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EVALUATION OF INPUT/OUTPUT INTERFACE USING WRINKLES ON CLOTHES

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Wearable computing has created textile-based interfaces utilizing the interaction between the user and cloth for operation, as well as the touch and the pinch input operation. The user wears and uses the device in various postures, environments, and operating positions that affect the operation speed and accuracy. However, no study has assessed such factors of touching and pinching using the same input interface. One of the textile interfaces has an input interface using wrinkles on clothes. 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. Additionally, the act touching or pinching wrinkles does not look strange to an onlooker, which reach that wrinkles have the potential suitable for the wearable computing operation. To reveal the potential, this paper evaluates the input performance using wrinkles on clothes. We designed three touch input methods and one pinch input method for the operation using wrinkles. We implemented the input and the output device which use wrinkles and carried out four evaluations. The results indicated that the pinch input reached the highest accuracy of 98% of four input methods after learning. The narrowing-down selection reached the fastest input time of 1.64 seconds of four methods after learning. The long press touch and the pinch input achieved the accuracy of 90% or more in all combination of operating environments and device positions. According to the result of the wrinkle recognition, users have a high accuracy of the identification of wrinkles of 89.4% and recognize their shape in approximately 12 seconds.

Keywords: Textile interface,Wrinkles,Wearable computing, Performance evaluation

1. Introduction

Wearable computing enables users to operate a computer anywhere and at any time. This change in computing style requires a change in interfaces, many innovative ones having been proposed by researchers. The miniaturization of sensors and toolkits, such as conductive threads and LilyPad [1], for integrating an electronic kit on the fabric, have enabled the emergence of textile-based interfaces. Textile interfaces can input information using the interaction between the user and cloth such as touching, pinching and folding without his/her carrying or holding any device since his/her clothing has the inbuilt function. Among these interactions, many textile interfaces use the touch [2, 3] and the pinch interaction [6, 8]. Since users operate a computer through the clothing they are wearing, their posture, environment, and the operating position affect the operation speed and accuracy of the textile interfaces. Although there are studies evaluating the performance of the touch or the pinch input of the textile interface [7, 14], no study has assessed several factors to both touching and pinching using the same input interface.

This study evaluates the input using wrinkles wherein one of the textile interfaces has the input interface using wrinkles on clothes [12]. The interface generates wrinkles according to the application requirement of the input. The user chooses a wrinkle and inputs a command by touching it. The generation pattern and number of wrinkles correspond to the applications and number of input choices, and supply information about the input through the tactile sense, which enables users to provide the input even if they are in a situation where the use of information presentation devices is challenging. We reviewed the input interface using wrinkles on clothes where pinching is suitable for the input since they have the shape that is easy to pinch and the act does not look strange to an onlooker. We adopted a pinch input in input methods and designed three touch input methods and one pinch input method. We evaluated the learning of input methods, the effect of the presence of wrinkles, the input performance in various combinations of operating environments and device positions, and the recognition of the wrinkle pattern.

2. Related work

2.1. *Textile interface*

There have been researches conducted on textile interfaces for wearable computing. Textile interfaces eliminate the need for the user to hold devices and do not impair the appearance of clothes since they are enclosed and the circuit is hidden, therefore, he/she is not reluctant to use them in daily life. The tactile inputs with embroidery and fabrics realize an eye-free operation, and the flexibility of cloth achieves new interaction styles such as folding and grabbing a cloth, and representatives of these interactions are a touch and a pinch.

