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Anthropomorphic robotic soft fingertip with randomly distributed receptors

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Abstract

To improve the manipulation ability of robotic fingers, this paper proposes a design of an anthropomorphic soft fingertip with distributed receptors. The fingertip consists of two silicon rubber layers of different hardness containing two kinds of receptors, strain gauges and PVDF (polyvinylidene fluoride) films. The structure of the fingertip is similar to that of a human's; it consists of a bone, a body, a skin layer, and randomly distributed receptors inside. Experimental results demonstrate the discriminating ability of the fingertip: it can discriminate five different materials by pushing and rubbing the objects.

Keywords: Anthropomorphic finger; Soft finger; Tactile sensor; Material discrimination; Distributed receptors

1. Introduction

A human being can manipulate various objects by fingers dextrously and adaptively. Although there have been an enormous number of studies on robot hands trying to reproduce such adaptive and dextrous manipulation [1], so far the performance is not satisfactory. One of the reasons is that these existing hands have too poor sensing modalities. Among such modalities, tactile sensing plays an important role to gather information about the manipulated object and contact conditions. Many kinds of tactile sensors have been proposed (we can find a comprehensive survey in [2] until 1999). Sensors with distributed receptors are especially effective to observe detailed contact conditions for adaptive manipulation. Several attempts have been made to develop such sensors with pressure-conductive rubber [3], an optical position sensitive detector [4], capacitor arrays [5–7], an LC network [8], ultrasonic sensors [9], force sensing resistance [10], conductive fabric [11], and conductive gel [12].

Almost all robotic fingertips that have been developed so far have their sensing receptors only on their surfaces. One of the reasons is that the fingers are basically made of rigid materials such as metals, and the receptors cannot be embedded in a deep part of the finger. Rigid fingertips make the control easy since the position of the manipulated object is simply calculated by configurations of the fingers. However, the fact that the receptors are only attached on the surface limits the sensing ability of existing robotic fingers. We humans utilize receptors (corpuscles) of several kinds broadly distributed inside the finger [13]. The receptors in a deep part of the finger (Pacini corpuscles and Ruffini endings) are able to acquire the information filtered by its material property whereas the ones in a shallow part (Meissner's corpuscles and Merkel's disks) are sensitive to high frequency transient phenomena. The robotic finger can also obtain more useful information about the object by combining the sensory information at many different locations inside the finger rather than just using receptors on the surface.

Several studies mentioned that receptors embedded in soft material could provide useful information such as slippage and friction coefficients [14–18]. Although it is promising to obtain more information about them by increasing the number of receptors at various depths, there have been very few studies on it. Only Shinoda and his colleagues have studied receptors at different depths [14], and discussed randomly distributed

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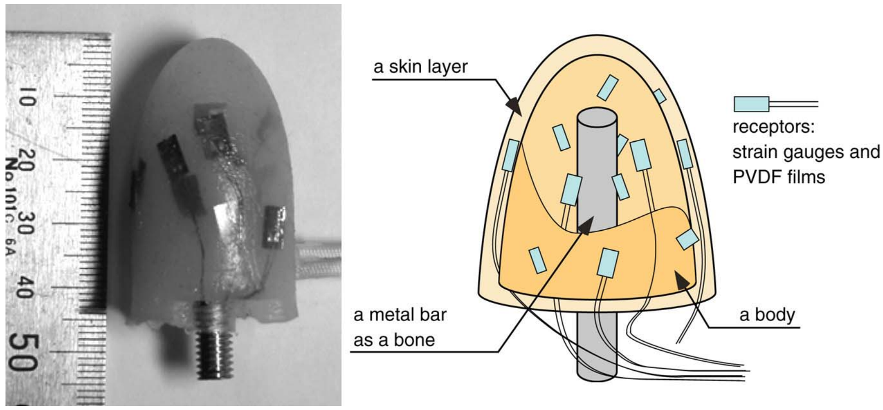

Fig. 1. A developed fingertip (left) and its cross sectional sketch (right): The fingertip consists of a metal bar, a body, and a skin layer inspired by the structure of the human finger. The body and the skin layer are made of different kinds of silicon rubber. Strain gauges and PVDF films are embedded randomly in the body and the skin layer as receptors.

receptors in soft material [19,20] to the best of the authors' knowledge. However, they studied only the characteristics of receptors and did not study the sensing ability provided by increased receptors in various depths and positions.

