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Proposal of Tactile Sensor Development based on Tissue Engineering

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Abstract—**The development of modern technologies, touch and/or tactile sensors have been well-developed, exploring various possible methods of transduction and available in many commercial products. The demand for more friendly and safe products, such as household robots, is growing up day by day. But the issues of tactile sensors such as wiring and robustness still remain. By researching human mechanoreceptors, we got an idea of a novel type of tactile sensor based on tissue engineering, which is expected to provide some solutions for those issues. In this paper, we propose the basic concept of tactile sensor based on tissue engineering and the hypotheses of approaching methods.**

I. INTRODUCTION

There is a growing demand for a tactile sensor covering the whole surface of the robots that work in our daily life [1][2] in order to interact with humans and environment softly and safely based on tactile information [3]. Several robots having tactile sensors on their bodies are demonstrated until now for the purpose of elder care [4] or touch interaction [5].

The tactile sensor arrays implemented on those robots are low resolution, i.e. a few sensors on each body parts. A higher-resolution tactile sensor array is desirable to detect detail touch information. Various kinds of tactile sensors have been reported for that purpose, e.g., piezoelectricity [6], 1-bit touch sensors [7], multi-valued touch sensors [8], capacitance [9], resistance [10], and so on.

The arrays of tactile sensors introduced above may suffer from wires from a huge number of sensors. In order to manage this problem, several approaches have been proposed. Telemetric skin [11] is an approach, in which tactile sensor chips are distributed within a silicone rubber body and both of signal transmission and power supply are based on inductive coupling. For more effective and high-speed communication, the two-dimensional signal transmission [12] is developed in after years, which uses microwaves propagating within a two-dimensional sheet instead of inductive coupling. In organic transistor matrixes [13], not only sensing elements but also wires are completed by printing technologies. The narrow flexible substrates with a serial bus enable us to change the network configuration easily in [14].

In this paper, we propose a new approach to manage the problem of wiring. We focused on human tactile sensors (i.e. mechanoreceptors) which a located densely underneath skins [15]. They are connected to the brain via axons, which are part of living neurons and assemble themselves in embryos. We got an idea from this process: If we can utilize axons as wires, it is possible to connect a huge amount of tactile sensors to a central computer thanks to the self-assembly feature of axons. In other words, the communication network is formed automatically in spite of its complexity. Besides, living axons are expected to be more extensive than electrical wires and more robust. While there are a lot of breakthroughs required to make this proposition practical, we believe it is worth considering and preparing it at the present stage.

In employing this approach, it is reasonable to utilize mechanoreceptors as tactile sensors because they are well compatible with each other. There are several kinds of mechanoreceptors in the human skin. Two mechanoreceptors, Merkel cells and Meissner corpuscles, have relatively higher spatial resolution among them. While a Merkel cell is a single cell, a Meissner corpuscle has a complex structure, which consists of helical-shaped axons, flat Schwann cells, collagen fibers, etc. Even though the generation process of Meissner corpuscles would provide us with helpful information in implementing cell-based tactile sensors, the detailed forming mechanism is still unknown.

This paper describes our concept of cell-based tactile sensors in Section II, surveys the literature of skins and Meissner corpuscles in Section III, discusses possible developing ways and hypotheses toward our goal based on the given knowledge in Section IV, and concludes in Section V.

II. CONCEPT OF NOVEL TACTILE SENSOR

In this section, we propose two types of tactile sensor based on tissue engineering: the flat sensor and the sphere-head one (Fig. 1). The mechanoreceptor illustrated in Fig.1 is Meissner corpuscle.