Holleis et al. [2] implemented touch controllers embedded with a glove and apron. Textile++ [3] is a touch interface consisting of two conductive clothes and a mesh fabric and can detect the XY coordinate position and the pressure of the touch. GestureSleeve [4] is an interface made out of touch enabled textile and can detect stroke based gestures or taps. FabricID [5] is a system which identifies user's hand using smart textile integrated into his/her sleeve. It can detect the user's hand from pressures when he/she puts his/her hand on the sleeve. Gilliland et al. [6] implemented three textile interfaces which were the rocker switch, menu, electronic pleat. The rocker switch and menu detect a touching on conductive embroideries, and the electric pleat trucks the location of user's finger and detects a pinching gesture by tracking two fingers. Pinstripe [7] 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 [8] is a textile sensor that has 30 hexagonal conductive pads and can detect the user pinching angle from an interconnection between some of the pads. The user can select a menu by pinching the fabric at a specific angle. There are also interfaces which could recognize both touching and pinching gestures. Komor et al. [10] implemented a multitouch interface having four embroidery buttons, and the user could perform the multitouch and pinch interaction using two buttons. SmartSleeve [11] is a textile sensor which can recognize surface and deformation gestures such as a hand or finger touch and twist. PocketThumb [9] is a wearable touch interface that is embedded into the front trouser pocket. The user controls a cursor with his/her thumb sliding the fabric from the inside and performs tapping or swiping gestures operation with fingers from outside at the same time, which resemble a pinch gesture. These interfaces supply no feedback to help users to access information about the input such as the current situation and the number of choices to be selected.

Ueda et al. [12] proposed an input interface using wrinkles on clothes. This interface generates wrinkles on clothes when an application requires inputs. The user can input a command when he/she touches a wrinkle. After the input operation is completed, this interface erases the wrinkles. This sequence, until the cessation of generation of wrinkles, provides input information to the user. We have reviewed this interface and outline the potentiality of wrinkles.

2.2. *Evaluation of factor affecting wearable operation*

The input interface for wearable computing has various factors in its operationality such as mounting positions, postures, and social acceptance since the user wears and uses the device, and researchers have examined those. Thomas et al. [13] investigated the effects of the mounting position of a touchpad on the input performance. They assumed the maintenance of a large piece of machinery as a use scene of wearable computing and investigated the performance of the touchpad in combinations of four postures (sitting, kneeling, standing and prone) and seven placements. The results showed that the front of the thigh was the best position of the touchpad in sitting, kneeling and standing postures, and the forearm touchpad position would be best for the prone position. Wagner et al. [14] systematized the multi-surface interaction with the user's body and created the guidelines. They looked into methods of touching the target on the body and carried out tasks in which participants touched 18 targets on different body parts in standing posture. The results showed that the touch to the target on the lower legs was slow and unacceptable socially, and touching it on the dominant arm was prone to errors and slow. In Pinstripe [7], they investigated pinching angles and preferences in 3 postures (sitting, standing and walking) and 16 mounting positions. According to the results, the uncomfortable placements were the lower leg, thigh, and waist since bending the body is inconvenient and touching the abdomen in public is unappealing. The placement of the highest preference was the upper arm of the non-dominant hand. However, these studies did not evaluate both the touch and the pinch input method in the same interface. This study evaluates these input methods using wrinkles on clothes and clarifies the advantages of wrinkles and the differences between touching and pinching.

3. Design of input and output method

Our textile interface uses wrinkles to input a command and output information about an input requirement. We design the input and output methods that use wrinkles on clothes.

3.1. *Input method*

We implemented three touch input methods and one pinch input method which use wrinkles on a cloth.

3.1.1. *Touch input method*

The touch detecting method consists of conductive threads and capacitive sensor controllers and detects a touch on the conductive threads by measuring the changes in capacitance through the controller.

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 of the wrinkle. 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 wrinkle at the same time and checks their position during selection. We hence designed three touch input methods: long-press touch, double touch, and narrowing-down selection input. The long-press touch input method distinguishes between a touch for selecting and a touch for inputting a command based on the time during touching on the wrinkle and recognizes an input touch when the user touches on the wrinkle for approximately one second. The double touch input method distinguishes those by the number of times of touching the wrinkle and recognizes the touch input when the user touches it twice within 0.2 seconds. These input methods apply to the former selection method in which the user touches the wrinkles one by one in searching for the target. The narrowing-down selection method separates the selection phase and the input phase and recognizes the touch input when the user touches only one wrinkle after touching all the generated ones. This input method uses the latter selection method, and the user touches all wrinkles simultaneously and searches for the target.

