Development of a Variable-Softness Robot by Using Thermoresponsive Hydrogels for Haptic Interaction with Humans

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***Abstract*— It is important for social robots to be capable of changing its behavior or other capacity to sustain interaction with the user. In this paper, we discuss changing the softness of the body of a robot. The robot is supposed to be used in haptic interaction contexts such as therapy. To sustain the interest of the user, the robot changes the softness of its body elements and provide the user with variable tactile sensations depending on the haptic interaction history. In this paper, we report the design process of our creating robot prototypes by using a thermoresponsive gel that changes in viscoelasticity with temperature variations. The gel is soft in an inactive state, whereas it becomes hard when it is activated by heat. After identifying a chemical composition that was suitable for building the variable-softness robot, we created octopus-like prototypes having tentacles whose softness could be changed based on tactile sensing. User tests were conducted to check if participants could recognize such softness changes and to discuss the feasibility and prospects of this approach.**

I. Introduction

Haptic interaction plays a crucial role in social robots [1]. A representative example is their use for therapeutic purposes and studies suggest that human psychological stress may be reduced by introducing touchable robots [2], [3]. However, on the other hand, it is widely known that social robots having constant capacity cannot maintain the interest of the user for a sustainable period of time [4], [5], [6]. Therefore, if a therapy robot can change its softness over time, according to the sequence of the user's touch, the robot could be used by the user for a longer period of time thus become a more effective therapy robot than the one with constant softness. By leveraging the soft material that has been used in the field of soft robotics, haptic interaction experience can be enriched [7]. In fact, a soft robotic haptic device that offers adjustable stiffness was proposed for a neuromuscular rehabilitation purpose [8].

In this study, we create a variable-softness social robot (Fig. 1) by utilizing a temperature-responsive gel that was originally studied and tested in haptic application devices such as a touch screen and a wearable protection [9], [10]. This gel changes the viscoelasticity with temperature. We started from exploring the use of this gel material for the purpose of building prototypes of the variable-softness robot. In this paper, we will document the process of developing these prototypes and present useful knowledge for the future development. In the latest prototype, the temperature of the gel is controlled by heating wires and water-cooling tubes. Flex sensors are embedded to detect the user's touch. We created octopus-like prototypes having soft tentacles whose softness was changing if the user continued touching them. User tests were conducted to check if participants could recognize softness changes on the prototype as we expected. The results are discussed to assess the feasibility, prospects, and the next step of this approach.

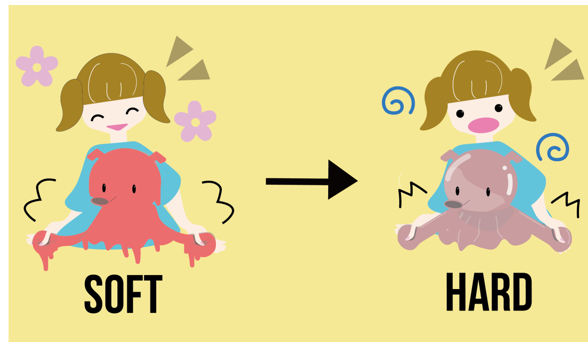

Fig. 1. Variable-softness social robot.

II. Related Works

A. Social Robot for Haptic Interaction

PARO [11] is a therapeutic robot covered with soft artificial fur. It is designed to be touched or stroked by humans. A number of studies has been conducted to investigate the social and haptic interaction between PARO and the users, and it was suggested that human psychological stress may be reduced by introducing the robot [2], [3].

The Huggable [1] is a robotic companion featuring somatic sensors over the whole surface of the robot. It is also covered by fur fabric and designed for haptic interaction, particularly targeting relational and affective touch, with the user. A recent study [12] suggested that this physically embodied social robot had an advantage in producing socially energetic conversations and promoting multi-party interactions in pediatric inpatient-care contexts involving young patients.

The Haptic Creature [13] was also developed to investigate fundamentals of affective touch. It is equipped with sensors and actuators to communicate its internal state via vibrotactile purring, stiffening its ears, and modulating its breathing. It was shown to be effective in communicating emotions to humans [14].

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Controlled studies exist investigating the effect of physical contact by humans with robotic devices. Sumioka, et al. revealed significant reduction in cortisol levels in participants who had conversations with a huggable device [15]. Hayashi examined the role of softness in therapeutic robot [16], including comparisons between a hard robot and a soft robot.

