2024 IEEE International Conference on Robotics and Automation (ICRA 2024)
May 13-17, 2024. Yokohama, Japan

WARABI Hand: Five-fingered Robotic Hand with Flexible Skin and Force Sensors for Social Interaction

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***Abstract*— A robotic hand for social interaction should be capable of comfortable touch with humans. However, it is difficult to mount skin, tactile sensors, and driving mechanism required for human contact, especially holding hands, on a slender finger. In addition, in order to unitize the hand for easy use with any robot and maintainability, the mechanism must be contained within the small space of the fingers and palms. In this paper, we propose a human-sized five-fingered robotic hand named WARABI Hand. It is covered with multi-layored rubber skin to realize human-like soft and pleasant feel. Force sensors on each finger link detect contact with humans and adjust gripping force. We conducted experiments in which a humanoid equipped with WARABI Hand grasped forearm, held hands, and interlocked fingers with a person. The performance for object grasping was also evaluated. We demonstrated that our proposed hand is useful for interaction with humans including receiving and handing over things.**

I. INTRODUCTION

Based on the fact that human-to-human contact has positive psychological effects [1]–[3], social touch between robots and humans has been studied [4]–[7]. Hand contact between humans has been shown to reduce pain [8] and increase appreciation of the partner [9]. Hand contact between robots and humans has been shown to have psychological benefits such as stress reduction [10]–[14].

Hand-holding between a robot and a person requires four elements (Chapter 2): A. Human-like soft and slender fingers, B. Tactile sense to know the state of contact with a person, C. Degree of freedom for wrapping a human hand, and D. Robot-independent compact hand. Five-fingered hands that mimic human hands and enable complex movements have been studied [15]–[17]. Some hands are designed for human contact, such as for massage and for holding hands [18]–[20].

However, no one has achieved both of the above four elements in the limited space of a hand, including an upper limb. In this study, we propose "WARABI" Hand for physical contact with humans. In particular, in order to conduct hand-holding with a person, a slender finger with tactile sense and flexible skin was developed by routing cables inside its finger. The hand-holding motion was realized with a minimum number of actuators by determining the degrees of freedom necessary for it. We show the effectiveness of our hand by evaluating its performance in object grasping experiments and by demonstrating holding hands with a human.

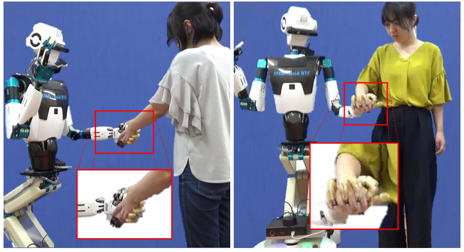

Fig. 1. A robot holds hands with a human in various ways by WARABI Hand. Shaking hands and interlocking fingers.

II. DESIGN PHILOSOPHY OF WARABI HAND

WARABI Hand is an acronym representing:

- W: **W**arm-hearted
- A: **A**nthropomorphic
- R: **R**ubber skin
- A: **A**nshin (peace of mind in Japanese)
- B: Adjusta**B**le to human
- I: **I**ntimate touch

Each word represents the design concept of this hand, which is described below. The name "WARABI" also contains our wish for pleasant touch of the hand as "warabi-mochi", the Japanese jelly-like confection.

A. Human-like Soft and Slender Fingers

For a robotic hand to interact with humans, its appearance that people want to touch is important. In our previous study, we investigated the impression of a robotic hand with no exterior [21]. Negative comments about hand-holding included that the hand seemed stiff and might squeeze the human hand. If skeleton is bare and rugged, people may hesitate to touch it. In order to avoid causing pain when touching a person, it is important that the hand has soft flesh that easily deforms. The deformation increases the contact area and distributes the contact pressure. Human skin tissue consists of three layers: epidermis, dermis, and subcutaneous tissue. The closer to the surface, the stiffer and the coefficient of longitudinal elasticity is larger [22]. Human epidermis has low adhesiveness and a fine mesh-like groove. This surface texture is thought to provide moderate skin friction. From the above, we considered that an exterior consisting of soft flesh that can deform to the contact surface and hard and slippery textured skin that limits deformation and protects the flesh would provide a comfortable touch. We designed the soft skin as humans and the outer shell made of curved surfaces (Fig. 2).

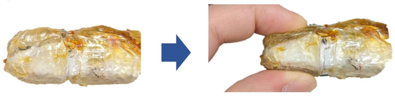

Fig. 2. Soft rubber skin. The surface is deformed when pressed with a human finger.