3.1.2. *Pinch input method*

The pinch detecting method consists of conductive threads and microcomputers. We connected a microcomputer to two conductive threads. The microcomputer applies a voltage to one of the two conductive threads through a resistance and grounds the other thread. This method detects pinching at the cloth when two threads come in contact by measuring the voltage of the thread where it is applied a voltage. The pinch detection does not require differentiation between the selection and decision of the targeted wrinkle since the user performs the different behavior in selecting and deciding it. The pinch input method recognizes the pinch when two conductive threads come into contact with each other for 0.5 seconds to prevent any misinterpretation.

3.2. *Wrinkle generating method*

The interface generates wrinkles to supply information about the input, which means that the generation of wrinkles helps the input. Therefore, we evaluate whether the user recognizes a pattern formed by wrinkles through the tactile sense.

The wrinkle generator consists of artificial muscles and springs. We used a Bio Metal heliX (BMX) for the artificial muscles, which is made by TOKI Corporation. BMX is a

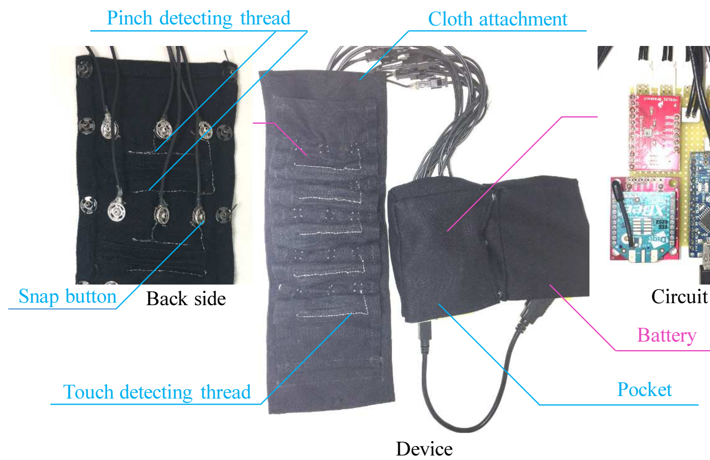

Fig. 1. Input device

helical artificial muscle that shrinks to half of its extended length. Although it shrinks when a current passes through it, it does not regain its original length when the current stops. Therefore, we used a spring for returning it to the original length. We pass the BMX through the spring. The artificial muscles generate wrinkles by pulling the cloth, and the springs remove them by extending the cloth.

4. Implementation

4.1. *Input device*

Figure 1 shows the input device that was used for the evaluation in this study. The size of the cloth is 27 × 7.5 cm, which can be covered by the hand of an adult male. We folded five wrinkles on the cloth and sewed three conductive threads in parallel along each of these wrinkles. We used a sewing machine of JANOME Monaze E2000 to sew conductive threads, and the top thread was nonconductive threads and the bobbin thread was conductive threads. Although we had sewed threads shaping the zigzag stitch to make a large contact area of the conductive thread, it had floated from the cloth. Therefore, we sewed threads shaping the straight seam. The center thread for detecting a touch was sewn along the top of the wrinkle. Both the side threads for detecting a pinch were sewn at a distance of approximately 0.7 cm from the back side center of the wrinkle. We used snap buttons for the connection between the cloth and the circuit and attaching the device. For the connection, we sewed a metal snap button on the one end of each conductive thread and soldered the pair of it to the wire connecting with the circuit. The interval between wrinkles was approximately one cm to sew metal buttons for connection between threads and a circuit. We used shielded wires for the connection of touch detecting threads to prevent the misrecognition of touching. To mount the device and fix wrinkles, we sewed 4 buttons on 4 corners of the cloth and 12 those on both of its long side at 3 cm intervals between wrinkles. To make it easy to change the placement of the device, we made an attachment and a pocket, where the circuit and a battery are

