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Input Interface Using Wrinkles on Clothes for Wearable Computing

Kentaro Ueda[1,a)] Tsutomu terada[1,2,b)] Masahiko Tsukamoto[1,c)]

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Abstract: Although wearable interfaces can enable computer operation anywhere and at any time, many current devices are too cumbersome or socially unacceptable to wear in daily life. In contrast, a ridge of cloth produces a wrinkle that forms naturally on clothes, and the shape of these wrinkles can be recognized by their tactile sensations. Hence, they can achieve eye-free input and output functions. We therefore propose an interface that uses the wrinkles on clothes to input and output information. The interface generates several wrinkles on an item of clothing when an application requires input. The user senses the current state and number of choices by touching these wrinkles. The user can then input commands by selecting one wrinkle. The wrinkles disappear after the operation is complete. We implemented a prototype of this interface and investigated the social acceptance of the device position. The results show that the various device positions (excluding the armpit) achieve a moderate level of social acceptance. We mounted the prototype on the front of the right thigh of a pair of trousers and evaluated the recognition accuracy of the wrinkle patterns as well as the learning curve with respect to input accuracy and time. The participants achieved a recognition rate of 89.4%, input accuracy of 95% or more, and an input time of approximately 2 s. This device has the potential to provide unobtrusive and eyes-free operation and the current results indicate directions for its future development.

Keywords: wearable computing, input interface, cloth, wrinkle

1. Introduction

Wearable computing technologies enable users to operate computers anywhere and at any time. This change in computing style requires changes in the input methods of computers. When using conventional input interfaces such as a mouse or trackball, the user needs to grasp the device and cannot operate the computer when their hands are busy. Although researchers have proposed several input devices that the user does not need to hold [1], [2], most of these devices use hand gestures. These gestures require unusual movements that people do not often perform in daily life to avoid misrecognition. Hence, the gestures look strange to others in public spaces. There are some small devices that do not require the user to gesture, such as the One-handed Keyboard [3]. However, the user needs to mount these devices on their body, and the user's appearance drastically changes.

In contrast, people wear clothing every day. If input interfaces are integrated into clothing, a user could input information using a natural motion on the clothing such as touching, pinching, folding, and stretching it, without the need to grasp another device. Clothes can present the user with a tactile sensation when he/she touches them, which assists eye-free operation. A tactile sensation can present some information such as the number of input command choices. Although several researchers have investigated input interfaces using clothes for wearable computing [10], [11], [12], these methods do not use tactile sensations to present information and cannot present contexts to users without additional devices such as head mounted displays (HMDs), watch-shaped displays, or vibration motors. Several methods have hence been proposed to deform the shape of the cloth [19], [20]. Because the user can determine the shape by touching the cloth, we can also use it to output information.

This paper proposes a new input interface using wrinkles on clothes. The wrinkles provide a user with information through the tactile sense since the user can recognize their shapes by touch. Wrinkles are naturally formed on clothes in daily use and do not change the user's appearance. The proposed interface generates several wrinkles on clothes in response to the input requirements of an application. The user inputs the command by touching one of these wrinkles, which disappear after the input operation is complete. The user can receive information on the current state of an application from the pattern of wrinkles, which is different from interfaces proposed in other studies.

The remainder of this paper is organized as follows. Section 2 reviews the related work. Section 3 describes the design of our proposed interface, and Section 4 explains the implementation of our prototype. Section 5 describes the evaluation experiment, and Section 6 discusses the problems and potential of the proposed interface. Finally, Section 7 gives the conclusion and outlines future work.

This paper is an extension of the paper published at WISS2014 [21] and ISWC2016 [22]. We added evaluations for the socially acceptable device positions and the recognition of

1 Kobe University, Kobe 657–8501, Japan
2 PRESTO JST, Department of Research Promotion, Research Division, Chiyoda, Tokyo 102–0076, Japan
a) ueda_kentaro@stu.kobe-u.ac.jp
b) tsutomu@eedept.kobe-u.ac.jp
c) tuka@kobe-u.ac.jp

wrinkle patterns.

2. Related Work

2.1 Input Interfaces in Wearable Computing

Trackballs and joysticks are often used as input interfaces in conventional wearable computing environments. In addition, Twiddler [4], which is a mobile one-handed chording keyboard, can be used in wearable computing environments. Its keypad layout is similar to that of a mobile phone, which makes it a potential alternative to text entry on mobile phones. However, users have to hold these devices during operation. Therefore, they cannot operate them when both hands are occupied by other tasks or the available space is limited such as on a crowded train.

Input interfaces that the user does not need to hold have also been studied. Xangle [1] is a pointing device that detects motion using sensors attached to body parts such as the fingertips. WearTrack [2] users wear 3 microphones on their head and point. Information is input to the device by detecting the position of the user's fingertips by ultrasonic triangulation. However, users cannot operate these devices when gazing at a display is difficult (such as when walking). Moreover, users must wear devices on parts of his/her body that are often needed in daily life (such as the fingertips), which means these devices are not always practical.

There have also been studies on input interfaces that employ operations other than pointing. Kuzume [5] implemented an input device using expiration air and tooth-touch sound signals. The user attaches a device that includes a piezo film sensor array in front of his/her mouth and operates it. The One-handed Keyboard [3] is a half-sized keyboard that is made by dividing an existing keyboard into left and right sides. Users can input text with one hand while wearing it on their body. EarPut [6] is a touch interface that is attached to a user's ear. The user touches the ear where the device is attached to operate it. OmniTouch [7] is a wearable depth-sensing and projection system. The user attaches a device consisting of a depth camera and a pico-projector on the shoulder. The user can then use hands, arms, legs, and surrounding objects as graphical interactive surfaces. The Imaginary Phone [8] enables a user to use user's hand as an input surface by tracking using a depth camera. However, users have to attach these devices to their body, which alters their appearance, making them reluctant to use these interfaces in daily life.