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TABLE I
COMPARISON AMONG PREVIOUS ROBOTIC HANDS

		Hirose's hand [18]	Ueno's hand [19]	Shadow Dexterous Hand [15]	ALPHA [17]	Gifu Hand Ⅲ [16]	WARABI Hand
A	Skin	✓ silicone rubber	✓ urethane gel, glove + warmth	-	-	-	✓ multi-layered rubber, soft and pleasant touch
	Finger slenderness	34 mm	✓ -	20 mm	18.6mm (estimated)	18 mm	✓ 18.2mm
B	Tactile sense	✓ proximity and force of each half of a finger	pressure at 3 pts.	✓ joint position, tension, pressure at fingertips	✓ motor encoders	✓ motor encoders pressure at 859 pts.	✓ pressure sensor at each finger link, wired inside finger
C	Dexterousness	spring multi-articulated tendon drive with variable stiffness	✓ tendon drive with 5 pneumatic artificial muscles	✓ tendon drive with 20 motors for 24 joints	✓ 8 motors for 16 joints, linkage+underactuated tendon	16 motors for 20 joints, linkage	✓ tendon drive with 8 motors for 20 joints, underactuated
D	Overall size	✓ Hand + wrist	Hand + forearm	Hand + forearm	✓ Hand + wrist	✓ Hand	✓ Hand

A hand with the same shape as that of a human hand promotes hand-to-hand interactions, such as interlocking fingers with a human. We aimed for a hand with five fingers and the same thickness and length as that of a human hand.

B. Tactile Sense

The robotic hand controls the contact force when it comes into contact with humans in order to avoid hurting them. Therefore, the hand must sense not only whether it is touching or not, but also the force applied to the contact surface. For example, when holding a person's hand, the fingers are considered to be sufficiently flexed if the force is applied to the fingertips. To detect that a person is about to touch the robotic hand, the force may be applied first near the palm of the hand, rather than at the fingertips. Therefore, we considered that force sensors were needed on the belly of each link of the fingers.

When a rigid sensor is used, it will be installed under the soft skin. The force on top of the skin should be transmitted to the sensor.

C. Degree of Freedom for Wrapping A Human Hand

The dexterous finger mechanism allows a robot to actively wrap around a person's hand or arm. Especially, the thumb exerts force from a different direction from that applied by the tips of other four fingers. It prevents the grasped object from being dropped or rotated. In order to grasp an object stably, the thumb must be able to change its posture and to face the other four fingers. The ability of the robot for grasping makes it possible to pass the object to and from a person.

D. Robot-independent Compact Hand

A mechanism that takes up little space and fits in the hand has the advantage of being easily attached to an existing robot. This makes it possible to interact with any robot and improves maintainability. In addition, the small size of the hand allows a robot to move the hand freely in a human living space. It reduces the risk of hitting the hand against surrounding objects or people.

III. RELATED WORK

Although there are notable technologies in previous studies, it is difficult to compactly fit a drive mechanism into a hand and to realize a slender finger with sensors and skin. Table I shows the specifications of WARABI Hand and hands in the previous studies.

Hirose et al. [18] has developed a robotic hand covered with flexible silicon skin. By selectively changing the degrees of freedom of the finger joints, the hand switches between dispersion and concentration of contact pressure. Coil springs built into the finger enable sensing of human proximity and contact force. The robot has three thick fingers for the purpose of massaging a human and washing human hair. Ueno et al. [19] proposes a warm hand that mimics human-to-human contact. It has gradations of flesh's softness and bone's hardness and wears a latex rubber glove. Pneumatic artificial muscles are placed in the forearm. Our hands are coated with latex solution on the surface and allowed to dry in order to make a low-moisture, slippery texture. Shadow Dexterous Hand [15] has 24 tendon-driven joints. It is capable of complex human-like movements such as handling tools. Twenty actuators are located outside the hand and makes the hand quite heavy. ALPHA [17] has self-adapdaple and under-actuated mechanisms in parallel. It enables hand gestures and object shape adaptation. The size is confined to the wrist because of fewer actuators for more degrees of freedom. Gifu Hand Ⅲ [16] has sixteen actuators mounted in the palm. Distributed tactile sensors can measure 859 contact forces of the palm and fingers. The fingers of ALPHA and Gifu Hand Ⅲ are considered to be thicker than a human's when skin is attached.

WARABI Hand was designed to have the functions necessary for human contact, yet be thin enough to interlock fingers with a person and easily attachable to existing robots. A multi-layered rubber skin with the softness and human-like feel was covered on the fingers. Force sensors were attached to each link of the fingers by wiring cables into the fingers. By using underactuated tendon drive mechanism, the actuators fit into a compact hand that ends at the wrist.

IV. SPECIFICATION OF WARABI HAND

A. Overview

Fig. 3 shows an overview of WARABI Hand. Each finger is equipped with force sensors over the skeleton and covered with rubber skin. The length and thickness of the fingers are about the same as those of a human. The total weight of the hand is about 320 g.

The structure of the skeleton excluding the skin is shown in Fig. 4. It was 3D printed in Acrylonitrile-butadiene-styrene (ABS) resin. It consists of an outer shell which imitates human palm and back of the hand, five fingers (thumb, index, middle, ring, little), and a wrist for attachment to the robot's arm. A total of 20 DOFs are driven by eight actuators.