This paper proposes a unique design of an anthropomorphic soft fingertip with distributed receptors. The word *anthropomorphic* has two meanings: one is that the structure of the fingertip is similar to that of a human's; it consists of a bone, a body, a skin layer, and randomly distributed receptors inside. The other is that, as a human does, the fingertip should learn to acquire meaningful information such as slippage and object texture from the outputs of receptors since the receptors are not calibrated. It would be possible for the robot to organize signals from different receptors through experience to acquire more information.

The rest of the paper is organized as follows. First, the design of the anthropomorphic fingertip is introduced. The fingertip consists of two silicon rubber layers of different hardness containing two kinds of receptors: strain gauges and PVDF (polyvinylidene fluoride) films randomly distributed. Following that, several experimental results are shown to demonstrate its sensing ability to discriminate several materials by haptic exploration, pushing and rubbing of the objects.

2. Design of anthropomorphic fingertip

2.1. Sensor design that relies on the learning ability

In order to translate raw signals into meaningful information, the underlying structure provided by bodily, environmental, and task constraints is essential. For example, the electrical resistance of a strain gauge of a force sensor itself does not make any sense. If the robot knows the resistance-to-strain function that is determined by the gauge material and structure and if it knows the strain-to-force function determined by the sensor physical structure, it can translate the measured resistance into force.

A human designer usually calibrates the function from the raw signals to meaningful information. He or she understands the constraints and implements knowledge about them as a *sensing model* for a robot. Then, the robot can behave properly even with a few receptors by compensating for missing information with the model. Receptors of the existing sensors are, therefore, placed regularly on a relatively hard surface so that the designer can easily analyze the structure. As long as the task of the robot is simple, such a sensing model is functional. Recently, however, the required task for the robots has become more complicated such as handling of objects with various properties (e.g. material, size, mass, etc.), and the physical interaction between the finger and an object has also become complicated (e.g. grasping with slippage, finger gait, etc.). Consequently, the realized behavior based on the human-designed sensing model is no longer robust against modelling errors and disturbances.

The learning ability enables the robot to deal with such problems. If the robot can acquire the sensing model through experience, the receptors can be distributed randomly in or on soft material. The softness of a finger provides not only stability of grasping and protection against strong impact forces, but also more sensing abilities than a hard finger. It is obvious that the variety of receptors provides more sensing abilities. Even with receptors of the same kind, the robot can acquire different information from them at different depths since material existing between receptors plays the role of a low-pass filter. In this sense, embedding many receptors provides not only redundancy, but also variety of sensing abilities. It would even be possible for the robot to have a sensing ability that is excluded by the human designed sensors whose receptors are placed regularly. In this sense, the learning ability will change the design of tactile sensors.

2.2. Structure of the finger

Fig. 1 shows the developed anthropomorphic fingertip. It consists of a metal bar that plays the role of a bone, a body, and a skin layer, inspired by the structure of the human finger. The silicon used for the skin layer is slightly harder than that for the body. Strain gauges and PVDF films are embedded randomly both in the body and in the skin layer as receptors. A PVDF film is sensitive to the strain velocity by the piezo effect, whereas a strain gauge measures static strain. Since these receptors are embedded randomly, the robot has to learn to acquire meaningful information such as slippage and object texture from the outputs of receptors through the interaction with the environment like a human does.

Fig. 1 (left) shows a complete soft fingertip. Its diameter and length are 2.5 cm and 4.5 cm, respectively. This finger has six strain gauges and six PVDF films both in the body and the skin layer, which results in a total of 24 receptors. As mentioned above, the positions and the orientations of these receptors have not been determined, i.e. the designer or the robot does not know the geometries of the finger beforehand.