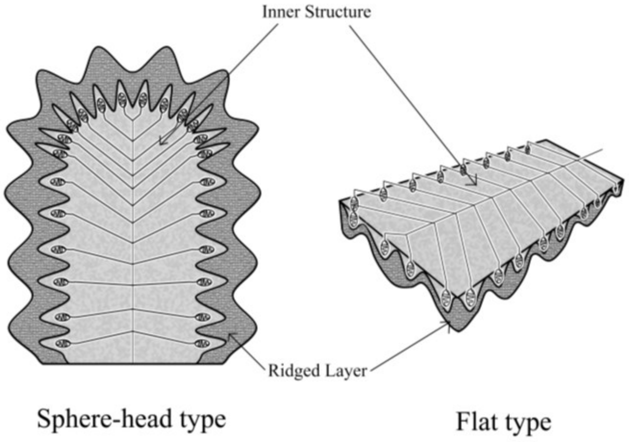

Figure 1. Concept of tissue engineering based mechanoreceptors

Both types consist of an outer layer and an inner structure including mechanoreceptors which is responsible for sensing and processing. The outer layer is an elastic artificial skin-like thin film which is responsible for absorbing interaction. Its

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outer and inner surfaces have the ridged texture like human finger-print. The inner structure consists of an artificially tissue-engineered axons, mechanoreceptor capsules, guide tubes, and growth solution, as shown in Fig.2. The guide tubes work as tunnels leading the axon terminals from parent fibers to prepared mechanoreceptor capsules. The growth solution provides inner pressure and keeps the mechanoreceptors living since organic components may decay easily. In order to supply growth solution frequently, we are thinking about using a two-way exchange system like human circulatory system, which is not illustrated here. This type of system may decrease the mobility but increase the stability of the tactile sensor.

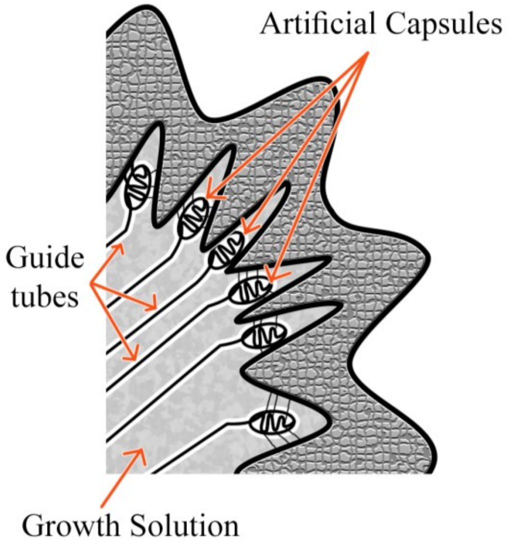

Figure 2. Inner structure of tissue-engineering-based mechanoreceptors

We intend to use tissue engineering merely for necessary components such as axons and/or inner components of mechanoreceptors, instead of all. The other component parts are appropriately produced by mechanical engineering methods. This conception is supported by some recent reports which showed the potentiality of the combination of cultured cell/tissue and particular mechanical material, such as tissue-engineered jellyfish [16] and biological machine [17]. The advantage of this method is the simplicity of producing, especially for outer components as ridged-layer, compared with pure biological method. Using mechanical engineering also costs lower and provides a high chance of mass-production. Meanwhile, the problem is that the high-accuracy of mechanical component production at micrometer level is required. The 3D printing technology which has capability of producing high-detailed tiny 3D objects is a solution for this issue. In recent years, the well-developed 3D printing technology somehow already surpasses micrometer level and may achieve nanometer level in model making [18]. The detailed developing or approaching methods are described in Section IV.

Mechanoreceptors are distributed in couples along the inner ridges of capsule similar to those in human skins [19] and shown in Fig.3 with the sphere-head type as example.

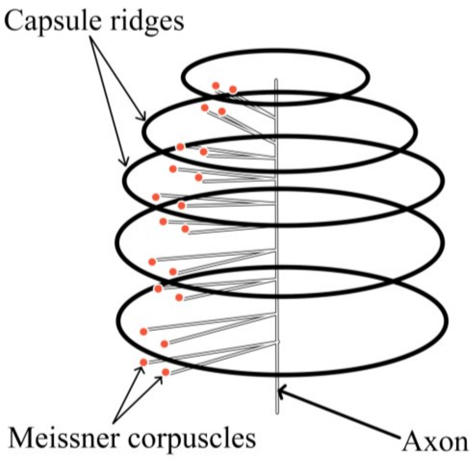

Figure 3. Concept of implanted mechanoreceptors distribution based on human distribution

The operation is based on deformation of the contact surface outside ridged capsule. Depend on interaction, various areas of surface are deformed and the deformation of inner surface connected to mechanoreceptors is involved. Therefore, the axon inside mechanoreceptor is also distorted and then generates changes of ion charge. In other words, contact interactions are encoded onto electrical signals and transmitted to computing system via the axon. The computing system processes analysis of the signals and extracts interaction properties.