2.2 Input Interfaces Using Clothes

Several input interfaces using clothes have been proposed. LilyPad [9] is a microcomputer that can be sewn into clothes and enables clothes and electronics to be combined. Komor et al. [10] implemented an input device in their research on a textile interface using embroidery made of conductive threads and a capacitance circuit. Holleis et al. [11] also implemented several input devices by attaching capacitance sensors to a phone bag, helmet, glove, and apron. Gilliland et al. [12] implemented three input devices that detect a finger touch on embroidery made of conductive threads by measuring the resistance and the capacitance between the embroidery and a finger. FabriTouch [13] is a flexible touch-sensitive fabric that consists of a layer of an ESD protective sheet, tulle (a fine mesh fabric), and conductive textile. SwitchBack [14] is an input interface that has a layered construction of conductive and non-conductive fabric and can recognize tapping and bi-directional swiping with minimal calibration. Argot [15] has conductive textile patches sewn onto a glove. The user places it in one hand and inputs text using it as a keyboard. Pinstripe [16] is an input interface that consists of clothes that have conductive threads sewn in parallel. The user can input continuous values by pinching and rolling the clothes. Grabrics [17] is a textile sensor that has 30 hexagonal conductive pads and can detect the user pinch angle using interconnections between some of the pads. The user can select a menu by pinching the fabric at a specific angle. Textile++ [18] is a touch-sensitive cloth consisting of two conductive textiles and one mesh fabric. It can detect XY coordinate positions and the pressure from a touch. Users are able to wear and use the clothes into which these interfaces are built without changing their appearance because the system can be implemented on the inside of the clothes. Moreover, these interfaces can provide users with a tactile sensation when they touch the clothes, which assists eye-free input. However, these interfaces supply no feedback to help users access information about the input such as the current state of the application and the number of choices that can be selected.

2.3 Deformable Clothes

There are some studies on the output interfaces that use the shape of cloth. Berzowska and Coelho [19] implemented a kinetic dress integrated with the shape memory alloy Nitinol and proposed the model and the usage of the dress. This study noted that the deformation of the cloth could have a role in output devices that connect to an interactive system. Moere and Hoinkis [20] implemented a folding fabric using a shape memory alloy as a wearable display. The deformation of the cloth can output information about the input such as the number of choices available to the user. The combination of these methods and input interfaces integrated into clothing enables users to get information and input commands even if in situations where there is no information presentation device.

3. Interface Design

We propose an input interface that uses wrinkles. The key idea of our proposed interface is to use the wrinkles to create input and output functions. In some situations in wearable computing, the user cannot hold a device or look at a display. Additionally, a device attached to clothes changes the user's appearance and causes them to look strange. In contrast, an interface that is integrated into clothes employs the interaction with the clothes such as touching and pinching, that achieves device operation without requiring grasping a device or attaching equipment to the device. Additionally, wrinkles naturally occur on clothes, and a user can recognize the shape and number of wrinkles by utilizing tactile sensation. This approach has a minimal deforming effect on the user's appearance and enables eye-free information acquisition. Therefore, wrinkles on clothes are suitable for wearable computing interfaces.

Our proposed interface uses wrinkles as both information dis-

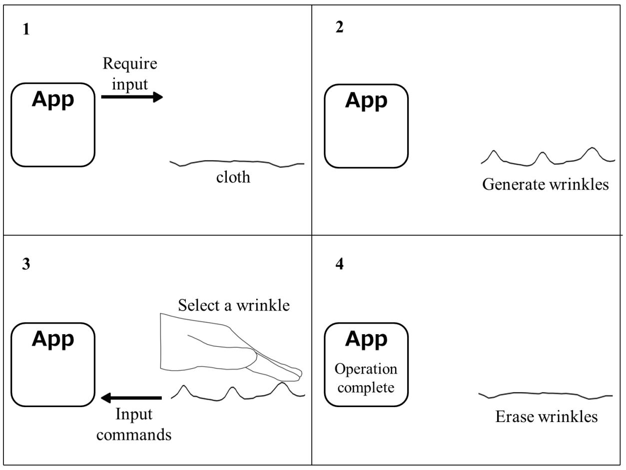

Fig. 1 Method of operation of the proposed interface.

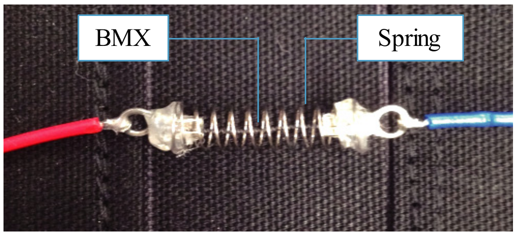

Fig. 2 Wrinkle generation mechanism.

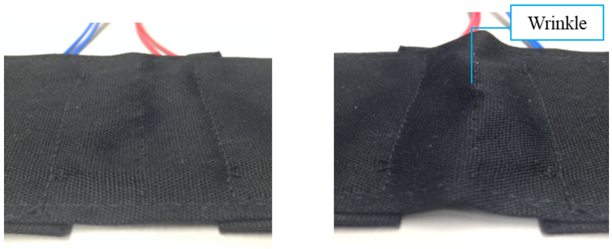

Fig. 3 Cloth without (left) and with (right) a generated wrinkle.