On the other hand, long-term, sustainable interaction between robot and the user has long been a challenge in HRI (human-robot interaction) researches. Many studies suggested that social robots having constant limited capacity could not maintain the interest of the user for a sustainable period of time [4], [5], [6]. Thus, despite the merits mentioned above, social robots having a fixed softness feature may not be used sustainably.

B. Softness Change

Diverse approaches exist in changing the softness of material. In the field of robotics, pneumatic variable-stiffness finger driven by an air-pressure actuator comprising a silicone oval tube and tendon was proposed [17]. Other approaches include the use of a jamming principle [18], magnetorheological fluid (MRF) [19] or electroactive polymers (EAP) [20]. However, large components such as a compressor or a solenoid are required for these approaches. In addition, EAP operates at high voltages (2-5 kV).

In contrast, there is a thermoresponsive hydrogel, a polymer material lubricated with water, whose viscoelasticity changes according to the temperature. If the gel temperature is below a threshold called the lower critical solution temperature (LCST), the gel becomes transparent and soft. On the other hand, if the gel temperature is above the LCST, the gel is dewatered, becoming white and hard. This material had been used in such applications as providing haptic feedback for touch screens [9] or an on-skin interface for body protection [10]. In the former application, the gel was up to 25 times stiffer when activated (LCST: 32 °C), whereas, in the latter application, the gel was up to 10 times stiffer when activated (LCST: 36 °C). System components required for this approach can be much smaller than the other approaches explained in the previous paragraph. There is a detailed review of hydrogel actuators and sensors in which we can find comparisons of this material with other solutions [21].

III. First Prototype

To make use of the thermoresponsive hydrogel explained in the previous section, we first explored the way of temperature control. The initial approach we tested was using a peltier cell as a temperature controller. A peltier cell is a thermoelectric element that generates heat transfer by causing a temperature difference between both the element surfaces by the flow of electric current. By changing the current direction, the direction of heat transfer on both sides of the element changes so that both heating and cooling can be performed.

We fabricated a texture unit (Fig. 2) to check the basic properties of the state change of the gel. A silicone skin having a thickness of 1.0 mm was formed using a mold made by a 3D printer. The silicone skin was created using Dragon Skin^{TM}10 product sold by Smooth-On Inc. The top surface of the unit was a 40 mm square having a height of 10 mm. Then, gel material was injected into the space between the silicone skin and the peltier cell by using a syringe.

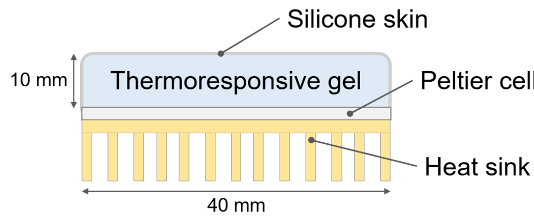

Fig. 2. Texture unit (first prototype).

TABLE I
CHEMICAL COMPOSITION OF THE GEL USED IN THIS STUDY.

NIPAM	Acryl	MBA	APS	TEMED
1.88 g	.12 g	12 mg	.50 g	150 μL

NIPAM: N-isopropylacrylamide
Acryl: Acrylamide
MBA: N,N'-Methylene-bis-acrylamide
APS: Ammonium persulfate
TEMED: Tetramethylethylenediamine

Previous studies reported 10 chemical compositions of the thermoresponsive hydrogel [9], [10]. By using the texture unit, we tested all the chemical compositions and then further searched for a suitable composition for our study. LCST was set to 36 °C considering the average temperature of the user's hand. Overall, we had an impression that we need to have a chemical composition that makes the gel harder than the previous attempts [9], [10]. Table I summarizes the chemical composition we chose in the end for our study.

The peltier cell could well perform heating and cooling functions, but the hardness of the cell itself hindered the softness of the whole texture unit, particularly when the gel was in an inactive soft state. In addition, it was necessary to dissipate heat by attaching a heat sink and a dc fan, which limited the arrangement of multiple texture units. Therefore, in practice, we needed to re-consider the whole component for temperature control to create a variable-softness robot.

IV. Second Prototype

Considering the volume and the thickness of variable-softness material, we decided to build an octopus-like robot having soft tentacles. We were also inspired by pioneering works in soft robotics researches creating octopus-like soft robots [22], [23].

In this second prototype, the gel was heated with a nichrome wire covered with silicone rubber. At the same time, the gel was cooled by circulating cold water through a silicone rubber tube. Consequently, the degree of freedom of the shape with variable flexibility was dramatically increased.