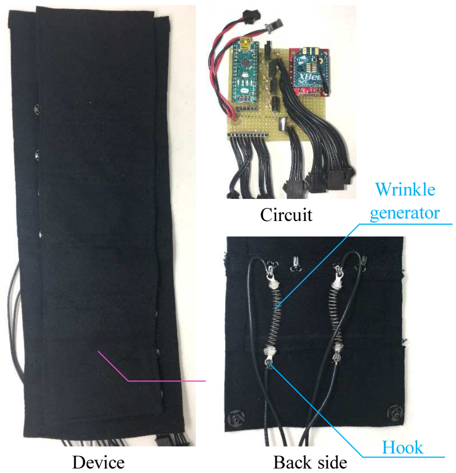

Fig. 2. Output device

inserted. The attachment size was 25 × 9 cm, and we sewed buttons which were the pair of those sewn on the input device. The interval of buttons for fixing wrinkles was 2 cm, and the wrinkle height was approximately 1 cm. We mounted the attachment and pocket to clothes using snap buttons.

The control circuit consisted of a microcomputer, a capacitive sensor controller, and a wireless communication module. We used Arduino Nano as the microcomputer to control the MPR121 capacitive sensor controller and detect a pinch. We used the resistance inbuilt to the Arduino Nano for the pinching detection. XBee was used as a wireless communication module for communication with a PC recognizing an input to a wrinkle.

4.2. *Output device*

We incorporated wrinkle generators into a piece of cloth (Figure 2). The piece of cloth is 28.5 × 10 cm, which was large enough to generate five wrinkles in parallel. We used the BMX150, which has the largest diameter available. The BMX is1.5 cm long when shrunk and 3 cm long when extended by the spring. We passed the BMX through the spring and attached two metal eyelets at both ends of the BMX. The spring is 3 cm long and has the outer diameter of 5 mm and the wire diameter of 0.3 mm. We fixed both ends of the spring to the eyelet and connected the BMX to the circuit wires with solder through both ends eyelets. We used hooks to attach the wrinkle generator, sewing four hooks to the lining to sandwich each wrinkle. The metal eyelet of the wrinkle generator was attached to the cloth using the hooks. Two wrinkle generators attached to the cloth in parallel generate one wrinkle. There are ten wrinkle generators on the cloth in total. 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 generator and generate wrinkles easily. The length of the wrinkle generator is 4.2 cm when extended and approximately 3.6 cm when shrunk. The microcomputer controlled the power to the wrinkle generators through transistors. The resistance of each wrinkle generator 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 the wrinkle generator. The voltage across the wrinkle generator 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 generator). The wrinkle generator required 3 or more seconds to shrink and 6 or more seconds to extend for repetitive motion.

We used an Arduino Nano to manage the devices and communicate with a PC that sent signals of wrinkles generation and disappearance. An XBee was used as a wireless communication module for communication with a PC.

We sewed snap buttons on the top two corners of the cloth and used the attachment and the pocket that contains the circuit and a battery to attach the device onto clothing. The attachment size is 30 × 11.5 cm. We mounted the attachment and pocket onto clothing using snap buttons.

5. Evaluation

This study assesses the effects of wrinkles on the cloth on the operation. We carried out four types of experiments to determine the efficiency of the operation using wrinkles and evaluated the following: (i) the learnability of the input using wrinkles, (ii) the effect of the presence of wrinkles, (iii) the input performance in various combinations of operating environments and device positions on the body, and (iv) the recognition of the generation pattern of wrinkles.

5.1. *Learning curve*

The user gets used to and learns the operation of our interface, which increases the user's input performance. We attached the input device to the front of the right thigh of a trouser and investigated the long-term change in input accuracy and time per input.

