finger skin is made as shown in Fig. 5 for analyzing the dynamic contact condition between the finger and a flat object. A purpose of the analysis is to confirm that the entire

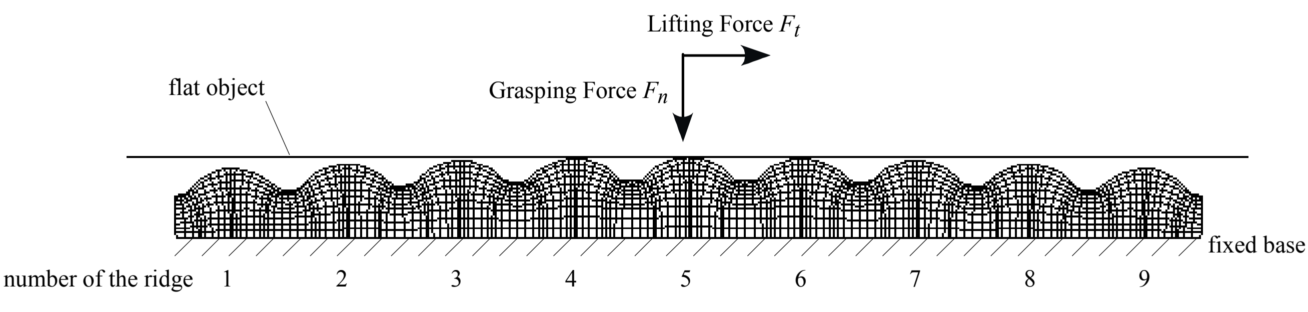


Fig. 5 Two dimensional FE model of designed artificial finger skin

slippage of the ridge near the edge of contact area can be detected by use of the velocity and acceleration of strains inside the ridge predicted in chapter 2, even when the applied force, the friction coefficient and the increment of applied force are changed. Displacement at the bottom edge of the artificial finger skin is fixed. The ridges are numbered from one to nine for identifying each other. Material properties, material type and applied external forces of the model are same as those of the analysis described in chapter 2.

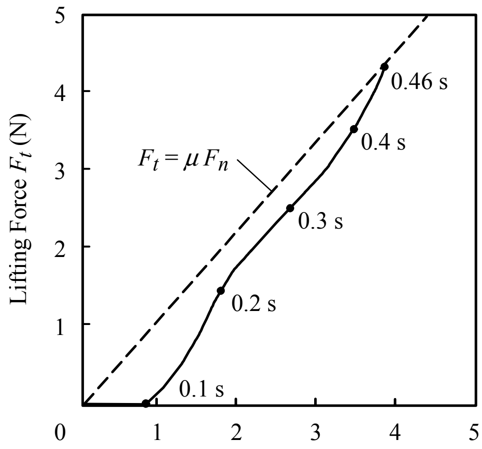
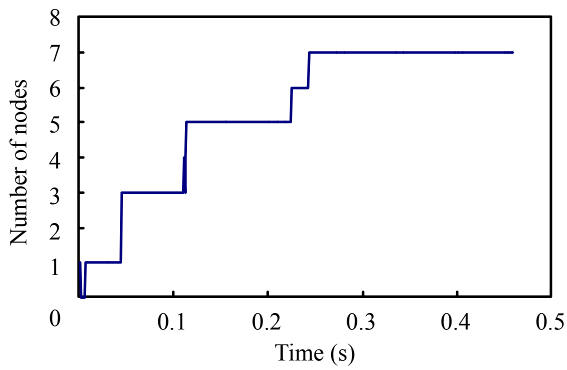