A block diagram of the tissue-engineering-based tactile sensor is demonstrated in Fig. 4.

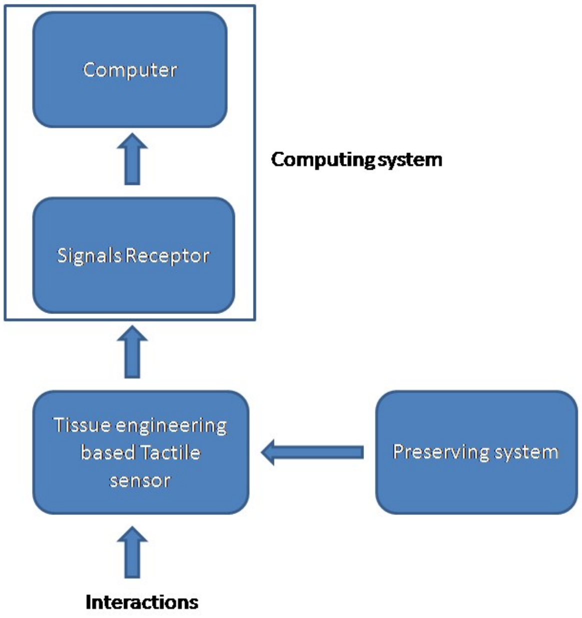

Figure 4. Block diagram of sensor system

The difference between the two types of tactile sensor is how they may be applied in robotics. The flat one is appropriate to being mounted on a flat surface or sensing one-directional pressure while the sphere-head one is appropriate to being mounted on a convex surface or sense multi-directional pressure.

III. SURVEY OF MEISSNER CORPUSCLE AND RELATED COMPONENTS

In order to make this concept practical, we took researches about related-components of this novel sensor, mainly axons and Meissner corpuscles.

A neuron cell and its axons are the first essential components in this concept. While a neuron cell is the main body, axons are projected toward out parts to gain information and connect neuron cells together. Reference [20] shows that a neuron cell could be cultured on a micro plate and the growth directions of its axons are manipulated. At an intersection or an appreciate environment, an axon may exhibit three trends of development as shown in Fig. 5. According to [21], these trends are respectively corresponded to three forms of axon branching: Arborization, bifurcation, and collateral formation. For short definition, arborization is the form in which an axon branches freely in all directions (two sub-directions and main direction) like tree-branching. Meanwhile, bifurcation is the form which branches only in sub-directions and collateral formation is the form which branches in main direction and one sub-direction. These three forms can be controlled by using specific chemical factors.

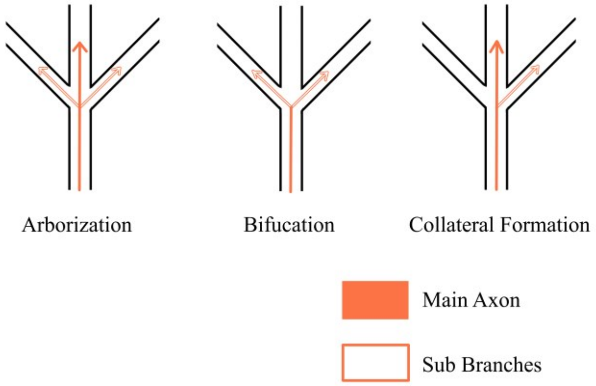

Figure 5. Three forms of axon branching at an intersection

The second essential component is a Meissner corpuscle, which consists of axons, flat Schwann cells, collagen fiber, etc. (as mentioned in Section I). Meissner corpuscles are rapidly adapting mechanoreceptors which exist at dermal papillae beneath epidermis. The axons inside the corpuscle are helical-shaped and sandwiched between lamellar cells (flat Schwann cells). Even though the core stacks of inner axons and lamellar cells are formed irregularly, a Meissner corpuscle is almost oval in shape. It is about 70 μm diameter and 150 μm in length. Figure 6 shows a simple illustration of a Meissner corpuscle.