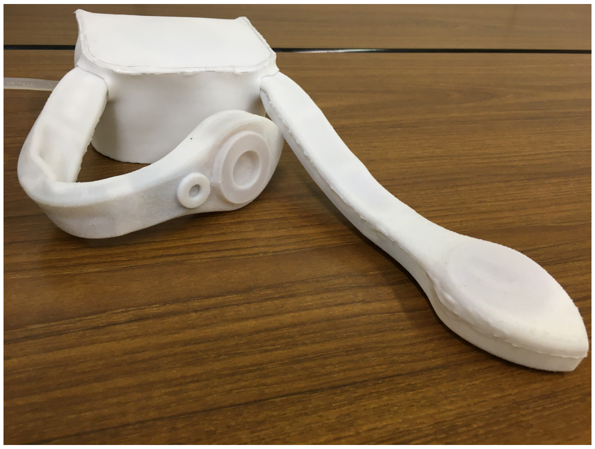

Fig. 3. Variable-softness tentacles (second prototype).

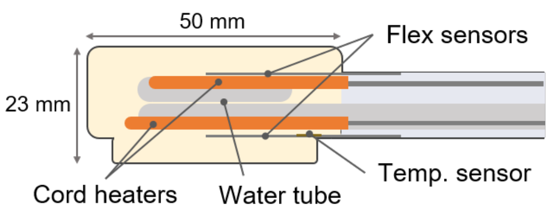

Fig. 4. Internal components of the tentacle (second prototype).

We assumed that the user grasped the tip of the tentacle, and thermoresponsive gel was filled inside the tip. The appearance of the created tentacles is shown in Fig. 3.

As was the case with the first prototype (Fig. 2), the gel was covered with a silicone skin. The internal components of the tentacle is shown in Fig. 4. A temperature sensor was mounted to detect the state of the gel. The gel was arranged so that the thickness of the gel measured from the surface of the cord heater and the silicone tube was less than 10 mm. In this setting, if the cord heater was heated to 50 °C and the temperature was adjusted by circulating cooling water at 20 °C, the state change was completed in approximately 1 to 2 minutes. Flex sensors were embedded to sense the haptic contact by the user. A simple wire-based actuator was also implemented so that the robot could exhibit simple movements. Fig. 5 shows the mold for the tentacle and the internal components. Supporting parts inside the tentacle were made by using Dragon Skin^{TM}10. After fixing the internal components, the upper and lower silicone skins were glued, and the gel material was injected into the space by using a syringe.

Arduino Uno was used to control the robot. Using a motor driver, we drove the cord heater and a pump for circulating water in the silicone tube. The wire attached to the guide part of the tentacle was actuated by a servomotor. Cooling water (5 liters) kept at 20 °C was put into a container, and the water was circulated using a pump. The tentacle surface temperature was controlled so that it remained within the range from 34 °C to 38 °C, and the time required for the

Fig. 5. A mold and internal components.

state change of the gel was approximately 1.5 minutes.

The second prototype was tested in an informal manner by seven students who belong to the same laboratory as the first and last authors of this paper. However, more than the half of the participants could not initially recognize the softness change of the tentacles. It was primarily due to the lack of a detailed instruction about how to interact with the device. Participants who could identify the tip location and find the way of activating the bending sensor by themselves well recognized the softness change. In addition, it was observed that those participants played with the robot longer compared with the control condition in which the temperature control was off (the softness was unchanged).

However, the second prototype required an external cooling water system that accommodated the 5 liters of water, which made us design and create the third prototype explained in the next section.

V. Third Prototype

We then developed a compact cooling system so that it could be accommodated inside the body of the octopus-like robot. Fig. 6 (top) shows the exterior of the robot. Two water tanks are built into the main body. Each tank is attached with a peltier cell and a heat sink. A DC fan is installed in the back side of the body. These two tanks provide circulating cool water within the tentacles.

The internal components of the tentacles were also improved. Instead of using a single chamber (Fig. 4), in the third prototype, we adopted two separated chambers (Fig. 7) each of which was capsuled by a silicone skin and was attached with a heating wire and a cooling tube. Aluminum plates were also installed on the surface of the chambers to improve the thermal conductivity on the capsules.