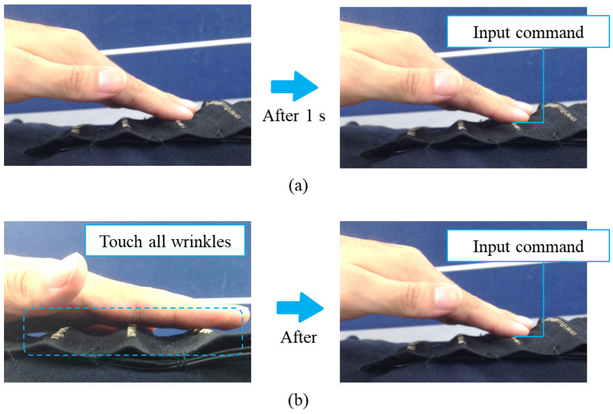

Fig. 4 Input methods: (a) long-press touch and (b) narrowing-down selection.

play and command input. **Figure 1** outlines the method of operation in our proposed interface. Our proposed interface generates several wrinkles on the clothes according to the input requirements of an application. The user inputs a command by selecting one of these wrinkles by touch. The wrinkles disappear after the input operation is complete. The user can receive information about the number of choices using the number of generated wrinkles. Moreover, the user knows the operation is complete when the wrinkles disappear. An interface that is integrated into clothes makes it unnecessary to attach devices to the body or change the user's appearance. Additionally, the generation of wrinkles provides the user with a tactile sensation when touching those wrinkles, thus facilitating eye-free operation. Moreover, this operation sequence is inconspicuous because wrinkles occur naturally on clothes and serve as a tactile feedback.

3.1 Interface Structure

The proposed interface consists of a wrinkle generation mechanism and a touch detection mechanism.

3.1.1 Wrinkle Generation Mechanism

To generate wrinkles, we explored three mechanisms: stepper motors, motor faders, and artificial muscles. The stepper motor generates a wrinkle by winding up thread sewn into the cloth. A motor fader generates a wrinkle by moving the fader fitted within the cloth. However, these two mechanisms require large and inflexible actuators that impair the functionality and comfort of clothes. Therefore, we decided to use artificial muscles, which are small actuators, to generate a wrinkle.

Figure 2 shows the wrinkle generation mechanism which consists of artificial muscles and springs. The artificial muscles shrink when a current passes through them. We use a Bio Metal heliX (BMX, TOKI Corp., Japan) for the artificial muscles. BMX is a helical artificial muscle that shrinks to half of its extended length. Although it shrinks when a current passes through it, it does not extend when the current stops. Therefore, we use a spring to return it to the original length. We pass the BMX through the spring. The artificial muscles generate wrinkles by pulling clothes, and the springs remove them by extending the cloth (**Fig. 3**).

3.1.2 Touch Detection Mechanism

The touch detection mechanism consists of conductive threads and capacitance sensing controllers. The interface uses the controller to recognize a touch on the conductive threads by measuring the changes in capacitance.

It is necessary to distinguish between a touch for selecting a wrinkle from a touch for inputting a command because the user touches the wrinkle in both cases. We assumed that users would employ one of two selection methods for our proposed interface. In the first method, the user touches the wrinkles one by one and checks their position. Then, the user selects the wrinkle. In the other method, the user touches all the wrinkles at the same time and checks their position during selection. We hence designed two input methods for selecting one wrinkle: long-press touch and narrowing-down selection input. The long-press touch method recognizes an input touch when it lasts for approximately one second as in **Fig. 4** (a). The narrowing-down selection method recognizes an input touch when the user touches only one wrinkle after touching all the generated wrinkles as in Fig. 4 (b).

3.2 Use Cases

In this study, we assumed that our proposed interface completes all operations using only the information from wrinkles. Because it has no information presentation devices such as an HMD, our interface generates several wrinkles that are assigned input commands when an application requires input. The user then operates the application by selecting one of the wrinkles. In addition, different patterns of wrinkles are generated depending on the application. These various patterns provide the user with information about the application requiring input. This enables the user to recognize it just by touching the wrinkles. In addition, our interface can generate wrinkles inside pockets, which enables the user to operate it discretely.

For example, our interface generates two wrinkles for incoming calls in a telephone application. The first wrinkle corresponds to taking the call and the second wrinkle corresponds to refusing the call. The user can hence deal with a mobile phone call without taking the mobile phone from a bag or pocket just by selecting and touching either wrinkle. These wrinkles disappear after the input is complete.

When the user makes a phone call, our interface generates several wrinkles for telephone numbers that the user has set up in the application. The user touches the wrinkle for the number that he/she wants to call. During the call, our interface generates one wrinkle, which corresponds to ending the call.

When the application runs in a music player application, our interface generates three wrinkles that correspond to play, volume control, and track selection. The user operates the application by selecting one of the three wrinkles. The "play" wrinkle switches between play and pause every time it is touched. To control the volume, the user touches the "volume control" wrinkle. The three wrinkles then disappear, and the interface generates two wrinkles that correspond to volume up and volume down. The interface generates two wrinkles corresponding to "play the next track" and "play the previous track" after the "track selection" wrinkle has been touched.

In addition to these examples, there may be situations in which a user would like to input commands using the proposed interface with an HMD.

When using an HMD, the interface outputs the choices that an application requires, and a user selects and touches one wrinkle while seeing the current commands superimposed on it, which helps him/her make the selection. In such situations, applications can present various kinds of information to the user, who can then perform complicated operations.

4. Implementation

Figure 5 shows the prototype of our proposed interface. We incorporated the wrinkle generation mechanism and touch detection mechanism into a piece of cloth. The piece of cloth is 27×10 cm, which is large enough to generate five wrinkles in parallel. The interval between each wrinkle is one cm, and a piece of lining cloth was sewn to both sides of each wrinkle to attach the wrinkle generation mechanisms and generate wrinkles easily.