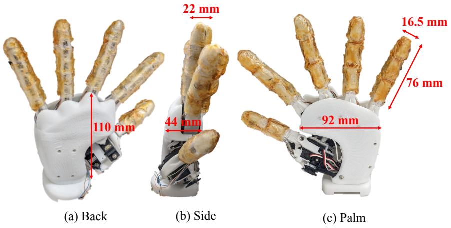
Fig. 5 shows a diagram of the overall system. The fingers are actuated by eight servo motors using microcontroller (Espressif Systems, ESP32-WROOM-32E). The voltage values between the 14 sensors attached to the fingers are obtained with voltage divider circuits in between. It communicates with external computer via bluetooth. Rosserial is used to exchange sensor data and command value of the servo motors.

B. Underactuated Finger Module

The four fingers except the thumb are the same module shown in Fig. 6. MCP1 joint connected to the outer shell does abduction and adduction motion by a micro servo motor (Futaba Corp., S3110M). A piece of rope made of ultra high molecular weight polyethylene fiber (Hayami Industry Co., Ltd., DB-16) runs through the skeleton as a tendon. When this rope is pulled in the direction of the arrow, DIP, PIP, and MCP0 joints rotate and flex. When it is loosened, the joints are extended by coil springs attached to each joint on the back side of the finger, and then return to their original position.

The ropes passing through the four fingers are connected two by two as shown in Fig. 7. The two ropes are pulled together by a metal loop through the ropes and wound by a pulley. The pulley is driven by a servo motor (Kondo Kagaku Co., Ltd., KRS-2572R2HV ICS).

Cables extending from the force sensors enter the central path through holes in the upper part. A total of six cables per finger are routed to the wrist.



(a) Back (b) Side (c) Palm

Fig. 3. WARABI Hand's dimentions.

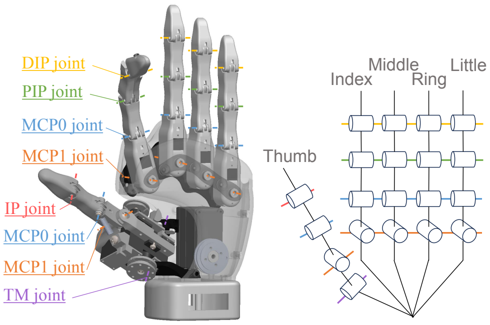


Fig. 4. Joint configuration of WARABI Hand.

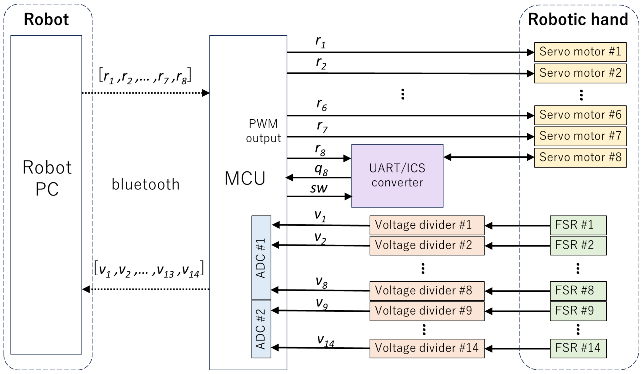


Fig. 5. System diagram. MCU sends target angles to eight servo motors and reads the voltages of fourteen sensors. Program executed on the robot's PC commands angles to MCU via bluetooth according to the sensor values.

C. Four Degree of Freedom Thumb

Fig. 8 shows the structure of the thumb. It is connected to the outer shell by TM joint. The bottom servo motor (Futaba Corp., S3103) flexes and extends the joint. The middle servo motor (Futaba Corp., S3103) adducts MCP1 joint as shown in Fig. 8(a). A pulley winds the rope attached to the finger. When the rope is loosened, a spring abducts the joint. IP joint and MCP0 joint are flexed and extended by the same tendon-driven and spring mechanism as the other four fingers described in the previous section (Fig. 8(b)). The pulley is wound by the top motor (Futaba Corp., S5102).

D. Human-like Multilayered Rubber Skin

As described in Chapter 3, soft flesh and the epidermis that envelops it are important to achieve a force sensation of human skin. We wrapped the finger skeleton and force sensors in multilayered rubber skin.

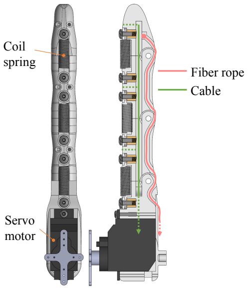


Fig. 6. Skeletal structure of a finger module. Cable for sensors and rope for tendon drive run through it.