5.1.1. *Participant and procedure*

We recruited nine right-handed participants (seven male, two female) for the experiment. The participants wore the trousers on which the input device was mounted and sat in a chair in front of a desk where we had placed a PC. We explained four input methods to them and asked them to select and provide the input to a targeted wrinkle shown on a PC screen without looking at the input device. When participants completed the input, the evaluation application gave audio feedback of different sounds according to the correctness of their selection of a wrinkle and showed a next targeted wrinkle and input method on the PC screen.

Each participant carried out five sets of trial per day. Each set consisted of 60 trials (12 times of input per wrinkle) for each input method. We switched Input methods every 60 trials. The order of input methods and the targeted wrinkle was random in a set. The evaluation took 6 days to confirm the learning curve effect, for a total of 30 sets for each participant.

5.1.2. *Result*

Figure 3 depicts the change of the input accuracy for six days. We calculated the input accuracy from the number of times that a participant had succeeded in inputting the targeted wrinkle with an input method in a set of trials. We used all touches recognized by the inter-

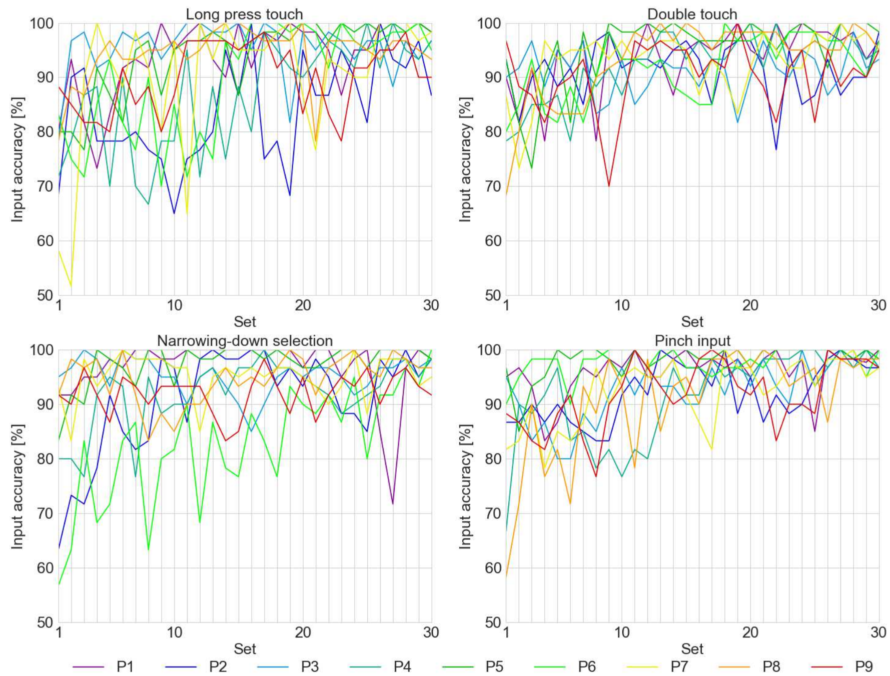

Fig. 3. The change of input accuracy in each input method

face for the accuracy calculation, including impulsive touches. The performance on the last day of the long press touch reached an average accuracy of 96%. P2, P3, and P9 achieved the accuracy of 95% or less and had a relatively large variance on the last day while other participants could acquire more than 95% of accuracy and small variation after the experiment. The double touch reached an average of 95% on the last day and the highest average accuracy of 87% of the four methods on the first day. The variance in the accuracy was smaller than the other touch input methods. P2 and P3 had the large variance but reached the high average accuracy on the last day. The reason would be that this method was similar to an operation on a touch screen like that of a smartphone. In the narrowing-down selection, we determined the 26th and 27th set of P1 as uncommon values and the performance on the last day reached an average of 97%. These low accuracies of P1 occurred on the first and second set on the last day, and we considered that P1 had confirmed the correct input in these sets. After these sets, P1 corrected the input and increased accuracy. Although the first set performance was the lowest of the four methods, the learning increased the input accuracy in the last set. The selection method of touching all wrinkles was complicated, and participants were not familiar with it, which probably caused the above. The pinch input reached an average of 98% on the last day and the highest accuracy of the four methods. Different behaviors in the selection and the decision realized the high precision operation.