We expect that receptors of the same kind embedded in different positions would be able to measure different physical properties. A strain gauge embedded near the skin surface is expected to sense the local static strain between the skin and the object surface whereas a gauge embedded near the bone is expected to sense the total force exerted to the finger and is expected to be insensitive to the local texture of the object. A PVDF film senses the strain velocity, which means that it is more sensitive to the transient and the rapid strain changes (or stick–slip motions) than the strain gauges whereas it cannot sense the static strain. The silicon between two PVDF films is expected to function as a low-pass filter, therefore the difference between the signals is expected to represent the local stick–slip interaction.

It may be interesting to compare the structure with that of the human finger [13]. The human skin has Meissner's corpuscles that are sensitive to strain and Merkel's disks sensitive to strain velocity in a shallow part. They may correspond to the strain gauges and PVDF films in the skin layer in this robot finger design. There are Pacini corpuscles and Ruffini endings in the deep part of human skin; those are sensitive to strain and strain velocity. In this sense, this design of the soft finger has a kind of similarity with a human's finger structure, which may make us understand the human from a constructivistic viewpoint.

2.3. Procedure to make a fingertip

Fig. 2 shows the procedure to make the fingertip. First, a metal bar and several receptors, strain gauges and PVDF films are inserted into a mold, and silicon rubber is cast into it. The mold is put into a vacuum to remove bubbles, and is baked in an oven to be solid. It is then inserted into another mold that is slightly bigger. The additional receptors are implemented in this layer. Another kind of liquid silicon rubber that is harder than the previous one is cast, and the mold is put into the vacuum and is baked in the oven again.

3. Experiments: discriminating several materials

To investigate the sensing ability of the anthropomorphic fingertip, it is mounted on a robotic finger that has three degrees of freedom (Fig. 3), and data from receptors are collected through haptic exploration involving pushing and rubbing of objects of five different materials: two kinds of wood, paper, cork, and vinyl. Pushing and rubbing are stereotyped movement patterns of humans to haptically explore the objects, which are referred to as exploratory procedures "pressure" and "lateral motion" [21].

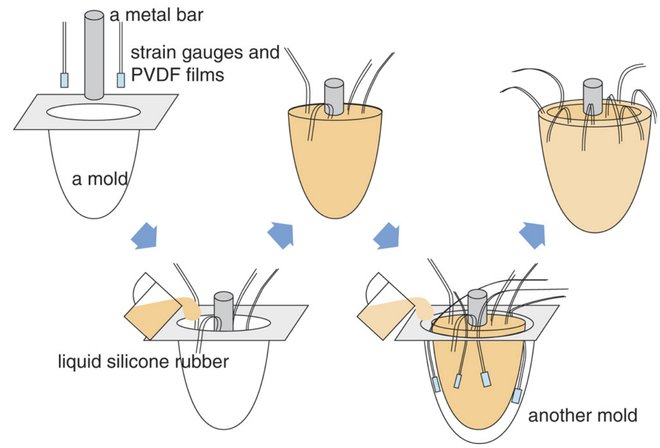

Fig. 2. The procedure to build a soft fingertip: a metal bar and several receptors, strain gauges and PVDF films are inserted into a mold, and silicon rubber is cast into it. This mold is then inserted into another mold that is slightly bigger. The additional receptors are implemented in this layer, then silicon rubber is again cast.

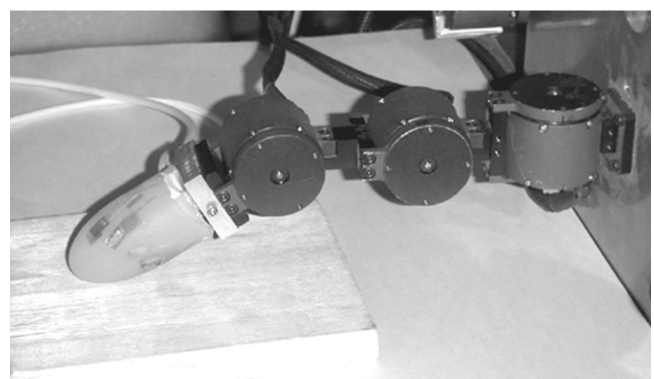

Fig. 3. The robot finger used for experiments: An anthropomorphic fingertip is attached at the tip of a robot finger.