We used the BMX150, which has the largest diameter available. The BMX is 1.5 cm long when shrunk and 3 cm long when extended by the spring. We attached metal eyelets at both ends of the BMX that then passed through the spring and were connected

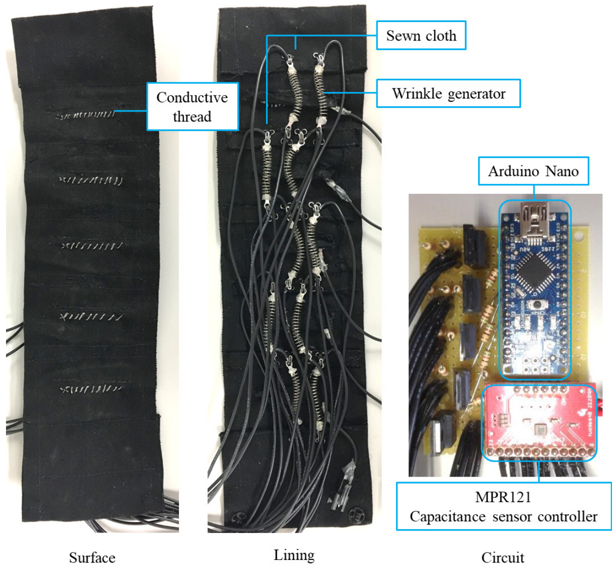

Fig. 5 Prototype interface.

to the circuit wires with solder. We fixed both ends of the spring to the eyelet. We used hooks to attach the wrinkle generation mechanisms, sewing four hooks to the lining to sandwich each wrinkle. The metal eyelet of the wrinkle generation mechanism was attached to the cloth using the hooks. Two wrinkle generation mechanisms attached to the cloth in parallel generate one wrinkle. There are ten wrinkle mechanisms on the cloth in total. The length of each mechanism is 4.2 cm when extended and approximately 3.5 cm when shrunk. The microcomputer controlled the power to the wrinkle generation mechanisms through transistors. The resistance of each wrinkle generation mechanism is 7.3 Ω. The BMX requires a current of 200 to 300 mA to deform the clothes and we designed the circuit to pass a current of approximately 200 mA to it. The voltage across the wrinkle generation mechanism when shrinking is approximately 1.5 V. Therefore, the power needed to generate a wrinkle is approximately 0.6 W (0.3 W per wrinkle generation mechanism). To confirm the time needed to grow and shrink a wrinkle, we investigated the minimum duration of current and no current needed for the BMX to move. We evaluated current flow durations of 2, 3, and 4 s and no current durations of 5, 6, 7, 8, 9, and 10 s. We repeatedly applied and stopped the current ten times for each possible combination of durations. We found the wrinkle generation mechanism required 3 or more seconds to shrink and 6 or more seconds to extend for repetitive motion.

We sewed conductive threads along the top of each wrinkle and connected them to an MPR121 capacitive touch sensor controller (Sparkfun Electronics, U.S.A) in order to recognize a touch on the wrinkles. We used wires to connect the conductive threads and an MPR12 sensor. We soldered the same metal eyelets used for the wrinkle generation mechanism to one end of the wire and sewed the conductive thread onto it. We used an Arduino Nano to manage the devices and send the wrinkle generation signal and capacitive touch sensor value to a PC. An XBee was used to wirelessly communicate with the PC.

The interface needs to be removable for washing and the mounting position should flexible. We hence sewed snaps to the

(a) Shoulder (b) Upper arm (c) Forearm (d) Armpit (e) Abdomen (f) Side (g) Front thigh (h) Outside thigh

Fig. 6 Candidates for device positions.

top of the cloth to attach the input device onto clothing and a pocket that contains the circuit and a battery. The attachment area is 30 × 11.5 cm.

5. Evaluation

We carried out four experiments.

5.1 Evaluation of Socially Acceptable Device Position

An input interface in wearable computing must remain socially acceptable when it is worn and operated. Therefore, we carried out a study that asked people to evaluate which areas were socially acceptable for the interface.

Wagner et al. [23] investigated the time, accuracy, and social acceptability of touching targets on 18 body locations. This research concluded that touching targets on the lower legs was slow and unacceptable socially, and a touch on the dominant arm was prone to errors. Hence, we evaluated areas of the body that users could touch without changing their posture, even if they were standing or sitting. For social acceptability, we did not consider areas that would cause discomfort in other people. We hence selected eight areas on the human body: the shoulder, upper arm, forearm, armpit, abdomen, side, front thigh, and outside thigh.

We recruited 20 participants: 2 females and 18 males. Participants watched eight videos in random order showing a standing man who did not mount the prototype interface but pretended to touch it on each area of his body. Then, they evaluated the social naturalness of his behavior in daily life using a five-level Likert scale (1: unnatural to 5: natural). **Figure 6** shows images of the man in the videos.

Results

The results in **Fig. 7** showing the maximum, minimum, and average points for each candidate area. The average points for the device position (excluding the armpit) were around 3, which means that these device positions had a moderate level of social acceptance. Fifteen participants evaluated the operation in the armpit as 1, and it was the location receiving the lowest score from most participants. Three participants evaluated the operation on the front of the thigh as 2, and no participants evaluated it as 1, so it had the fewest participants who gave it a low score. We conducted an ANOVA and found a significant difference between device positions ($F(7, 133) = 5.90$, $p < .01$). Fisher's least significant difference test found that the armpit achieved the lowest score of all device positions.

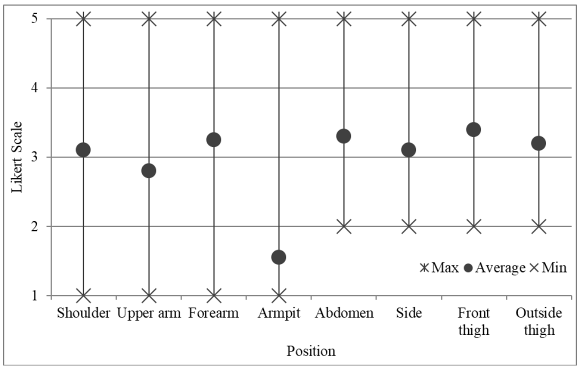

Fig. 7 Socially acceptability of the candidate positions in Fig. 6.