Fig. 6 History of external force

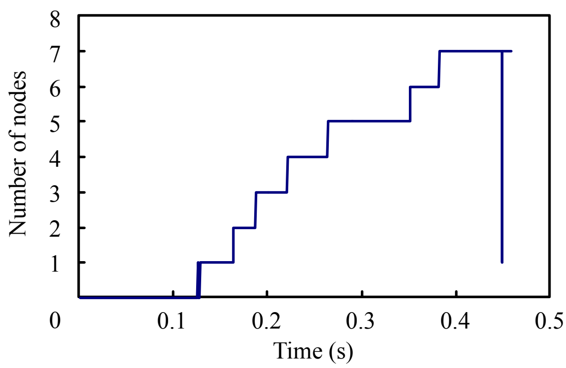
3.2 Condition of calculation

The external force, i.e. grasping force F_n and lifting force F_t (see Fig. 5), is increased as shown in Fig. 6. Only the grasping force is applied at first for avoiding entire slippage when the lifting force is initially applied same as human do. Then, the grasping and lifting forces are increased. The partial incipient slippage easily occurs from 0.4 to 0.5 s because a ratio F_t / F_n is approaching to the friction coefficient μ. Slip area must gradually increase from the edge of the contact area at that period. Total time of the analysis is 0.46 s and entire slippage occurs at that time. Kinetic friction coefficient is 1.0. Static friction coefficient is 1.05.

Above-mentioned condition is called a "basic case". Analyses for some other cases are also conducted when friction coefficient, maximum value of grasping force and total time throughout the analysis are changed.



(a) Fifth ridge



(b) Third ridge

Fig. 7 Number of nodes which sticks

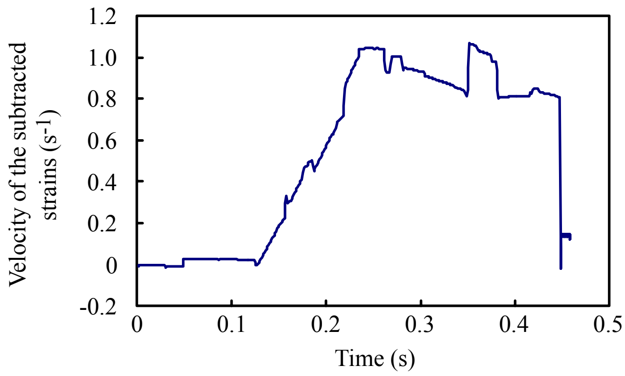


Fig. 8 Velocity of the subtracted strains inside third ridge for basic case

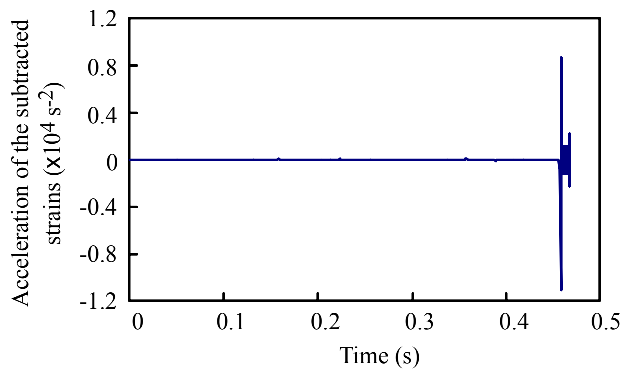


Fig. 9 Acceleration of the subtracted strains inside third ridge for basic case

3.3 Results of FE analyses

First, an analysis for the basic case is conducted. Histories of number for sticking nodes in the third and fifth ridge are shown in Fig. 7. The number of sticking nodes of both the third and fifth ridge is zero at first. It gradually increases and reaches seven. The gradual increase of the stick area is due to the gradual increase of contact area caused by the increase of the grasping force. Increment of the stick area is almost constant because it depends on a viscosity of the material of the artificial finger skin. The number of sticking nodes of the third ridge is suddenly decreased at the time 0.45 s as shown in Fig. 7 (b) because the entire slippage of the ridge occurs. However, that of the fifth ridge is not changed, i.e. the fifth ridge is not slipping. This means that only the ridges at the edge of the contact area slip as expected in chapter 2. Now, the predicted phenomena are seen in the result of FE dynamic contact analysis.

First and second time derivatives of the subtracted strains inside the third ridge, which we call a velocity and an acceleration of subtracted strains, are shown in Fig. 8 and Fig. 9, respectively. The velocity of the third ridge increases gradually from time 0.13 s to 0.23 s. Then, it decreases when the incipient slippage occurs at time 0.45 s, because the tangential deformation of the third ridge is released when the entire slippage occurs at the ridge. The acceleration of the third ridge responds with large amplitude at time 0.45 s as shown in Fig 9, because the velocity decreases at that time. An absolute value of the amplitude of the acceleration is larger than 4.0×10^{3} s^{-2}. On the other hand, the large response of acceleration is not seen in the fifth ridge at the same time, because the entire slippage of the fifth ridge doesn't occur even when the slippage of the third ridge occurs.