Fig. 4 shows an example of receptor outputs through one pushing and rubbing trial. The fingertip contacts the object at 0.8 s and exerts static force until 2.1 s. Then, the finger rubs the object along a pre-defined desired trajectory until 5.2 s, and exerts a static force again. Even during static contact, some outputs of strain gauges decrease because of the softness of the fingertip. Note that the output magnitude of a receptor does not necessarily correspond to its depth since its orientation also affects the magnitude. The receptor producing the largest response in the figure was actually in the body, which was accidental.

3.1. Discrimination by pushing the object

In the previous work [17], they reported that strain gauges in the soft material could sense the friction coefficient. Following their result, we tested the discriminating ability of the developed fingertip by statically pushing the object.

First, we did several preliminary experiments to find out the most sensitive receptors in the body and the skin layer through

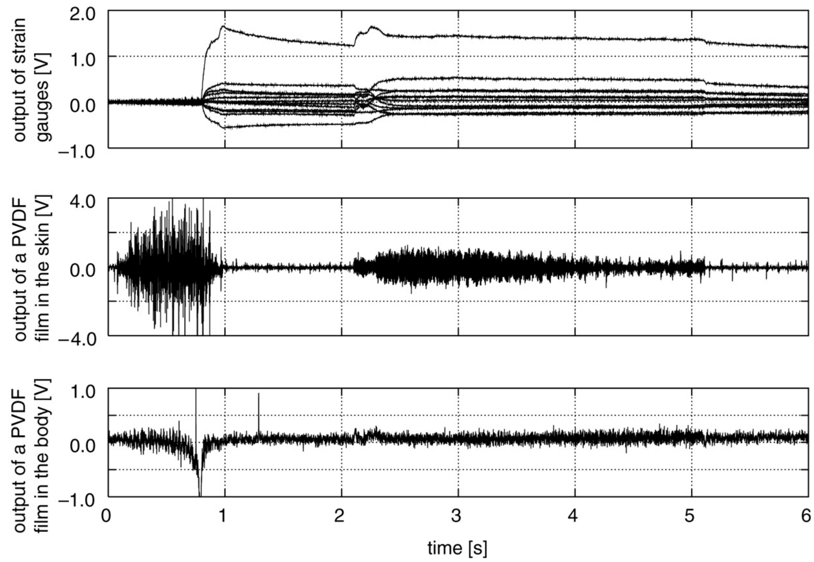

Fig. 4. Outputs of receptors through pushing and rubbing the object.

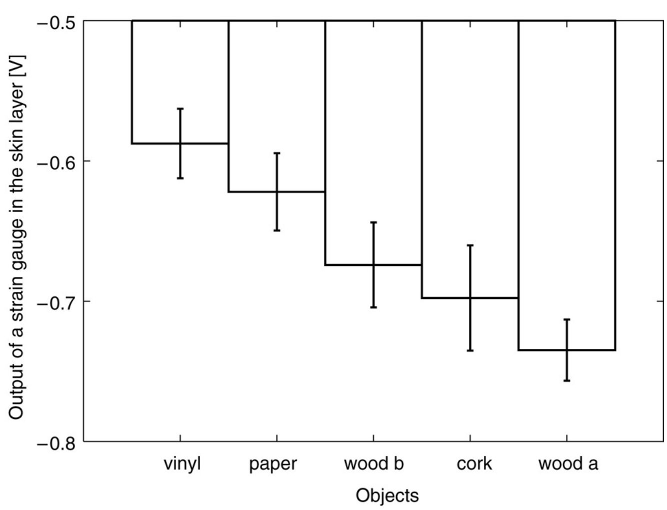

Fig. 5. Results of pushing experiments: the averages and standard deviations of a strain gauge in the skin layer of 50 trials for each object. They are not distinguishable just from this result.