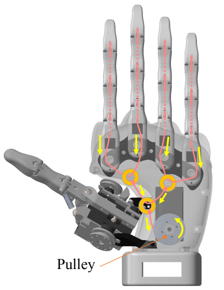
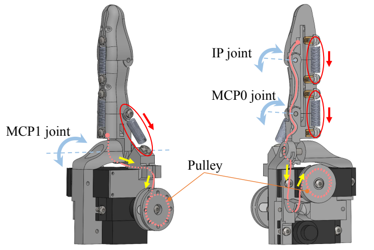


Fig. 7. Underactuated flexing mechanism. The rope is reeled in by a pulley.



(a) (b)

Fig. 8. Thumb structure. (a) Tendon-driven adduction and spring-driven abduction. (b) Tendon-driven flexion and spring-driven extension.

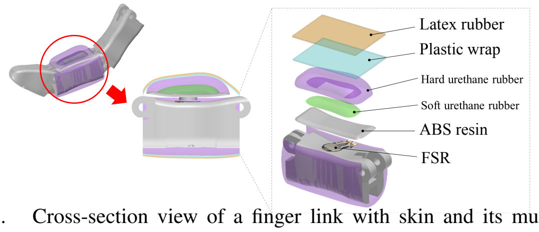


Fig. 9. Cross-section view of a finger link with skin and its multilayor structure.

Fig. 9 shows the structure of a part of the finger. The innermost flesh layer is made of two different urethane rubber. The urethane sealed in the belly of the finger is so soft that it is easy to lose shape. Its deformation is suppressed by a little harder urethane, which used for the outside of the belly and the back side of the finger. This two-layered structure allows the finger belly to be both thick and soft. The surface of the urethane rubber is very sticky, so it is coated with latex. The gaps between the flesh and the skeleton are covered with plastic wrap to prevent the latex from entering.

Fig. 10 shows the detailed fabrication process. First, the upper and lower flesh of the finger is molded separately and glued to each skeleton link of the finger. The mold cavities are 3D printed. They are assembled on one finger and the whole finger is wrapped in plastic wrap. It is coated with liquid latex and dries for a few days. The surface is no longer sticky and becomes comfortable to the touch.

E. Tactile Mechanism Using Force Sensors

Force-sensing resister (FSR) exhibits a decrease in resistance with increase in force applied to the surface of the sensor. Fourteen FSR (Interlink Electronics, FSR 400 Short) are used to measure the force applied when the robotic hand comes into contact with the outside world. Forces of 20-2039 g can be measured over an area of 5.08 mm in diameter. The weight of a human finger on a scale was measured to be approximately 20 g. Considering that the rubber skin prevents the force transmission, we thought that the force sensitivity range would be enough to detect a person's soft touch.

Fig. 11 shows the arrangement of the sensors attached to the hand. As shown in Fig. 9, a board with a projection is placed between the sensors and the rubber skin. Since the reaction region of the sensor is small, this projection limits the contact area between the skeleton and the skin to just above the sensor.

In the experiments, sensors were used to detect contact and to adjust the force of flexion. A contact is considered to have occurred when force of 1.04 g or more is applied to one or more sensors. When gripping something, flexion was stopped when force of 1.04 g or more was applied to one of the fingertip sensors (e.g. middle_dp).

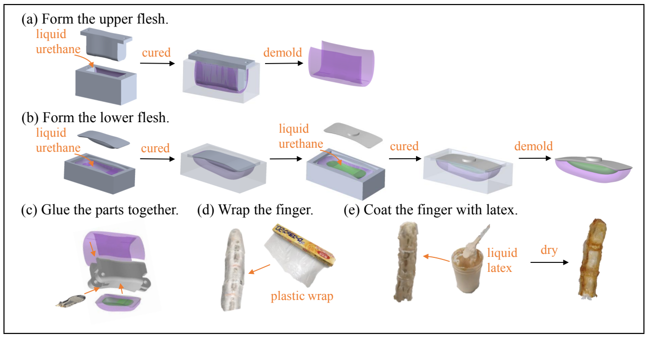


Fig. 10. Fabrication process of the rubber skin. (a) Pour urethane rubber liquid into the mold and let it cured to make the flesh on the finger's back. (b) Pour two types of urethane rubber liquid into the mold and let it cured in sequence to make the flesh on the front of the finger. (c) Glue FSR and the flesh on both sides to the finger skeleton. (d) Wrap the assembled fingers in plastic wrap. (e) Apply latex to the fingers and allow it to dry.

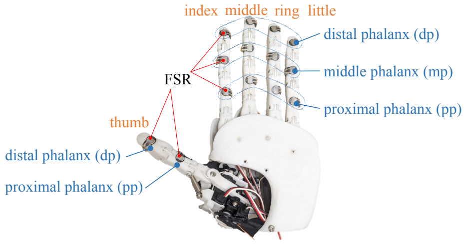


Fig. 11. Arrangement of force sensors in the balls of the fingers.

V. EXPERIMENTS

We applied WARABI Hand to a humanoid robot Seed-Noid (THK Co., Ltd.) and conducted five experiments. The hand was attached to the left arm of the robot. The graphs show the force applied to fsr, and the labels correspond to the finger names and the link names in Fig. 11.