According to the observations in [22], the generation process of Meissner corpuscles is revealed but still unclear. After the establishment of secondary dermal ridges, the process occurred in the gestation period with an axon firstly penetrated to a dermal papilla. It is also known that the corpuscle has the same configuration as mature one after a while. But the mechanism for axons and Schwann cells to form a Meissner corpuscle is still unknown.

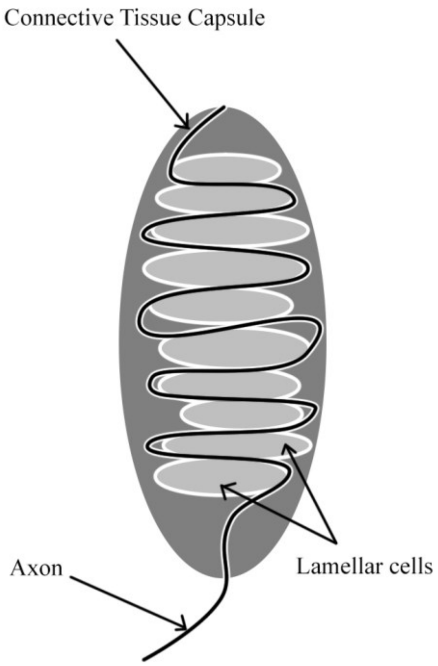

Figure 6. Illustration of Meissner corpuscle

The regeneration of a Meissner corpuscle is revealed quite clearly as mentioned in [23]. In these experiments, pad skin at the toe tip of mice was frozen and thawed repeatedly. By this treatment, axons and lamellar cells of the corpuscle disintegrated to cell debris remaining hollow tubes and loops of basal lamina. Through these basal lamina tubes and hollow loops, an axon penetrated into the corpuscle accompanied by Schwann cells and began to branch terminals. The result of experiments proved that some damaged Meissner corpuscles remaining hollow capsule were successfully regenerated due to penetration of generating axons accompanied by Schwann cells.

IV. HYPOTHESES AND DISCUSSION

To utilize tissue engineering in tactile sensor development, it is necessary to manufacture Meissner corpuscles artificially since its size is too small to be extracted directly from skin. Based on the previous knowledge mentioned above, we propose two hypotheses, which may become the premises for manufacturing this novel sensor.

A. Engineering based hypothesis

This hypothesis concerns manipulation of cultured axons and the regeneration process of Meissner corpuscles.

There would be a main axis at the center of tactile sensor, which can orient the development direction of axons. The problem occurs when axons reach intersections. In the simple examples in Fig. 5, the choices of axon development are limited (toward, right, left). But in reality, an axon has a large number of choices. Therefore, using specific chemical factors which make axon arborize (as the first form of branching introduced in Section II) is the simplest approaching method for production so that we can use a single neuron for all mechanoreceptors. The locations of the specific chemical factor are at intersections and the places of mechanoreceptors as shown in Fig. 7.

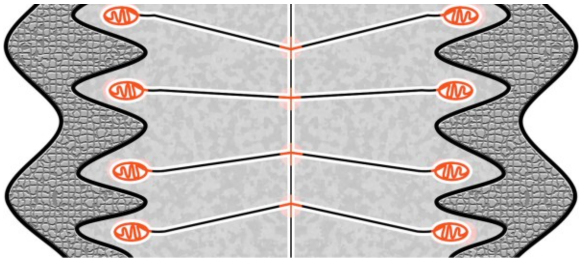

Figure 7. Locations of axon chemical factor (red colored)

The creation of sensing elements (or Meissner corpuscles) is essentially based on the regeneration process. We suppose to create artificial corpuscle capsules with inner hollow loops and basal lamina–like tubes for cultured axons. These artificial capsules locate below the inner surface of ridged-layer and connect directly to guide-tubes and ridged-layer. The axons will be guided to corpuscle capsules and the regeneration process may occur naturally. Figure 8 demonstrates the regeneration process of each mechanoreceptor. Inside the artificial corpuscle, axons not only follow the hollow loops but also need to begin arborizing in order to make the same configuration as real one.