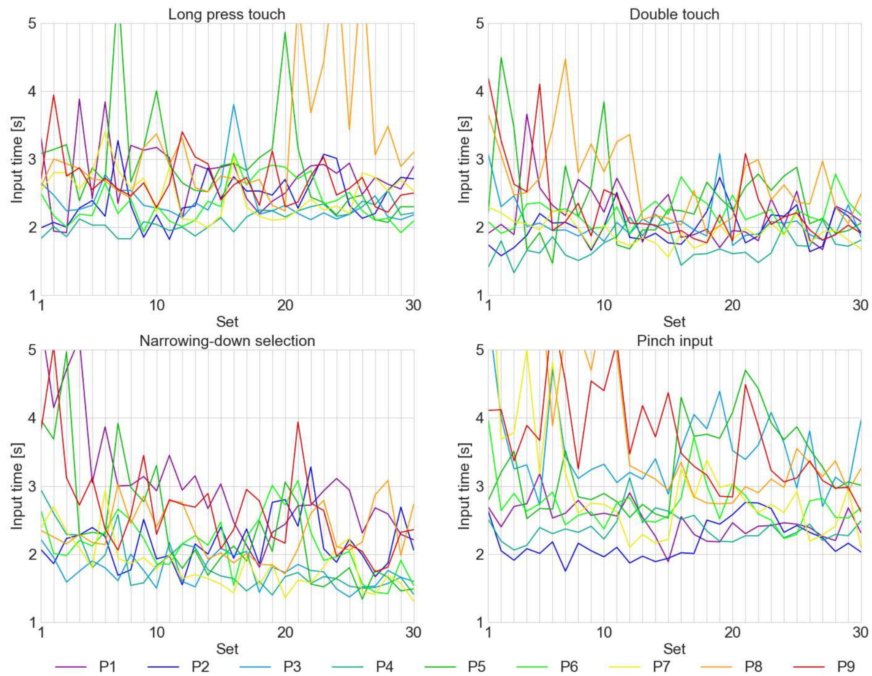

Fig. 4. The change of input time in each input method

Figure 4 depicts the change of the input time for six days. The input time was the average time in a set of trials between showing the indication of a targeted wrinkle on a PC screen and completion of the input with an input method. The performance of the long press touch on the last day reached an average time of 2.46 seconds, and we determined the 26th set of P8 as uncommon values. The long press touch has a time constraint, and participants took approximately 2 seconds at a minimum. P8 took 5 or more seconds per input on 21st, 24th, 26th set. P8 had touched a targeted wrinkle, however, the interface had taken such a long time until the recognition of the touch, which would be caused by the drying finger. The double touch performance on the last day reached 2.02 seconds and achieved the smallest variance of the four input methods. The performance of the narrowing-down selection on the last day reached 1.87 seconds and the fastest input speed of the four input methods. The selection method of the narrowing-down selection was complicated and caused the largest variance out of the three touch input methods. The performance of the pinch input on the last day reached 2.74 seconds and the slowest speed among the four methods. This was because of the separation between the selecting and deciding behavior. In addition, the wrinkles had a lining inside the top, which made it difficult to pinch them.

5.2. *Effect of wrinkles*

Wrinkles supply information to the user through their tactile, which helps the user to input to a targeted wrinkle. We compared the inputs to investigate the effect of the presence of wrinkles.

5.2.1. *Participant and procedure*

We recruited eight participants (six male, two female) who had finished the experiment in Section 5.1. We erased the wrinkles on the cloth used in the experiment in Section 5.1 with a steam iron and attached the cloth to the front of the right thigh of the trousers. The participants wore the trousers and sat in a chair and were asked to select and input following the instruction on the PC screen without looking at the input device. We used the same application, and they carried out three sets of the same trials as in Section 5.1.