A. Gripping a Person's Forearm

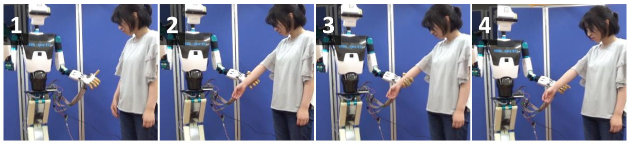
The robot gripped a person's forearm with suitable strength as shown in Fig. 12. The person put their arm in front of WARABI Hand and the robot moved the hand closer to them. Contact was detected when force was applied to middle_pp. Then, the robot gripped the forearm by flexing the fingers until force was applied to index_dp and middle_dp. After a while, the robot opened the hand and no more force is put on any of the sensors.

B. Interlocking Fingers with a Person

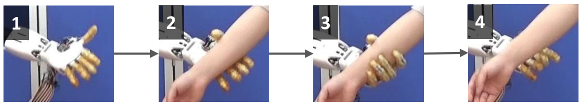
The robot and a person interlocked their fingers as shown in Fig. 13. First, the robot outstretched WARABI Hand toward them. The person placed their hand on it and it was detected by force on ring_pp, ring_mp and little_mp. The robot opened the space between the fingers and flexed them until force was applied to middle_dp. After the robot interlocked its fingers alternately with the person's, it escoated her forward. Finally, it let go of the person's hand.

C. Shaking Hands with a Person

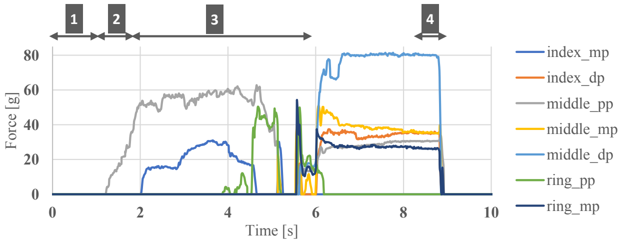
The robot and a person shook hands as shown in Fig. 14. The robot bowed to them and then held out WARABI Hand.



(a) Overall view



(b) Enlarged view of the hand



(c) Force on each finger link

Fig. 12. Experiment of gripping a person's forearm. The chart legend corresponds to the sensor positions in Fig. 11. (1) The robot holds out WARABI Hand. (2) It presses the hand against the person's arm until middle_pp reacts. (3) It flexes its fingers until index_dp and middle_dp react. (4) It releases the person's arm.

She put her hand against it and force on middle_pp was detected. The robot flexed the fingers until force was applied to middle_dp. They held each other's hands and shook them up and down. Then the robot released the person's hand.

D. Picking Up a Piece of Paper

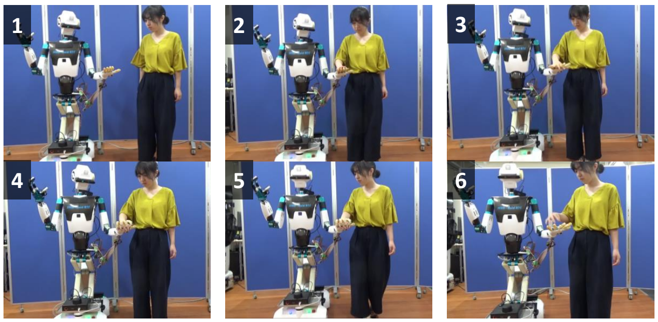
The robot picked a piece of paper placed on the desk as shown in Fig. 15. First, the robot lowered WARABI Hand toward the paper. When it held it with the thumb, it flexed its fingers and picked the paper. The robot did not drop the paper when it raised the hand.

E. Shaking a Bottle

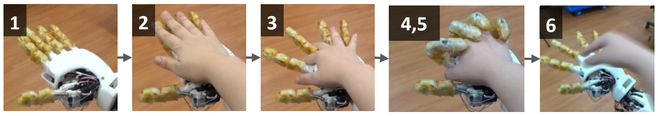
The robot shook the PET bottle as shown in Fig. 16. First, the robot held out WARABI Hand. The person places the PET bottle on the robot's hand. It was detected by force applied to middle_pp. The robot flexed the fingers until force was applied to middle_dp. Next, the bottle was turned vertically and shaken up and down. When the person pulled on the bottle after that, the robot detected it by force on middle_pp and ring_pp. It took the hand off the bottle and handed it to the person.