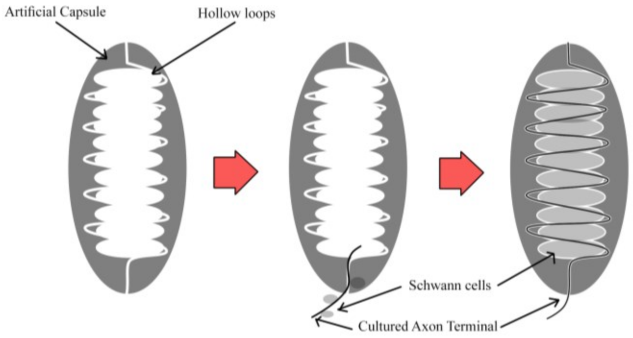

Figure 8. Illustration of Meissner corpuscle production based on regeneration process

Even though this hypothesis provides potentiality of manufactured novel sensor practically and we considered it is the most suitable approaching method for engineering and mass-production in the future, there are some remaining issues which are required to be solved. First is the low rate of successful regeneration, which is also reported in [22]. The regenerated corpuscle size is also smaller than original one. But we found no evidence of the influence of corpuscle size to its functions. And we believe an appropriate environment which can be discovered in experiments may improve the rate of success and furthermore quality of artificial corpuscle. The second is the structure of artificial capsule, which is still unclear under conventional microscope.

B. *Biology based hypothesis*

This hypothesis concerns the natural generation of Meissner corpuscles, which is still unclear as mentioned above.

The observation of the generation process gave us a great wonder. If we made an environment such as an artificial dermis layer with similar components, would the process occur naturally? If so, it also means that the axons could find its own way. The manufacture of novel sensor would be simpler while the density of sensing elements might be higher than the first hypothesis introduced above.

Moreover, the unclear processes during generating stages (as mentioned above) would be also revealed. These generated sensing elements may open an approach for individually analysis of naked mechanoreceptors, which cannot be observed directly due to the difficulty of extraction while conventional analyses are processed with cut-away skin and involved all mechanoreceptors.

V. CONCLUSION

We provided the basic concepts and discussed the two hypotheses of manufacturing tissue-engineering-based tactile sensor. We also pointed out some advantages of this novel sensor such as, axons self-assembly characteristic which may be solutions for wiring problem.

For future work, we are going to start culturing neuron cells and experiment the second hypothesis. In the following stages, we will manufacture the first practical prototype of this novel sensor. And we are supposed to discover more about mechanoreceptor generations which is still unclear and artificial production methods towards a tactile sensor consisting of multiple kinds of mechanoreceptors.

REFERENCES

[1] Y. Sakagami, R.Watanabe, C. Aoyama, S. Matsunaga, N. Higaki, and K. Fujimura: The intelligent ASIMO: System overview and integration, Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2002), vol. 3, pp. 2478-2483, 2002.

[2] K. Kaneko, F. Kanehiro, S. Kajita, H. Hirukawa, T. Kawasaki, M. Hirata, K. Akachi, and T. Isozumi: Humanoid robot HRP-2, Proc. 2004 IEEE International Conference on Robotics and Automation (ICRA 2004), vol. 2, pp. 1083-1090, 2004.

[3] M.H. Lee and H.R. Nicholls: Tactile sensing for mechatronics - a state of the art survey, Mechatronics, vol. 9, pp. 1-31, 1999.

[4] T. Odashima, M. Onishi, K. Tahara, K. Takagi, F. Asano, Y. Kato, H. Nakashima, Y. Kobayashi, T. Mukai, Z.W. Luo, and S. Hosoe: A soft human-interactive robot RI-MAN, Proc. 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2006), video, 2006.

[5] N. Mitsunaga, T. Miyashita, H. Ishigro, K. Kogure, and N. Hagita: Robovie-IV: A communication robot interacting with people daily in an office, Proc. 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2006), pp. 5066-5072, 2006.