VI. User Tests

To check the basic functioning of the third prototype and to observe how people perceive it, we conducted user tests. We recruited test participants and asked them to perform three interaction tasks: in task-1 and task-3, they were given

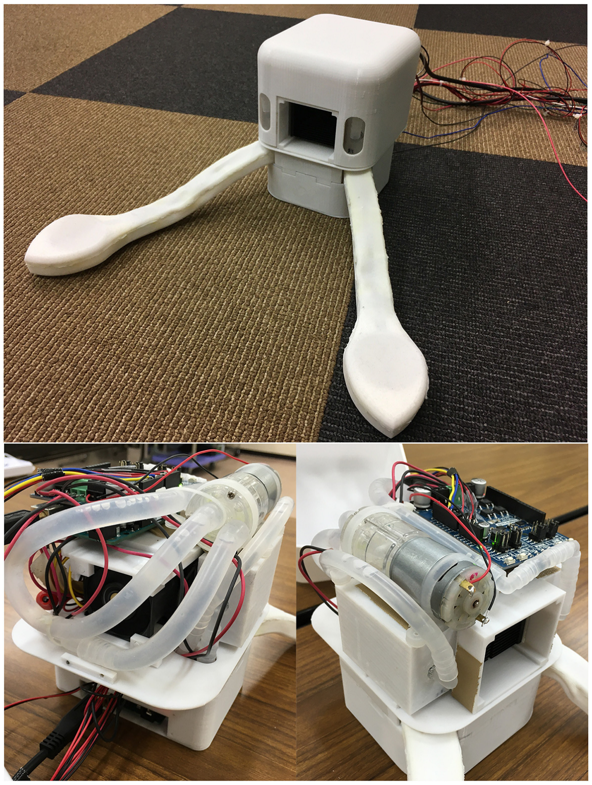

Fig. 6. Third prototype: the exterior and internal components.

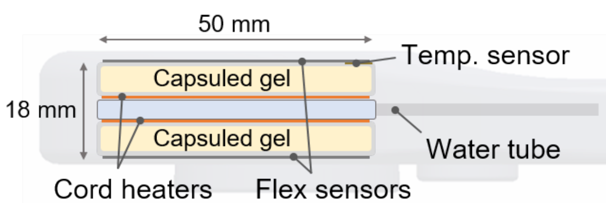

Fig. 7. Internal components of the tentacle (third prototype).

a robot whose softness in its tentacles was changed according to a previously determined protocol, whereas, in task-2, they were allowed to freely play with the robot. In task-2, two conditions were compared: in condition-1 (variable-softness), the viscoelasticity of the thermoresponsive hydrogels embedded inside the robot's tentacles was changed based on the detection of the participant's touch, whereas, in condition-2 (constant-softness), the viscoelasticity of the hydrogels was unchanged. In the procedure explained in Section VI-B, participants were randomly assigned into each of the two conditions.

A. Participants

Ten male students ($M = 24.2$ years old, $SD = 2.64$) were recruited at the University of Tsukuba. Their participation was compensated with 850 yen/hour. The test protocol was approved by the ethical committee of the University of Tsukuba, and all tests were conducted after obtaining a written consent from the participants.

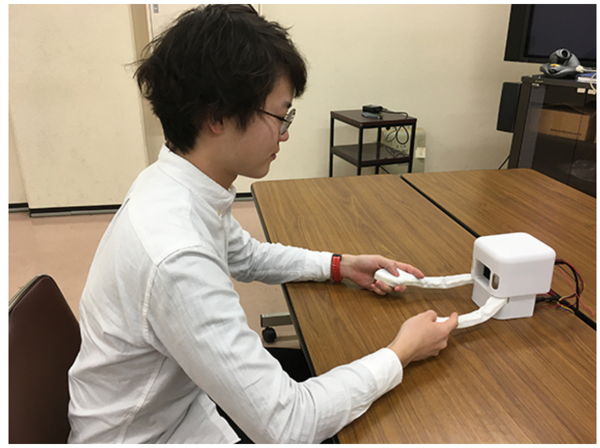

Fig. 8. A free play session (task-2).

B. Procedure

After an experimenter explained the general goal as well as the functioning of the robot to each of the participants, task-1 was started. The instruction included the precise location (the tip of the tentacles) whose softness was variable and how to activate the change. At this moment, the participants were told that the change may or may not occur even if they actually touch the robot. The participants were randomly divided into two condition groups (condition-1 and condition-2) in task-1 as well; however, in task-1, the softness of the gels was not controllable by the participants, instead, it was controlled by a previously determined protocol: the temperature was initially set at 40 °C (the gel was in a *hard* state), and then cooling water (20 °C) was kept being circulated for 150 seconds (the gel was changing to a *soft* state). The participants were instructed to keep touching the robot by their dominant hand. Then, once the session started, the participants were asked to raise the other hand when they felt that the softness was changed. The session lasted for 180 seconds. After the session ended, the participants filled out a questionnaire comprising the following three question items: (Q1) Did you feel a softness change on the tentacles? (yes/no), (Q2) Did you feel a temperature change on the tentacles? (yes/no), and (Q3) Did you find any relationship between the softness change and the temperature change? (yes/no) If yes, please describe it in detail. All ten participants tested the two conditions (within participants design) whose order was counter-balanced.