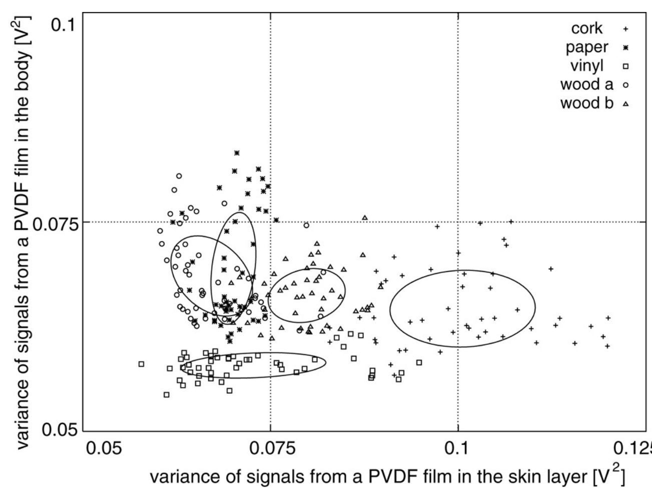

Fig. 6. Results of rubbing experiments: variance of signals of a PVDF film in the skin layer and that in the body layer are plotted. Cork, vinyl, wood b and paper (or wood a), are distinguishable by combining the outputs of these two PVDF films.

several pushing trials. Since the receptors were embedded randomly, and since not only the position but the orientation of the receptors affected the sensitivity, the positions were not precisely known from the preliminary experiments. Then, to regulate the pushing force, we applied feedback control to make an output of the strain gauge in the body converge to 0.1 V. By the preliminary experiments, we found that the force corresponding to 0.1 V was approximately 1.0 N, which was not exact since we did not calibrate the receptors precisely.

Fig. 5 shows averages and standard deviations of the outputs of the strain gauge in the skin layer of 50 trials for each object. Since the distributions are overlapping, it is difficult to distinguish the materials only by this result.

3.2. Discrimination by rubbing the object

Next, we collect data from the PVDF films through rubbing procedures. In these experiments, the finger is not force controlled but position controlled along a pre-determined trajectory. Actually, it is difficult to regulate the force during rubbing because of stick–slips. Fig. 6 shows variance of signals originating from a PVDF film in the skin layer and that from another PVDF film in the body. Since the fingertip has six films in the skin layer and six in the body, there are 36 combinations to be investigated. Since the purpose of this experiment was to investigate the ability of discriminating objects, a human designer looked through all the results, and found an appropriate combination for the discrimination.

In the figure, crosses, stars, squares, circles, and triangles represent the data obtained during rubbing cork, paper, vinyl, wood a, and wood b, respectively. One point indicates a result of one rubbing trial, and 50 trials are conducted for each material. A ellipsoid represents the variance for each material. Since variance ellipsoids depicted in this figure do not overlap each other except those of wood a and paper, we can conclude

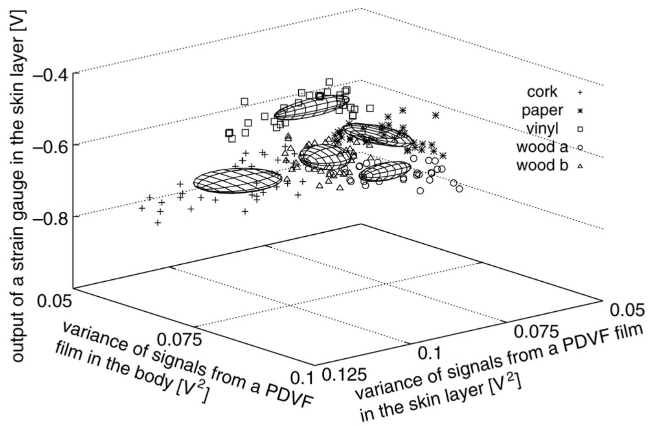

Fig. 7. Results of pushing and rubbing experiments: by combining the results of pushing and rubbing, we can discriminate the five materials.

that four materials, cork, vinyl, wood b and paper (or wood a), are distinguishable by combining the outputs of these two receptors. It is important to note that, as illustrated in this figure, the vinyl, the wood b, and the paper cannot be identified only from the film in the skin layer. The same holds for the paper, the wood b, and the cork measured by the film in the body. In this sense, two films embedded in different layers provides more information about the object than just using one film.