VI. DISCUSSION

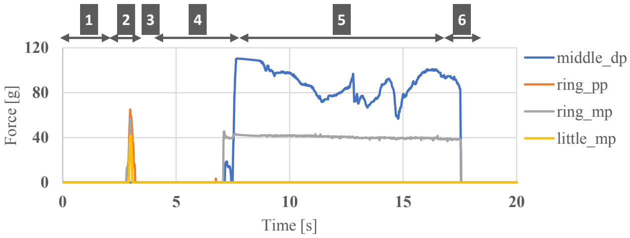
In the experiment, the robot was able to adjust the force of gripping the person and objects by detecting contact to the outside with sensors. The robot stops flexing when the sensors react, which prevents it from gripping with more force than necessary. Additionally, if the robot has proximity sensors, it can predict a person's movement not only after contact, but also before contact. It can also detect motion in the shear direction, which is undetectable with our force sensors. By detecting the minute rubbing of the skin surface, the robot and a human simultaneously try to hold hands in accordance with the other's movement. More human-like hand holding with a sense of security can be expected.



(a) Overall view



(b) Enlarged view of the hand

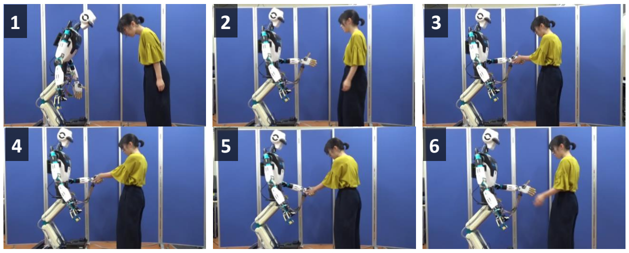


(c) Force on each finger link

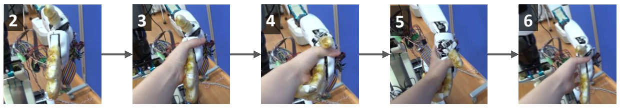
Fig. 13. Experiment of interlocking fingers with a person. The chart legend corresponds to the sensor positions in Fig. 11. (1) The robot holds out WARABI Hand. (2) The person places their hand on it. (3) The robot opens its hand when ring_pp, ring_mp and little_mp react. (4) It flexes its fingers until middle_dp reacts. (5) They move forward with holding hands. (6) The robot releases the person's hand.

Sensor values in the experiment showed that the sensors of the middle and ring fingers were more reactive. It was sufficient to get the contact of any of the fingers for a four-finger grasping. However, the response of the other fingers is sometimes necessary for various interactions, such as pinky swear. One reason for differences in reactivity may be that the ropes for flexing were subjected to more force than the ropes of the other fingers. Since the diameter of the human arm and the bottle used in the experiment was small, the ropes of all fingers were able to flex under the force applied to them. If the length and the way of connecting the ropes of each finger are adjusted, it will become possible to flex the fingers slightly with a small force, such as stroking a person's head. Another cause may be that the force transmission was not constant due to differences in the way the sensors are attached in the fabrication process, or due to changes in the skin condition during repeated grasping. Information processing that can flexibly cope with such uncertainties is necessary when using sensor values. Humans can feel the softness of an object even when wearing gloves. As time goes by, they become accustomed to the gloves and even forget that they are wearing them. It is thought that humans are constantly calibrating themselves by using their physical and visual senses, such as making a tight fist, interlocking fingers, and touching objects they know the feel of. The robot hand can also respond to changes in reactivity by regularly touching certain objects like its own body.

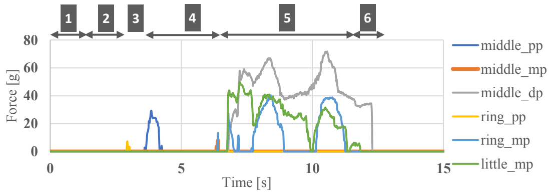
In the paper picking experiment, it was found that if the



(a) Overall view

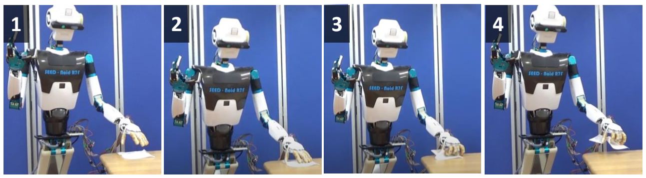


(b) Enlarged view of the hand

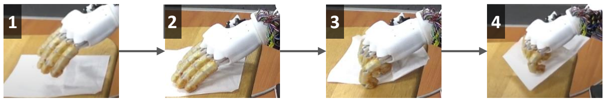


(c) Force on each finger link

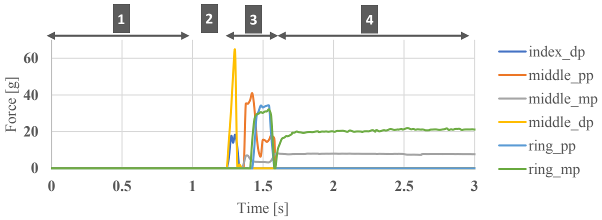
Fig. 14. Experiment of shaking hands with a person. The chart legend corresponds to the sensor positions in Fig. 11. (1) The robot takes a bow. (2) It holds out WARABI Hand. (3) The person puts their hand against it. (4) When middle_pp reacts, the robot starts flexing its fingers. (5) After middle_pp reacts, it shakes its hand up and down twice. (6) It releases the person's hand.