Next, the experimenter gave a detailed instruction again to the participants, in preparation of task-2. The participants were kept being told that the change may or may not occur even if they actually touch the robot. Then, a free play session (task-2) was started (Fig. 8). Both conditions started with a gel state: *hard* (40 °C). In condition-1, every time when the participant's touch was detected more than three times in 30 seconds, either cooling/heating was started, and the state was changed to the opposite state. Plus, every time when the touch was detected, the tentacle was slightly moved by pulling a wire by a servomotor, thus providing the participant with a feedback. In condition-2, the same feedback was provided; however, the temperature of the tentacle surface was kept at 40 °C, and the thermoresponsive gels were kept at the *hard* state. There was no time limit, and the participants were told that they could stop the session anytime he/she wanted to. They filled out a questionnaire at the end of the session: (Q4) Please describe freely your thought and what you felt during the tests. As was the case with task-1, all ten participants tested the two conditions, and the order was counter-balanced. The interaction duration was measured and compared between the two conditions.

Finally, task-3 was performed with the same protocol as task-1. However, before it was started, the experimenter explicitly told each participant the condition-type, i.e., variable-softness or constant-softness.

VII. Results and Discussion

A. Questionnaire

Seven out of ten participants answered that they felt a softness change in condition-1. However, three of them answered that they also felt a softness change in condition-2, suggesting that it was not so straightforward for the participants to clearly judge if a softness change occurred or not. Due to the limited number of participants, we did not perform a statistical test; however, there seemed to be no clear order effect.

Six participants in condition-1 and seven participants in condition-2 answered that they felt a temperature change, suggesting that it was difficult to measure a temperature change by using a subjective questionnaire scale. In addition, there was only one participant in condition-1 (and two in condition-2) who answered that they found a relationship between the softness change and the temperature change.

The free description (Q4) provided us with insightful comments from the participants. Most participants showed their preference to the softness change and acknowledged the merit of utilizing it for social robots. However, at the same time, many of them commented that judging a softness change was not obvious, which is consistent with the result of Q1.

It is interesting that three participants mentioned temperature factors as well as softness factors. One of them commented: "*I think I had a perceived notion of warm objects being soft. So, during the tests, sometimes I was wondering if I feel soft because it is warm or I feel warm because it is soft.*" This suggests a promise for social robots that can change the skin temperature [24], [25] and the importance of maintaining consistency between different tactile factors.

Two participants commented that operating noise coming from the body of the robot could have affected their judgment on softness. In case of assessing the softness/temperature factors precisely, we would need to consider the noise factor.

B. Behavioral results

We also performed objective measurement. Fig. 9 gathers up the results. Besides the user tests, we measured