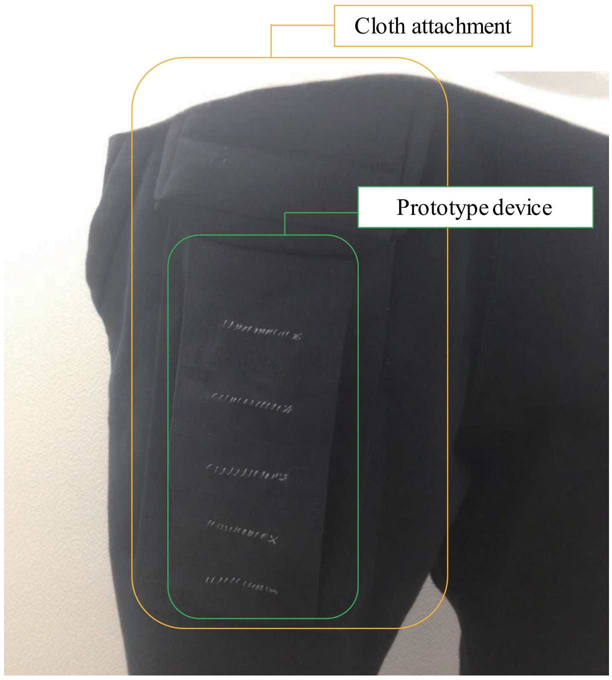

Fig. 8 Prototype interface attached to trousers.

We chose the front thigh for further evaluation because it had no problem with social acceptability. In addition, we used it because it also had a fast pointing time in the study by Wagner et al. We hence mounted the prototype on the front of the thigh on the trousers in the following experiments. **Figure 8** shows the prototype attached to the trousers.

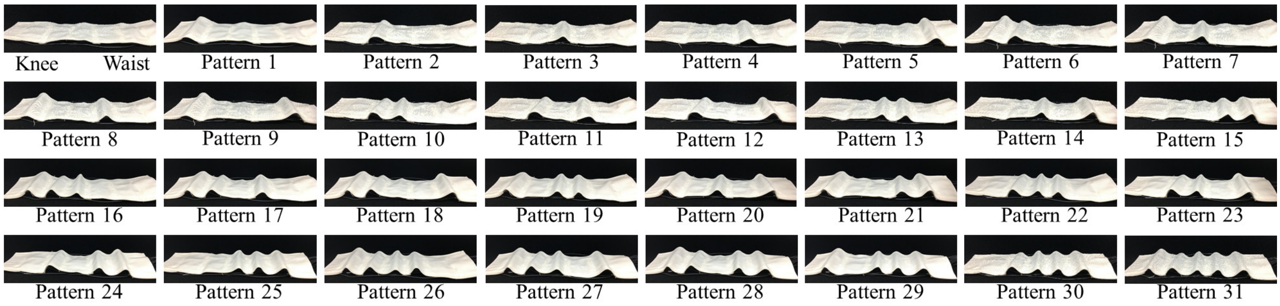

Fig. 9 All pattern of wrinkles on the interface.

5.2 Evaluation of Wrinkle Pattern Recognition

We assume that our interface outputs information to the user by the generation pattern of wrinkles. To confirm whether a user can recognize the shape and number of wrinkles when touching them, we evaluated the recognition of generated patterns of wrinkles.

Eleven all-male, right-handed participants were recruited for the experiment. The participants wore trousers on which the prototype device was mounted and sat in a chair in front of a desk where we had placed a PC. In order to evaluate just the tactile sensations from the wrinkle, no conductive threads were sewn with the device used in this experiment.

Before the test started, participants performed one training phase. The learning phase had the same content of the test and gave audio feedback when the participants chose the current pattern. In contrast, the test phase had no feedback.

In the experiment, the wrinkles generated a pattern on the device, and instructions asking participants to touch the device were shown on the PC screen after the pattern was completely generated. When the participants read the instructions, they touched the wrinkles without looking at them and chose the same pattern on the PC screen using a trackpad. The wrinkles on the device and the instruction on the PC then disappeared and another pattern appeared with instructions on the PC when the generation was again complete. The prototype could generate up five wrinkles and 31 patterns (not counting the pattern of no wrinkles). **Figure 9** shows all the wrinkle patterns used in the evaluation. Each participant felt each pattern, which appeared randomly once in the test.

Results

This result achieved an 89.4% (SD = 11.8%) average accuracy for all participants and the average recognition time was approximately 17 seconds (SD = 6.46 seconds). We calculated each accuracy from the number of times that the participant succeeded in selecting the correct pattern in one test. The recognition time was the average time between the completion of the generation of wrinkles and the selection of the pattern on the PC screen. These results show that the users can recognize the change in the shape of clothes using just the tactile sense. The time to select the pattern on the PC took approximately five s on average for all participants.

Figure 10 shows the confusion matrix indicating the number of times that participants recognized each pattern of wrinkles. Participants tended to be unable to recognize that there were three wrinkles on the upper thigh. Mistakes occurred for patterns 13, 21, 22, 24, 25, 27, 28, 29, 30, and 31. When three or more wrinkles were generated, mistakes were likely to occur. All participants touched the pattern going from the lower thigh to the upper thigh side. Moreover, none of them touched all the wrinkles at the same time. It was hard to generate wrinkles on the upper thigh because the amount of the cloth pulled up was increased. These factors could be a reason for the mistakes.

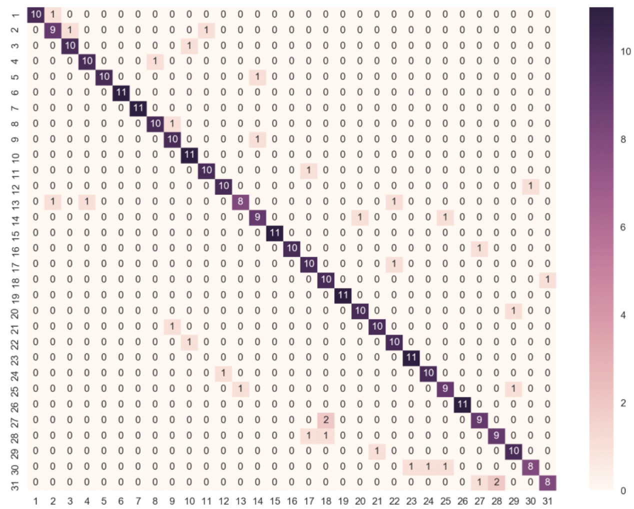

Fig. 10 Confusion matrix of the results.