Analyses for other case when the applied force, the friction coefficient and the increment of applied force are changed are also conducted. Phenomena agree well with those of the basic case, even when the parameters are changed. The incipient slippage of the ridges near the edge of contact area occurs when the contact condition is changed from "stick" to "slip". Stepwise decreases of the velocity of subtracted strains are surely seen at the ridge near the edge of contact area when the entire slippage of the ridge occurs. Then, the absolute values of the amplitude of the acceleration are always larger than 4.0×10^{3} s^{-2} when the entire slippage of a certain ridge occurs.

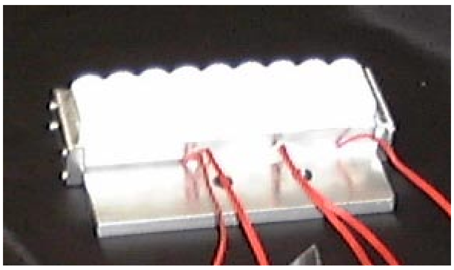


Fig. 10 Artificial finger skin

Consequently, the velocity of subtracted strains inside the ridge near the edge of contact area largely decreases when the contact condition changes from "stick" to "slip" because the entire slippage of the ridge occurs. The absolute value of the amplitude of acceleration is always larger than 4.0×10^{3} s^{-2} at the ridge which slips. Large acceleration is not seen in other time. Therefore, the partial incipient slippage can be detected by the change in velocity and the absolute value of the acceleration of the ridges near the edge of the entire contact area as expected in chapter 2.

Grasping force will be controlled in the future study by monitoring the stick/slip condition of each ridge. Procedure of the control is as follows: Grip force will be increased when the incipient slippage at the edge of the contact area occurs. Lift force will be increased when most of the ridges are sticking. By continuing this procedure, objects whose weight and friction coefficient are unknown can be grasped and lifted.

The method is considered to be the same as that of human because human seems to detect the partial insipient slippage wherever the contact surface exists. Therefore, the proposed method for detecting the partial incipient slippage should be extended to develop a two-dimensional finger pad as well in the future study.

4. Experimental analysis

4.1 Equipment and condition of experiment

The artificial elastic finger skin (Fig. 10) is produced to confirm the results of FE analyses. It consists of a silicone rubber whose material properties are the same as the FE model described in section 2.2. Strain gauges are embedded underneath each ridges at the location and direction as shown in Fig. 3. Measurement system of the experiment is as follows. The produced artificial finger skin is connected to a pedestal to fix on ground. A flat object whose material is aluminum is fixed on an *x-y* stage. Then, external forces are applied to the artificial finger skin by controlling the position of the aluminum plate. The position of *x-y* stage is controlled by computer program in order to apply the external forces same as those of the numerical analyses shown in Fig. 6.

4.2 Results of experiment

Figures 11 and 12 show histories of velocity and acceleration of subtracted strains inside the third ridge, respectively. These results are similar to those of numerical analyses shown in Fig. 8 and Fig. 9.

velocity and acceleration of the subtracted value of strains inside the ridges.

Acknowledgement

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Reference

[1] T. Maeno, K. Kobayashi and N. Yamazaki, “Relationship between the Structure of Human Finger Tissue and the Location of Tactile Receptors”, *Bulletin of JSME International Journal*, Vol. 41, No. 1C, pp. 94-100, 1998.

[2] R. S. Johansson and G. Westling, “Roles of Glabrous Skin Receptors and Sensorimotor Memory in Automatic Control of Precision Grip When Lifting Rougher of More Slippery Objects”, *Exp. Brain Res.*, Vol. 56, pp. 550-564,1984.

[3] R. S. Johansson and G. Westling, “Signals in Tactile Afferents from the Fingers Eliciting Adaptive Motor Responses During the Precision Grip”, *Exp. Brain Res.*, Vol. 66, pp. 141-154, 1988.