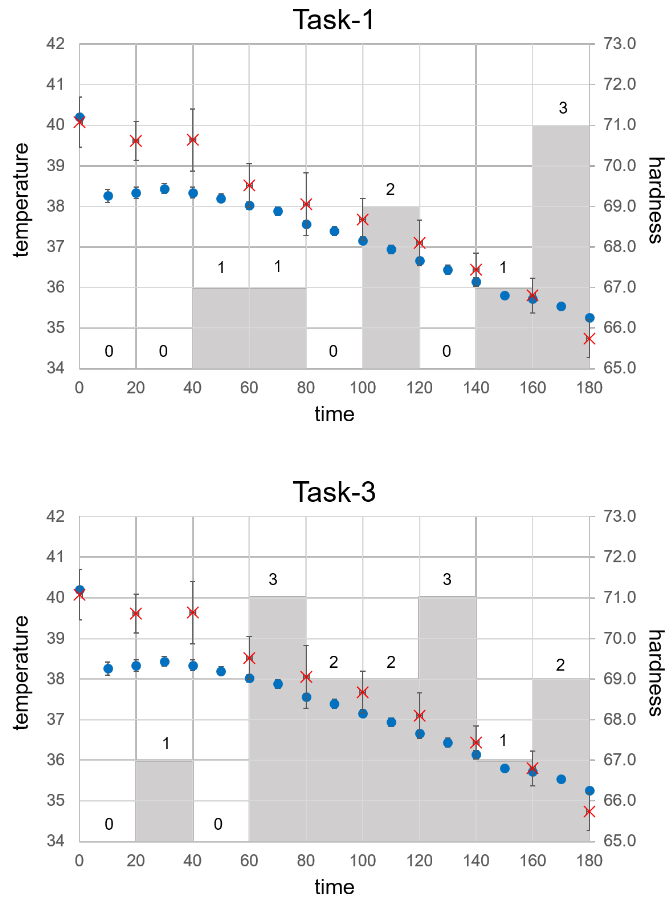

Fig. 9. The states (temperature: blue dots and hardness: red Xs) transition of the tentacle, and the number of participants who had declared that they felt that the softness of the tentacle was changed in the corresponding time window in task-1 and task-3.

the hardness of the tentacle surface by using a durometer (TECLOCK GS-744G). The measurement procedure followed the protocol of task-1 (Section VI-B): initially, we heated and kept the gel at 40 °C, and then measurement started with an experimenter pushed the tentacle surface by his thumb (to simulate the user tests). The blue dots in Fig. 9 show temperature values (Celsius)[1] and the red Xs show the hardness values measured by the durometer. In the background, bar charts representing the number of participants who raised their hand during the corresponding time window are presented (task-1 and task-3).

The results show that the hardness overall followed the temperature change as we expected; however, it was again observed that human judgments estimated by their raise-hand behaviors are diverse. It was also observed that in task-3 in which participants were given the condition-type information beforehand, they tended to become sensitive to and report the softness change earlier than the case (task-1) in which no such information was provided.

[1]The temperature values at 10-20 seconds had been affected by the skin temperature of the experimenter thus showed a temporal sharp decrease.

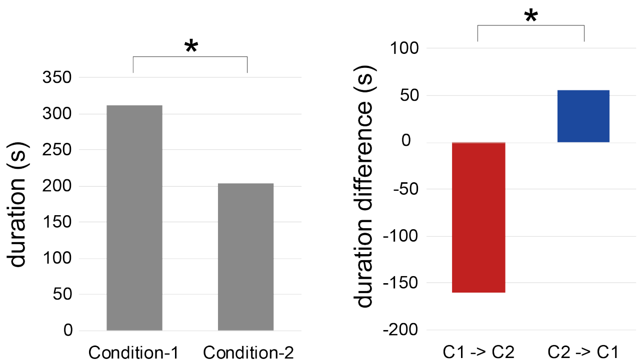

Fig. 10. Duration analyses (task-2). (Left) comparison between condition-1 (variable-softness) and condition-2 (constant-softness). (Right) the growth/decay of the duration across the two conditions. 'C1->C2' denotes the group where condition-1 was performed first.

C. Duration of interaction

Fig. 10 shows the results of task-2 (free-play session). The participants played with the robot significantly longer in condition-1 (variable-softness) than in condition-2 (constant-softness) ($t(9) = 2.335$, $p < 0.05$, $r = 0.62$).

We also analyzed the growth/decay of interaction time across the two conditions. The red bar in Fig. 10 (right) shows that in the participants group where condition-1 was performed first, their average interaction time in condition-2 was shorter (-159.8 seconds) than the case with the condition-1. On the other hand, the blue bar shows that in the participants group where condition-2 came first, their interaction time in condition-1 was longer (+55.6 seconds) than the case with the condition-2. The difference between the two time differences was statistically significant ($t(8) = 2.376$, $p < 0.05$, $r = 0.64$).

Both the results suggest that the participants may have been more interested in the variable-softness condition than the constant-softness condition.

D. General discussion

The results told us the complexity and difficulty of measuring human perception of softness. Judging from the data obtained by the durometer, we consider that the robot overall functioned as we expected. However, the effect has not yet been so clear. We confirmed that some participants who were confident of recognizing the softness change provided us with positive comments and prospects. However, there were also participants who could not distinguish the two conditions. The duration analyses in task-2 showed relatively clean results that support the basic assumption of this study. On the other hand, in the user tests reported in this paper, we gave rich instructions to the participants, which soiled the ecological validity of the interaction.

As a material providing variable softness, thermoresponsive hydrogels have several merits. However, as the participant's comment suggested (Section VII-A), the property may not always be consistent with human natural notion or intuition, which has to be taken into consideration when we design a variable-softness social robot.