(a) Overall view



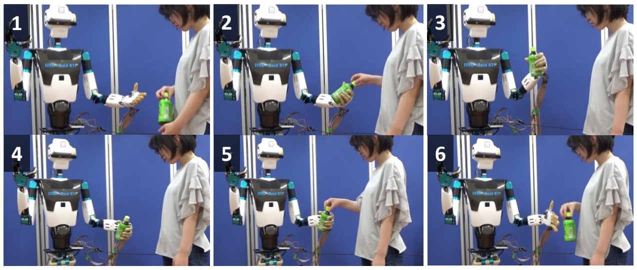
(b) Enlarged view of the hand



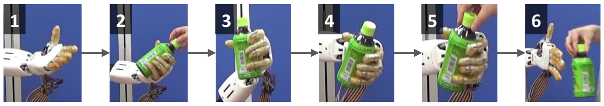
(c) Force on each finger link

Fig. 15. Experiment of picking up a piece of paper. The chart legend corresponds to the sensor positions in Fig. 11. (1) The robot reaches for the paper. (2) It presses the paper under the thumb. (3) It grasps the paper in the hand. (4) It raises the hand.

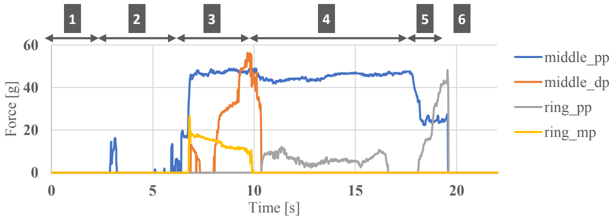
thumb held the paper and the other fingers that slightly touched the paper flexed, friction caused the paper to roll in together and be grasped. However, since the range of motion of this hand's MCP joint is smaller than that of a human, the dorsal side of the thumb touches the paper. When the fingers are pressed against the paper, they naturally flex, making it difficult to adjust the posture while holding the paper down. While the space between the thumb and other fingers was sufficient for grasping small objects, the range of motion of the thumb needs to be further extended in order to successfully apply force to objects that do not fit within the hand. This problem can also be applied to massaging a person's back or picking up clothes to put them on a person.



(a) Overall view



(b) Enlarged view of the hand



(c) Force on each finger link

Fig. 16. Experiment of shaking a bottle. The chart legend corresponds to the sensor positions in Fig. 11. (1) The robot holds out WARABI Hand. (2) The person pushes a bottle into the hand and the robot flexes its fingers until middle_dp reacts. (3) It turns the bottle vertical. (4) It shakes the bottle. (5) The person pulls the bottle held by the robot. (6) The robot opens its hand when middle_pp and ring_pp react.

VII. CONCLUSION

The purpose of this paper is to realize a robot hand that enables a robot to touch and interact, especially hold and interlock hands, with a human. We proposed WARABI Hand, a robot hand with soft and slippery skin that and force sensors that can detect the force applied to the hand. In order to hold hands with a human, the fingers are as slender as a human's. The overall size is kept down to the wrist so that any robot can be used. We attached the hand to an real humanoid and showed that the robot can perform touching behaviors such as grasping forearm, interlocking fingers, and shaking hands. In these actions, the robot was able to detect contact by the changes in the force on sensors. Flexion strength was also adjusted. In addition, we conducted experiments in which the robot grasped a piece of paper and a bottle. It showed that this hand can be used to grasp an object for passing it to and from humans.

Several limitations to this study need to be acknowledged. Firstly, what the person would do in response to the robot's actions was determined. For future work, we plan to mount proximity sensors on the hand to detect human motions even before contact. We believe that hand-holding can be more comfortable and reassuring when the robot and a human are simultaneously adapted to the partner. Secondly, ”soft and pleasant touch” is subjective. We will assess the psychological contribution of our hand with all other basic functions fulfilled and clarify system architecture of robotic hand for social interaction.

REFERENCES

[1] Matthew J Hertenstein, Rachel Holmes, Margaret McCullough, and Dacher Keltner. The communication of emotion via touch. *Emotion*, Vol. 9, No. 4, p. 566, 2009.

[2] Pavel Goldstein, Irit Weissman-Fogel, and Simone G Shamay-Tsoory. The role of touch in regulating inter-partner physiological coupling during empathy for pain. *Scientific reports*, Vol. 7, No. 1, p. 3252, 2017.

[3] Robert-Vincent Joule and Nicolas Guéguen. Touch, compliance, and awareness of tactile contact. *Perceptual and motor skills*, Vol. 104, No. 2, pp. 581–588, 2007.