[6] E.S. Kolesar and C.S. Dyson: Object imaging with a piezoelectric robotic tactile sensor, IEEE Journal of Microelectromechanical Systems, vol. 4, pp. 87-96, 1995.

[7] Y. Hoshino, M. Inaba, and H. Inoue: Model and processing of wholebody tactile sensor suit for human-robot contact interaction, Proc. 1998 IEEE International Conference on Robotics & Automation (ICRA 1998), pp. 2281-2286, 1998.

[8] R. Kageyama, S. Kagami, M. Inaba, and H. Inoue: Development of soft and distributed tactile sensors and the application to a humanoid robot, Proc. IEEE International Conference on Systems, Man, and Cybernetics, vol. 2, pp. 981-986, 1999.

[9] F. Castelli: An integrated tactile-thermal robot sensor with capacitive tactile array, IEEE Transactions on Industry Applications, vol. 38, no. 1, pp. 85-90, 2002.

[10] O. Kerpa, K. Weiss, and H. Worn: Development of a flexible tactile sensor system for a humanoid robot, Proc. 2003 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2003), vol. 1, pp. 1-6, 2003.

[11] M. Hakozaki, H. Oasa, and H. Shinoda: Telemetric robot skin, Proc. 1999 IEEE International Conference on Robotics and Automation (ICRA 1999), pp. 957-961, 1999.

[12] H. Chigusa, Y. Makino, and H. Shinoda: Large area sensor skin based on two-dimensional signal transmission technology, Proc. 2nd Joint

Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (World Haptics 2007), pp. 151-156, 2007.

[13] T. Someya, Y. Kato, T. Sekitani, S. Iba, Y. Noguchi, Y. Murase, H. Kawaguchi, and T. Sakurai: Conformable, flexible, large-area networks of pressure and thermal sensors with organic transistor active matrixes, Proc. National Academy of Sciences (PNAS), vol. 102, no. 35, pp. 12321-12325, 2005.

[14] Y. Ohmura, Y. Kuniyoshi, and A. Nagakubo: Conformable and scalable tactile sensor skin for curved surfaces, Proc. 2006 IEEE International Conference on Robotics and Automation (ICRA 2006), pp. 1348-1353, 2006.

[15] Å.B. Vallbo and R.S. Johansson: Properties of cutaneous mechanoreceptors in the human hand related to touch sensation, Human Neurobiology, vol.3, pp. 3-14, 1984.

[16] J.C. Nawroth, H. Lee, A.W. Feinberg, C.M. Ripplinger, M.L. McCain, A. Grosberg, J.O. Dabiri, and K.K. Parker: A tissue-engineered jellyfish with biomimetic propulsion, Nature biotechnology, vol. 30, pp.792-797, 2012.

[17] V. Chan, K. Park, M. B. Collens, H. Kong, T.A. Saif, and R. Bashir: Development of miniaturized walking biological machines, Scientific Reports, vol. 2, article number 857, 2012.

[18] A.M. Greiner, B. Richter, and M. Bastmeyer: Micro-engineered 3D scaffolds for cell culture studies, Macromolecular Bioscience, pp. 1301-1314, 2012.

[19] Z. Halata and K.I. Baumann, Anatomy of receptors, Human Haptic Perception: Basic and Applications, chap. 6, 2008.

[20] S. Yoshida, T. Teshima, K. Kuribayashi-Shigetomi, and S. Takeuchi: Single neural cells on mobile micro plates for precise neural network assembly, Proc. 15th International Conference on Miniaturized Systems for Chemistry and Life sciences, pp. 1749-1751, 2011.

[21] D.A. Gibson and L. Ma: Developmental regulation of axon branching in the vertebrate nervous system, Development, vol. 138, pp. 183-195, 2011.

[22] W.E. Renehan and B.L. Munger: The development of Meissner corpuscle in primate digital skin, Developmental Brain Research, pp. 35-44, 1990.

[23] C. Ide: Basal laminae and Meissner Corpuscle Regeneration, Brain Research, vol. 384, pp. 311-322, 1986.