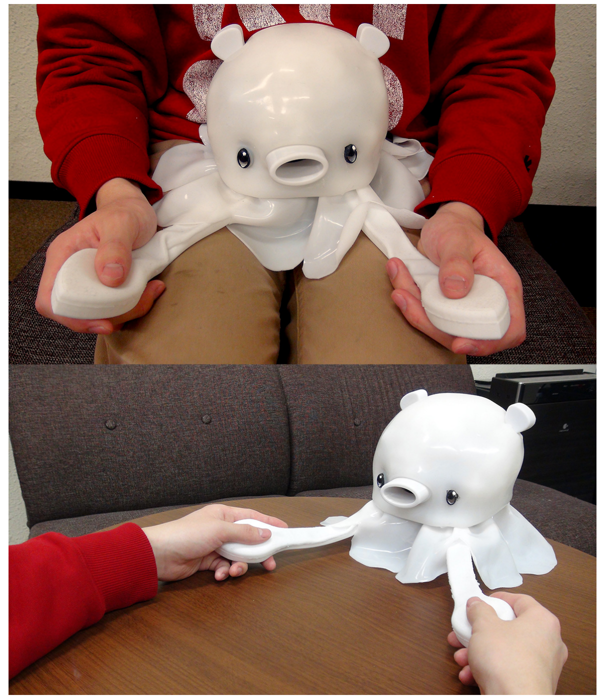

Fig. 11. The fourth prototype of a variable-softness social robot that is an extension of the third prototype (Fig. 6).

E. Next step

We would need a more natural interaction setting to study the effect of introducing a variable-softness social robot. Based on this consideration, we further created the fourth prototype (Fig. 11) that is an extension of the third prototype, being covered with a silicone exterior.

Our next step is to plan for a field test in a more natural and longitudinal setting than the tests reported in this paper. We will bring specific interaction scenarios and test the robot.

VIII. Conclusion

To create a variable-softness social robot, we examined the use of thermoresponsive hydrogels. Starting from prototyping a texture unit where we explored a suitable chemical composition, we created robot prototypes and reported the design process. User tests were conducted in a laboratory setting. Although we confirmed the functioning of the robot, the results showed a difficulty of measuring human softness perception. At the same time, the results showed the feasibility of this study, which shows prospects. The participants who perceived changes in the robot's softness were enthusiastic about the contact. The average interaction duration with such a robot was longer than the case with a constant-softness robot.

Acknowledgment

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References

[1] W. D. Stiehl, J. Lieberman, C. Breazeal, L. Basel, L. Lalla, and M. Wolf, "Design of a therapeutic robotic companion for relational, affective touch," in *Proceedings of the IEEE International Workshop on Robot and Human Interactive Communication*. IEEE, 2005, pp. 408–415.

[2] T. Saito, T. Shibata, K. Wada, and K. Tanie, "Relationship between interaction with the mental commit robot and change of stress reaction of the elderly," in *Proceedings of the 2003 IEEE International Symposium on Computational Intelligence in Robotics and Automation*. IEEE, 2003, pp. 119–124.

[3] K. Wada and T. Shibata, "Robot therapy in a care house - its sociopsychological and physiological effects on the residents," in *Proceedings of the 2006 IEEE International Conference on Robotics and Automation*. IEEE, 2006, pp. 3966–3971.

[4] R. Gockley, A. Bruce, J. Forlizzi, M. Michalowski, A. Mundell, S. Rosenthal, B. Sellner, R. Simmons, K. Snipes, A. C. Schultz, and J. Wang, "Designing robots for long-term social interaction," in *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 2005, pp. 2199–2204.

[5] F. Tanaka, J. R. Movellan, B. Fortenberry, and K. Aisaka, "Daily HRI evaluation at a classroom environment: Reports from dance interaction experiments," in *Proceedings of the 1st ACM SIGCHI/SIGART Conference on Human-Robot Interaction*. ACM, 2006, pp. 3–9.

[6] M. M. de Graaf, S. B. Allouch, and J. A. van Dijk, "Long-term acceptance of social robots in domestic environments: Insights from a user's perspective," in *Proceedings of the 2016 AAAI Spring Symposium Series: Enabling Computing Research in Socially Intelligent Human-Robot Interaction*. AAAI, 2016, pp. 96–103.