[4] Marika Hayashi, Takashi Sagisaka, Yui Ishizaka, Tomoaki Yoshikai, and Masayuki Inaba. Development of functional whole-body flesh with distributed three-axis force sensors to enable close interaction by humanoids. In *IROS*, pp. 3610–3615, 2007.

[5] Hideki Kozima, Marek P Michalowski, and Cocoro Nakagawa. Keepon: A playful robot for research, therapy, and entertainment. *IJSR*, Vol. 1, pp. 3–18, 2009.

[6] Alexander Alspach, Joohyung Kim, and Katsu Yamane. Design of a soft upper body robot for physical human-robot interaction. In *Humanoids*, pp. 290–296, 2015.

[7] Mahdi Khoramshahi, Gustav Henriks, Aileen Naef, Seyed Sina Mirrazavi Salehian, Joonyoung Kim, and Aude Billard. Arm-hand motion-force coordination for physical interactions with non-flat surfaces using dynamical systems: Toward compliant robotic massage. In *ICRA*, pp. 4724–4730, 2020.

[8] Pavel Goldstein, Irit Weissman-Fogel, Guillaume Dumas, and Simone G Shamay-Tsoory. Brain-to-brain coupling during handholding is associated with pain reduction. *PNAS*, Vol. 115, No. 11, pp. E2528–E2537, 2018.

[9] Jeffrey D Fisher, Marvin Rytting, and Richard Heslin. Hands touching hands: Affective and evaluative effects of an interpersonal touch. *Sociometry*, pp. 416–421, 1976.

[10] Tiffany L Chen, Chih-Hung King, Andrea L Thomaz, and Charles C Kemp. Touched by a robot: An investigation of subjective responses to robot-initiated touch. In *HRI*, pp. 457–464, 2011.

[11] Masahiro Shiomi, Kayako Nakagawa, Kazuhiko Shinozawa, Reo Matsumura, Hiroshi Ishiguro, and Norihiro Hagita. Does a robot's touch encourage human effort? *IJSR*, Vol. 9, No. 1, pp. 5–15, 2017.

[12] Chie Hieida, Kasumi Abe, Takayuki Nagai, and Takashi Omori. Walking hand-in-hand helps relationship building between child and robot. *JRM*, Vol. 32, No. 1, pp. 8–20, 2020.

[13] Kazuko Itoh, Hiroyasu Miwa, Yuko Nukariya, Massimiliano Zecca, Hideaki Takanobu, Stefano Roccella, Maria Chiara Carrozza, Paolo Dario, and Atsuo Takanishi. Development of a bioinstrumentation system in the interaction between a human and a robot. In *IROS*, pp. 2620–2625, 2006.

[14] Joao Avelino, Filipa Correia, Joao Catarino, Pedro Ribeiro, Plinio Moreno, Alexandre Bernardino, and Ana Paiva. The power of a handshake in human-robot interactions. In *IROS*, pp. 1864–1869, 2018.

[15] Shadow Robot. Shadow Dexterous Hand Technical Specification. `https://www.shadowrobot.com/wp-content/uploads/2022/03/shadow_dexterous_hand_e_technical_specification.pdf`, (accessed Aug. 23, 2023).

[16] Tetsuya Mouri, Haruhisa Kawasaki, Keisuke Yoshikawa, Jun Takai, and Satoshi Ito. Anthropomorphic robot hand: Gifu hand iii. *ICCAS*, pp. 1288–1293, 2002.

[17] Giulio Cerruti, Damien Chablat, David Gouaillier, and Sophie Sakka. Alpha: A hybrid self-adaptable hand for a social humanoid robot. In *IROS*, pp. 900–906, 2016.

[18] Toshinori Hirose, Shingo Kitagawa, Shun Hasegawa, Yohei Kakiuchi, Kei Okada, and Masayuki Inaba. Waterproof soft robot hand with variable stiffness wiredriven finger mechanism using low melting point alloy for contact pressuredistribution and concentration. In *RoboSoft*, pp. 109–116, 2022.

[19] Azumi Ueno, Ikuo Mizuuchi, and Yukio Morooka. Proposal for robot hand and forearm design to reproduce human-to-human physical contact. In *ROBIO*, pp. 971–976, 2019.

[20] Alexander Alspach, Joohyung Kim, and Katsu Yamane. Design and fabrication of a soft robotic hand and arm system. In *RoboSoft*, pp. 369–375, 2018.

[21] Aoi Nakane, Iori Yanokura, Aiko Ichikura, Kei Okada, and Masayuki Inaba. Development of robot guidance system using hand-holding with human and measurement of psychological security. In *RO-MAN*, p. 0576FI, 2023.

[22] Takashi Maeno, Kazumi Kobayashi, and Nobutoshi Yamazaki. Relationship between the structure of human finger tissue and the location of tactile receptors. *JSME International Journal Series C Mechanical Systems, Machine Elements and Manufacturing*, Vol. 41, No. 1, pp. 94–100, 1998.