5.3 Evaluation of Targeted Wrinkle Touch

We evaluated the input accuracy of our wrinkle-based interface using the two input methods (long-press touch and narrowing-down selection). Five all-male, right-handed participants were recruited. Participants wore the trousers having the prototype interface attached on the right thigh and sat in a chair. We explained the two input methods to them and asked them to select and touch the targeted wrinkle. The prototype generated five wrinkles on the cloth during this experiment and did not remove them until the experiment was finished. The evaluation application showed the targeted wrinkle and the input method on a PC screen. Participants input a command using a targeted wrinkle with the input method shown on a PC screen and pushed the key on the keyboard when they had completed the touch input without looking at the prototype interface. The evaluation application output the next targeted wrinkle after they had pushed the key. Participants began this experiment with visual feedback that showed the wrinkle they had touched and the completion of the input on the PC screen. Then, they performed the last part of the experiment without it.

Table 1 Accuracy of touching the target wrinkle.

Accuracy [%]					
Participant	A	B	C	D	E
	With visual feedback				
Long-press touch	98.3	98.3	96.6	100	100
Narrowing-down selection	100	96.7	98.3	100	96.7
	Without visual feedback				
Long-press touch	65.0	76.7	76.6	91.6	68.8
Narrowing-down selection	60.0	98.3	95.0	83.3	-

A set consisted of 20 inputs (four times inputs per wrinkle). Participants started a set with the long-press touch input method. The application switched the input method every set and chose the targeted wrinkle from the five wrinkles randomly. They performed six sets (three sets per input method) with the visual feedback, then performed six sets without it.

Results

Table 1 summarizes the accuracy obtained in this experiment. We calculated the accuracy using the number of times out of 60 that participants touched the correct wrinkle using the same input method. We used all touches recognized by each input method to calculate the accuracy.

When visual feedback was shown, the average accuracy of all participants for both input methods was approximately 98%. Many of the failures occurred when no wrinkles were touched. We believe that this occurred because participants pushed the key before the system recognized the touch input. Even if participants touched a wrinkle, the MPR121 did not always detect the touch. This occurred when participants touched a thread with a single fingertip. Participants rarely touched the wrong wrinkle. These experimental results suggest that we could input commands using the proposed interface without looking at it if there is visual feedback.

Without visual feedback, an average accuracy of approximately 75% was yielded for all participants using the long-press touch input method and approximately 84% was yielded using narrowing-down selection input method. We found from our evaluation of participant E that the system recognized that one wrinkle was always touched. Therefore, we evaluated the remaining four wrinkles with the long-press touch input method for participant E. However, we could not evaluate the narrowing-down selection input method because it recognized a touch on only one wrinkle. Failures, especially when no wrinkle was touched, increased compared with the experiment with visual feedback. We believe this occurred because participants were not familiar with the feel of wrinkles or the operation method. The accuracy of narrowing-down selection was higher than that of the long-press touch. We believe this occurred because, during narrowing-down selection, participants touched all wrinkles with the palm once, which indicates that simultaneously touching all wrinkles with the palm might be an efficient way to check the position of the wrinkle.

In addition, we observed some distinctive methods of touch in participants who achieved high accuracy without visual feedback. Participant B moved his palm quickly and touched wrinkles many times when using the narrowing-down selection input method. Participant C moved his fingers laterally along the wrinkle to confirm the seams of the conductive thread and the wrinkle, and he touched two wrinkles on the upper thigh with his thumb. Participant D touched the wrinkle on the upper thigh with his palm by raising his fingers. These results demonstrate that these methods of touch are useful for input using the proposed interface.

5.4 Evaluation of the Interface's Learning Curve

We believe that the proposed interface has the potential to allow operation even when no information is presented on a device. However, the experimental result of Section 5.3 indicate that the accuracy without visual feedback is not sufficient. We hence evaluated the long-term change in input accuracy and the time per input for each input method.

To eliminate system errors occurring in the experiment of Section 5.3, we changed the wires connecting the conductive threads and the MPR121 to shielded wires and modified the touch and release thresholds in the MPR121. Seven all-male, right-handed participants were recruited who were different from those who participated in the experiment described in Section 5.3. Participants wore trousers with the prototype device attached to the right thigh and sat in a chair in front of a desk with a PC placed on it. We explained the two input methods to the participants and asked them to select and touch the targeted wrinkle that was shown on the PC screen without looking at the device. We started this experiment using the prototype interface after it had generated five wrinkles, and we did not remove them until the end of the experiment. Participants selected the targeted wrinkle using the input methods shown on the PC screen. No visual feedback was given in the evaluation process, but audio feedback consisting of different sounds was given according to the correctness of the selection. Then, the application showed the next targeted wrinkle.

Each participant carried out five experiment sets per day. Each set consisted of 60 trials (12 inputs per wrinkle) for each input method, and the input methods switched after 60 trials. The evaluation took six days to confirm the learning curve effect, using a total of 30 sets for each participant. Participants P1–P4 performed a set using long-press touch before using the narrowing-down selection, and the remaining participants P5–P7 performed the set in reverse order.

Results

Figures 11 and **12** show the change in the input accuracy for each participant for 30 sets of trials, and **Figs. 13** and **14** show the change in the time per input operation. We calculated the input accuracy from the number of times that participants had succeeded in touching the targeted wrinkle in a set using all touches recognized by the interface.