[7] Y. Hu and G. Hoffman, "Using skin texture change to design emotion expression in social robots," in *Proceedings of the 14th ACM/IEEE International Conference on Human-Robot Interaction*. IEEE, 2019, pp. 2–10.

[8] F. Sebastian, Q. Fu, M. Santello, and P. Polygerinos, "Soft robotic haptic interface with variable stiffness for rehabilitation of neurologically impaired hand function," *Frontiers in Robotics and AI*, vol. 4, no. 69, 2017.

[9] V. Miruchna, R. Walter, D. Lindlbauer, M. Lehmann, R. Von Klitzing, and J. Müller, "Geltouch: Localized tactile feedback through thin, programmable gel," in *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*. ACM, 2015, pp. 3–10.

[10] H.-L. C. Kao, M. Bamforth, D. Kim, and C. Schmandt, "Skinmorph: texture-tunable on-skin interface through thin, programmable gel," in *Proceedings of the 2018 ACM International Symposium on Wearable Computers*. ACM, 2018, pp. 196–203.

[11] (2004) Mental commitment robot, PARO. [Online]. Available: http://www.paro.jp/english/

[12] S. Jeong, C. Breazeal, D. Logan, and P. Weinstock, "Huggable: The impact of embodiment on promoting socio-emotional interactions for young pediatric inpatients," in *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, 2018.

[13] S. Yohanan and K. E. MacLean, "A tool to study affective touch: Goals & design of the haptic creature," in *CHI '09 Extended Abstracts on Human Factors in Computing Systems*. ACM, 2009, pp. 4153–4158.

[14] ——, "Design and assessment of the haptic creature's affect display," in *Proceedings of the 6th ACM/IEEE International Conference on Human-Robot Interaction*. ACM, 2011, pp. 473–480.

[15] H. Sumioka, A. Nakae, R. Kanai, and H. Ishiguro, "Huggable communication medium decreases cortisol levels," *Scientific Reports*, vol. 3, no. 3034, 2013.

[16] R. Hayashi, "Development of therapeutic robots extracting the stress relaxation effect focused on the tactile sensation," Ph.D. dissertation, Nagoya Institute of Technology, 2018.

[17] J. Nagase, S. Wakimoto, T. Satoh, N. Saga, and K. Suzumori, "Design of a variable-stiffness robotic hand using pneumatic soft rubber actuators," *Smart Materials and Structures*, vol. 20, no. 10, p. 105015, 2011.

[18] J. R. Amend, E. Brown, N. Rodenberg, H. M. Jaeger, and H. Lipson, "A positive pressure universal gripper based on the jamming of granular material," *IEEE Transactions on Robotics*, vol. 28, no. 2, pp. 341–350, 2012.

[19] Y. Jansen, T. Karrer, and J. Borchers, "Mudpad: Tactile feedback and haptic texture overlay for touch surfaces," in *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces*. ACM, 2010, pp. 11–14.

[20] A. Mazzone, R. Zhang, and A. Kunz, "Novel actuators for haptic displays based on electroactive polymers," in *Proceedings of the ACM Symposium on Virtual Reality Software and Technology*. ACM, 2003, pp. 196–204.

[21] H. Banerjee, M. Suhail, and H. Ren, "Hydrogel actuators and sensors for biomedical soft robots: Brief overview with impending challenges," *Biomimetics (Basel)*, vol. 3, no. 3, pp. 1–41, 2018.

[22] M. Calisti, M. Giorelli, G. Levy, B. Mazzolai, B. Hochner, C. Laschi, and P. Dario, "An octopus-bioinspired solution to movement and manipulation for soft robots," *Bioinspiration & Biomimetics*, vol. 6, no. 3, p. 036002, 2011.

[23] C. Laschi, M. Cianchetti, B. Mazzolai, L. Margheri, M. Follador, and P. Dario, "Soft robot arm inspired by the octopus," *Advanced Robotics*, vol. 26, no. 7, pp. 709–727, 2012.

[24] D. Peña and F. Tanaka, "Validation of the design of a robot to study the thermo-emotional expression," in *Ge S. et al. (eds) Social Robotics. ICSR 2018. Lecture Notes in Computer Science, vol.11357.* Springer, Cham, 2018, pp. 75–85.

[25] J. Nie, M. Park, A. L. Marin, and S. S. Sundar, "Can you hold my hand?: Physical warmth in human-robot interaction," in *Proceedings of the 7th ACM/IEEE International Conference on Human-Robot Interaction*. ACM, 2012, pp. 201–202.