[4] M. R. Tremblay and M. R. Cutkosky, “Estimation of Friction Using Incipient Slip Sensing During a Manipulation Task”, *Proc. IEEE Int. Conf. Robotics and Automation*, Vol. 1, pp. 429-434, 1993.

[5] G. Canepa, R. Petrigliano, M. Campanella and D. De Rossi, “Detection of Incipient Object Slippage by Skin-Like Sensing and Neural Network Processing”, *IEEE. Trans. on Systems, Man, and Cybernetics -- part B:Cybernetics*, Vol. 28, No. 3, pp. 348-356, 1998.

[6] T. Maeno, K. Kobayashi and N. Yamazaki, “Sensing Mechanism of the Partial Incipient Slip at the Surface of Cylindrical Fingers During the Precision Grip”, *Proc. ASME Summer Bioengineering Conf.*, pp. 117-118, 1997.

[7] T. Maeno, T. Kawai and K. Kobayashi, “Analysis and Design of a Tactile Sensor Detecting Strain Distribution inside ad Elastic Finger”, *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, pp. 1658-1663, 1998.

[8] T. Maeno, S. Hiromitsu and T. Kawai, “Control of Grasping Force by Detecting Stick/Slip Distribution at the Curved Surface of an Elastic Finger”, *Proc. IEEE Int. Conf. Robotics and Automation*, pp. 3896-3901, 2000.

[9] Y. Yamada, Y. Morita and Y. Umetani, “Slip phase isolating : impulsive signal generating vibrotactile sensor and its application to real-time object re-grip control”, Robotica, Vol. 18, No. 1, pp.43-49, 2000.

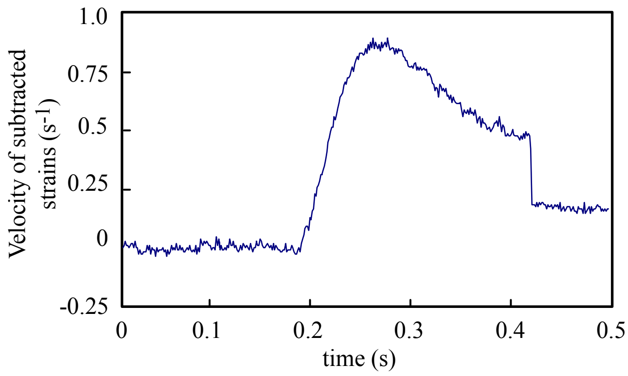

Fig. 11 Velocity of the subtracted strains inside third ridge in experiment

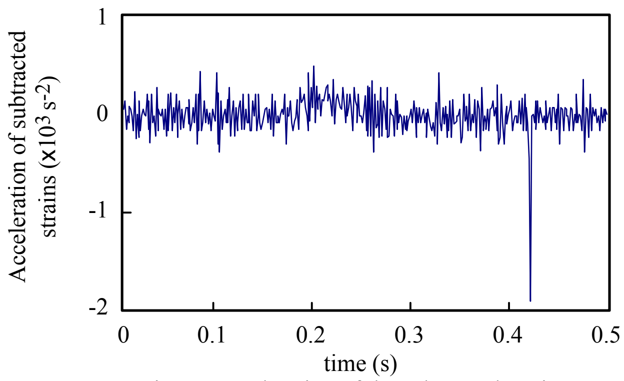

Fig. 12 Acceleration of the subtracted strains inside third ridge in experiment

Particularly, when the entire slippage occurs at the third ridge, the velocity largely decreases and the acceleration shows a negative impulse. Therefore, we can conclude that the results of analyses are confirmed and the incipient slippage of the ridge near the edge of contact area can be detected by the change in the velocity and the acceleration. As the acceleration due to the slippage of the ridge shows an impulse, PVDF films will be an adequate sensor to detect this information in the future study. Grasp force control using the artificial finger skin will also be conducted in the future study.

5. Conclusions

An elastic finger skin is proposed for grasping an object whose weight and friction coefficient are unknown. It has a unique geometry imitating a configuration of ridges and FA I receptors of finger of human. First, precise geometry of the artificial finger skin is designed using FE analysis. Then, it is confirmed by FE analysis and experiment that the incipient slippage of the ridges at the edge of the contact area is detected by change in