The input time was the average time between the output of a targeted wrinkle and the completion of a touch input in a set. The performance on the last day of the experiment reached an average accuracy and variance of 98% and 2.06, respectively, for long-press touch input method, and 98% and 2.74, respectively, for narrowing-down selection input. Moreover, the average time and variance were 1.96 s and 0.19, respectively for long-press touch and 2.14 s and 0.54, respectively, for narrowing-down selection. The learning effect of long-press touch input method was confirmed in that the accuracy of all participants increased as they continued the trial for six days. However, P4 and P7 demon-

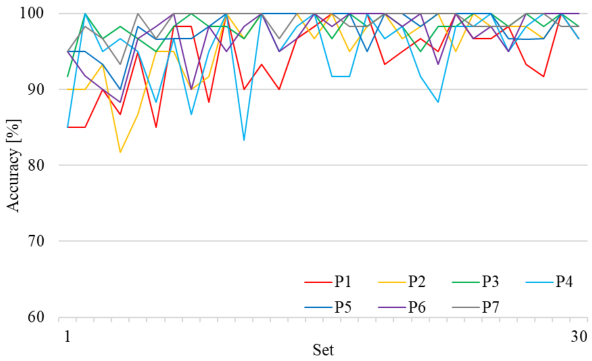

Fig. 11 Change in accuracy for long-press touch.

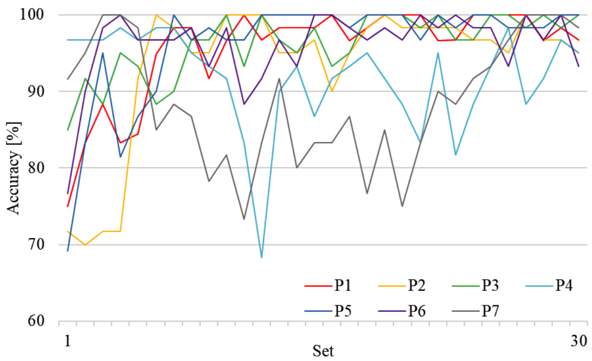

Fig. 12 Change in accuracy for narrowing-down selection.

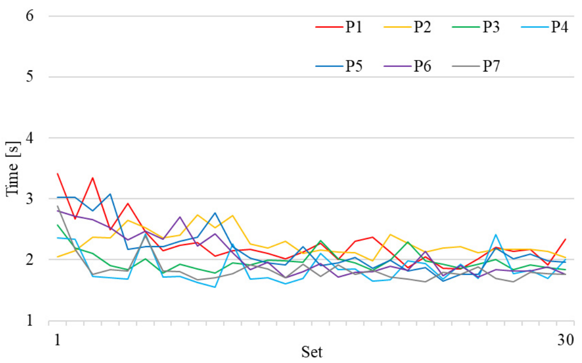

Fig. 13 Change in input time for long-press touch.

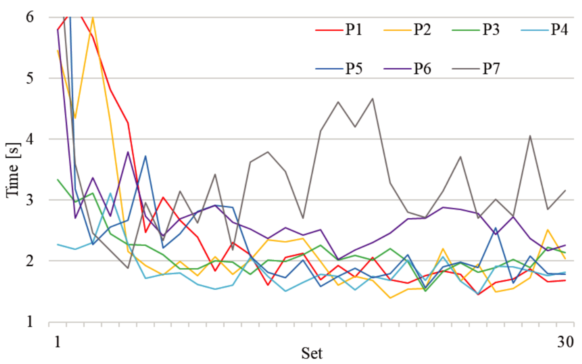

Fig. 14 Change in input time for narrowing-down selection.

strated a decrease in accuracy once in the middle of the experiment for narrowing-down selection but they recovered their performance at the end. Moreover, P7 touched the targeted wrinkle for approximately 3 s on average using narrowing-down selection, while the other participants did so for approximately 2 s.

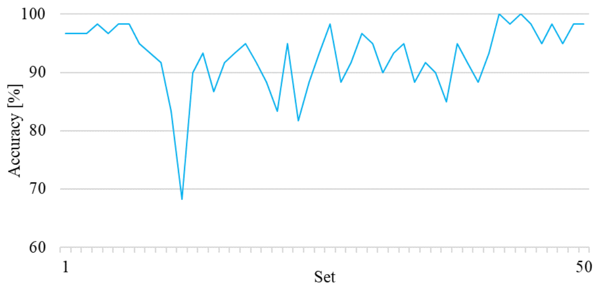

Fig. 15 Change in the input accuracy of P4.

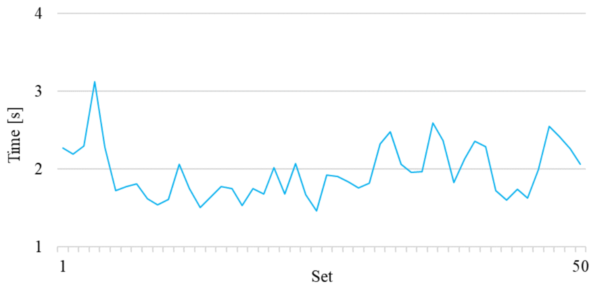

Fig. 16 Change in input time of P4.

The above results show that most users can master the operation of our proposed interface using the long-press touch input method in 30 sets of trials over six days. However, P4, who had the lowest average accuracy (94%) and biggest variance (3.59) was not able to acquire sufficient operating skill using narrowing-down selection in such a short time. Most of the participant's errors were to touch the wrinkle next to the target and touch the wrinkle on the lower thigh using their fingertips. System error did not occur in this experiment. We continued the experiment for another 20 sets (for four days) for P4. **Figures 15** and **16** show the change in the input accuracy and time per input of P4 for 50 sets of trials. As a result, the performance on the last day reached an average accuracy and variance of 97% and 1.62, respectively, and an average time and variance of 2.26 s and 0.21, respectively. The average accuracy and variance were improved by training with 30 sets of trials; however, the average time became longer.