According to the work [17], the magnitude order of the outputs in the Fig. 5 corresponds to the order of friction coefficients of the materials. However the order does not correspond to the order in Fig. 6, which indicates the existence of a more complex micro-dynamic phenomenon between the fingertip and texture of the material. This clearly shows that this kind of dynamic exploration will provide more information about the interaction between the surface and the fingertip.

Since the finger is not force controlled and the height of the surface is also not precise, it is very hard for the robot to control the contact force constant through the rubbing process. This could be the main reason for the relatively large variance in the data points obtained from the same material. We expect that, if the finger is precisely controlled, the variance should be smaller so that one receptor is sufficient to identify the material. However, even without precise control, it is shown that the distributed receptors are able to distinguish the different materials. Since the sensor is not calibrated with respect to the external force, this characteristic would be particularly important since the robot would not be able to perform the precise position and force control.

3.3. *Combination of pushing and rubbing*

Before rubbing the object, the fingertip should exert force against it. It is natural, therefore, to utilize the information obtained by pushing together with rubbing it. Fig. 7 shows a 3D plot with an output of a strain gauge in the skin layer, variance of signals originating from a PVDF film in the skin layer, and that from another PVDF film in the body layer. Finally, we can distinguish five materials.

In the previous work of discriminating materials, they usually used only one kind of sensor signal. However, in a realistic situation of haptic exploration of objects, it naturally contains procedures providing rich information of some kinds which can be utilized for more complicated discrimination. Having two kinds of receptors at various depths enables the finger to discriminate materials more reliably.

4. Conclusion and discussion

This paper has described a new design of an anthropomorphic fingertip. The sensing ability is investigated to discriminate vinyl, cork, paper, and wood that is provided by its softness and placement of receptors.

Since the receptors are randomly distributed in the soft fingertip, the designer cannot map the physical phenomenon with the receptor outputs explicitly. Therefore, the robot has to learn the mapping through its own experience, and to organize the outputs of receptors. If the learning is not supervised by the robot designer, it should be done with another modality that can observe the object, vision for example. The learning is supposed to be divided into two phases:

(1) First, the robot should select the receptors that are providing meaningful information about the contact and the slippage which is done manually by the designer in this paper. One of the simplest solutions with vision is to pick up receptors whose outputs have a certain correlation with them [22].

(2) Second, the robot should process the outputs of concerned receptors to get meaningful information about the object, which is also done manually by the designer in this paper. In the object discrimination experiments, the category is given by him/her. However, the category should be obtained by the robot itself based on its behavioral result. It does not have to discriminate the objects as long as the probability of achieving a given task (e.g. manipulating or grasping an object) does not change. In this sense, the robot should experience manipulating several objects, and gather information to process the outputs.

The learning and organizing process is one of most important developmental aspects of an autonomous robot, and should be studied immediately. In this sense, this design will shed light on the developmental study of robots.

We expect that the study of an anthropomorphic fingertip could also provide an additional insight to the developmental process of human manipulation. We humans have corpuscles of several kinds broadly distributed in the finger, and utilize the obtained information to perform tasks. These corpuscles are not precisely calibrated.

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References

[1] A. Bicchi, V. Kumar, Robotic grasping and contact: A review, in: Proc. of the IEEE Int. Conf. on Robotics and Automation, 2000, pp. 348–353.

[2] M.H. Lee, H.R. Nicholls, Tactile sensing for mechatronics — a state of the art survey, Mechatronics 9 (1999) 1–31.
[3] M. Shimojo, M. Ishikawa, K. Kanayama, A flexible high resolution tactile imager with video signal output, in: Proc. of the IEEE Int. Conf. on Robotics and Automation, 1991, pp. 384–391.
[4] H. Maekawa, K. Tanie, K. Komoriya, M. Kaneko, C. Horiguchi, T. Sugawara, Development of a finger-shaped tactile sensor and its evaluation by active touch, in: Proc. of the IEEE Int. Conf. on Robotics and Automation, 1992, pp. 1327–1334.
[5] R.S. Fearing, Tactile sensing mechanisms, The International Journal of Robotics Research 9 (3) (1990) 3–23.
[6] D. Johnston, P. Zhang, J. Hollerbach, S. Jacobsen, A full tactile sensing suite for dextrous robot hands and use in contact force control, in: Proc. of the IEEE Int. Conf. on Robotics and Automation, 1996, pp. 3222–3227.
[7] M. Hakozaki, H. Shinoda, Digital tactile sensing elements communicating through conductive skin layers, in: Proc. of the IEEE Int. Conf. on Robotics and Automation, 2002, pp. 3813–3817.
[8] M. Nilsson, Tactile sensors and other distributed sensors with minimal wiring complexity, IEEE/ASME Transactions on Mechatronics 5 (3) (2000) 253–257.
[9] B.L. Hutchings, A.R. Grahn, R.J. Petersen, Multiple-layer corss-field ultrasonic tactile sensor, in: Proc. of the IEEE Int. Conf. on Robotics and Automation, 1994, pp. 2522–2528.
[10] R. Lazzarini, R. Magni, P. Dario, A tactile array sensor layered in an artificial skin, in: Proc. of the RSJ/IEEE Int. Conf. on Intelligent Robots and Systems, 1995, pp. 114–119.
[11] M. Inaba, Y. Hoshino, K. Nagasaka, T. Ninomiya, S. Kagami, H. Inoue, A full-body tactile sensor suit using electrically conductive fabric and strings, in: Proc. of the RSJ/IEEE Int. Conf. on Intelligent Robots and Systems, 1996, pp. 450–457.
[12] R. Tajima, S. Kagami, M. Inaba, H. Inoue, Development of soft and distributed tactile sensors and the application to a humanoid robot, Advanced Robotics 16 (4) (2002) 381–397.
[13] M.R. Miller, H.J. Ralston III, M. Kasahara, The pattern of cutaneous innervation of the human hand, American Journal of Anatomy 102 (1958) 183–197.
[14] H. Shinoda, M. Uehara, S. Ando, A tacile sensor using three-dimensional structure, in: Proc. of the IEEE Int. Conf. on Robotics and Automation, 1993, pp. 435–441.
[15] D. Yamada, T. Maeno, Y. Yamada, Artificial finger skin having ridges and distributed tactile sensors used for grasp force control, in: Proc. of the RSJ/IEEE Int. Conf. on Intelligent Robots and Systems, 2001, pp. 686–691.
[16] Y. Yamada, T. Maeno, I. Fujimoto, T. Morizono, Y. Umetani, Identification of incipient slip phenomena based on the circuit output signals of pvdf film strips embedded in artificial finger ridges, in: Proc. of SICE 2002, 2002, pp. 3272–3277.
[17] K. Nakamura, H. Shinoda, A tactile sensor instantaneously evaluating friction coefficients, in: Proc. of the 11th Int. Conf. on Solid-State Sensors and Actuators, 2001, pp. 1430–1433.
[18] K. Yamada, K. Goto, Y. Nakajima, N. Koshida, H. Shinoda, Wire-free tactile sensing element based on optical connection, in: Proc. of the 19th Sensor Symposium, 2002, pp. 433–436.
[19] M. Hakozaki, K. Nakamura, H. Shinoda, Telemetric artificial skin for soft robot, in: Proceedings of TRANSDUCERS '99, 1999, pp. 844–847.
[20] H. Shinoda, H. Oasa, Wireless tactile sensing element using stress-sensitive resonator, IEEE/ASME Transactions on Mechatronics 5 (3) (2000) 258–265.
[21] S.J. Lederman, R.L. Kaltzky, Hand movements: A window into haptic object recognition, Cognitive Psychology 19 (1987) 342–368.
[22] K. Hosoda, Y. Tada, M. Asada, Internal representation of slip for a soft finger with vision and tactile sensors, in: Proc. of the RSJ/IEEE Int. Conf. on Intelligent Robots and Systems, 2002, pp. 111–115.

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