6. Discussion

6.1 Wearability and Social Acceptability

We investigated how socially acceptable various positions for the interface were. Operations on the armpit achieved the lowest score among the natural behaviors, and other positions scored moderately. These results suggest all the device positions except for the armpit can satisfy social acceptability. We consider that the device position that has the best operation performance would be different depending on the users or environmental factors. Changing the position where the device is mounted may be necessary to maintain operation performance.

Our proposed interface has an effect on its wearability. The current prototype generates wrinkles on a piece of cloth mounted on the trousers but does not pull up the trousers. Therefore, we believe that the generation of wrinkles does not impair the comfort of the trousers. However, the circuit and the heat radiated from the BMXs reduce its comfort. Miniaturization of the circuit and the use of another type of actuator would solve this problem.

6.2 Wrinkle Patterns

Our proposed interface generates several wrinkles corresponding to the input required by an application. A designer would design an application and the wrinkle patterns simultaneously.

The evaluation results indicate the following guideline for designing the wrinkle pattern. Patterns consisting of three wrinkles are accurately recognized. However, the recognition accuracy of patterns consisting of four wrinkles is low. Therefore, eye-free operations using our proposed interface should be designed to have three or fewer commands. Complicated operations requiring four more commands should be designed using a different display.

6.3 Operation Accuracy

The recognition accuracy of the wrinkle patterns was 89.4%. This accuracy could increase if the interface was improved. The current prototype generates five wrinkles on a piece of cloth, and some of the wrinkles are difficult to generate. We are currently considering implementing the interface by combining fabrics that generate one wrinkle. Each fabric generates a wrinkle with a different texture, which would increase accuracy.

The input accuracy for each wrinkle reached 98.6% for the long-press touch input method and 96.9% for the narrowing-down selection input method. The user hence can recognize and use each wrinkle for input. Just as for the recognition accuracy, the improved interface would increase these accuracy rates.

These results suggest that the currently proposed interface has an eye-free operation accuracy that is close to 90%.

6.4 Operation Time

In the current prototype, generating a wrinkle takes 5 s, and removing it takes up to 12 s. The recognition of the wrinkle takes 12 s, and the input takes 2 s. The total operation from the request for input from an application would take 31 s, and this time needs to be reduced. An actuator that moves the cloth more quickly than the artificial muscle would reduce the wrinkle generation and removal times. To reduce the input time, for the long-press touch input method, we changed the optimum touch detection time. If users master the operation of the narrowing-down selection input method, they can perform inputs more quickly. An interface generating wrinkles in different shaped could shorten the wrinkle recognition time.

6.5 Power Consumption

Our current prototype interface requires 0.6 W to generate a wrinkle. When the number of input commands increases, the number of wrinkles on the device increases and the interface requires more power. In addition, the interface continues to consume power to retain the generated wrinkles. The power consumed by this device must be reduced. This could be solved by using an actuator that consumes less power than the BMX. For example, we could use an actuator such as a small motor that does not consume power when retaining the generated wrinkles. The design of the cloth structure could also solve the problem. Attaching a mechanism for fixing wrinkles such as hooks to the cloth would reduce the power needed to generate them.

7. Conclusion

We propose an input interface that generates several wrinkles on clothes in response to the input requirements of an application. Users can input commands by selecting and touching these wrinkles, which disappear after the input operation is complete. Users can also receive information about an application state from the pattern of the wrinkles. This sequence achieves eye-free input because touching wrinkles works as both the tactile feedback and input operation. In addition, our proposed interface does not change the appearance of users because it is natural for there to be wrinkles on the clothes. We implement a prototype interface that consists of the wrinkle-generation and touch-detection mechanisms. The former mechanism uses artificial muscles and springs, and the latter uses conductive threads and a capacitance sensor controller. We investigated which device position is the most socially acceptable to operate. The investigation result suggests that all mounting positions except for the armpit are satisfactory. We evaluated the output function of wrinkles and the learnability of the input accuracy and speed using the interface attached to the right thigh. Users had a high recognition rate of 89.4% and recognized the shape of the wrinkles in approximately 12 s. This time will need to be reduced. Users obtained a better recognition accuracy of more than 90% after learning the operation of our proposed interface. The input time decreased as learning progressed and was lowered to approximately 2 s for both methods. The long-press touch method set the optimum touch detection time to reduce the input time. When users master the operation of the narrowing-down selection method, they can input commands more quickly. It takes more than 17 s to complete an operation in the current prototype.

To improve the performance of proposed interface, the structure of interface should be modified. The current prototype generates five wrinkles on a piece of cloth, which has areas that cannot easily generate wrinkles. We plan to implement our proposed interface using fabrics in which one wrinkle is generated. The improved interface would be able to generate wrinkles with various tactile sensations, which would improve the interface performance. We plan to consider and implement a notification method that informs the user that wrinkles have been generated. It will be necessary to carry out further evaluation experiments on the wearability in the future. We also intend to consider and implement applications using the proposed interface.

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Kentaro Ueda is in the doctoral course at Graduate School of Engineering, Kobe University. He received B.Eng. and M.Eng. degrees from Kobe University in 2014 and 2016, respectively. His research interest is wearable computing and ubiquitous computing.

Tsutomu Terada is a Professor at Graduate School of Engineering, Kobe University. He received B.Eng., M.Eng. and Ph.D. degrees from Osaka University in 1997, 1999, and 2003, respectively. He is currently working on wearable computing, ubiquitous computing, entertainment computing technologies. He is a member of ACM and IEEE.

Masahiko Tsukamoto is a Professor at Graduate School of Engineering, Kobe University. He received B.Eng., M.Eng. and Ph.D. degrees from Kyoto University in 1987, 1989, and 1994, respectively. He is currently investigating wearable computing and ubiquitous computing. He is a member of eight learned societies, including ACM and IEEE.