5.2.2. *Result*

Figure 5 shows the average, maximum, and minimum accuracies calculated from the results with and without wrinkles of all the participants. We used the result of the last three sets that each participant performed in the experiment Section 5.1 as the result of the input using wrinkles. We used all touches recognized by the application and calculated the accuracy from the total number of successes which each participant had inputted the targeted wrinkle in three sets of trials. In all the input methods, the input with wrinkles achieved higher accuracies and smaller variances than when there were no wrinkles. Notably, the narrowing-down selection achieved a higher average accuracy of 4%.

Figure 6 shows the average, maximum, minimum times per input with and without wrinkles. The input time was the average time in the three sets between showing the instruction on the PC screen and the completion of the input with each input method. When the interface had generated wrinkles, all input methods achieved a faster input time and input methods excepted the long press touch achieved a smaller variance than when no wrinkles. When there were wrinkles, the input time of P8 in Section 5.1 was slower than when no wrinkles. This would be because of the drying of the fingers. The pinch input with wrinkles got faster 1.5 seconds, and the variance of its input time did smaller, and those change amounts were the largest of four input methods.

The two-way ANOVA showed a statistically significant difference in the presence of wrinkles on the input accuracy ($F(1, 21) = 4.75, p < .10$). Also, the ANOVA showed a significant difference of interaction between input methods and the presence of wrinkles on the input time ($F(3, 21) = 10.48, p < .01$). The analysis of the interaction showed significant differences of a main effect of input methods on the input time using wrinkles ($F(3, 21) = 11.59, p < .01$) and no wrinkles ($F(3, 21) = 14.40, p < .01$). The Fisher's LSD test showed that the double touch and narrowing-down selection were faster than the long press touch and pinch input using wrinkles, and the pinch input was the slowest without wrinkles. In addition, a main effect of the presence of wrinkles has significant differences when the double touch ($F(1, 21) = 6.87, p < .05$), the narrowing-down selection ($F(1, 21) = 5.31, p < .10$) and the pinch input ($F(1, 21) = 16.84, p < .01$).

5.3. *Input performance in various combinations of operating environments and device positions*

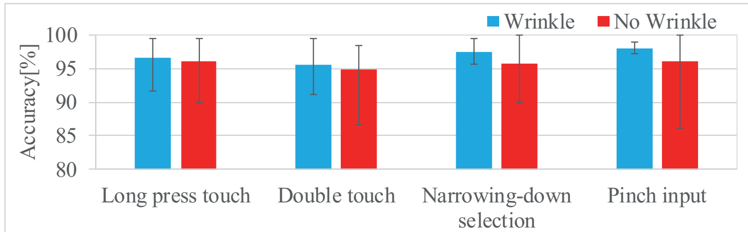

Fig. 5. The comparison of input accuracy with and without wrinkles

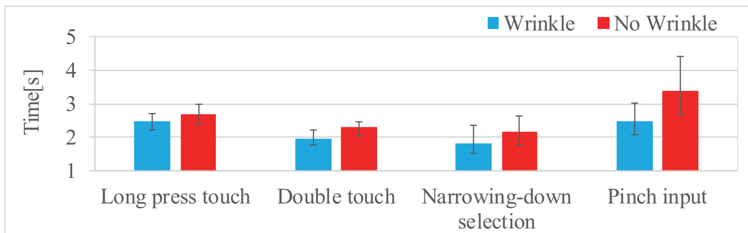

Fig. 6. The comparison of input time with and without wrinkles

We assumed that the user operates in various environments and operating positions of the device on his/her body. The input method having excellent operationality would vary according to the operating environment and operating position. Therefore, we evaluated the input accuracy and input time in different environments and operating positions.

We considered that the interface using wrinkles enabled users to operate in situations where the use of information presentation devices is difficult, such as walking, or when the action needs to be concealed from surrounding people, such as during a meeting. The user operates it in the place where available spaces are restricted or being shaken, such as on a train. Therefore, we decided sitting in a chair, standing, walking, and riding a train as the evaluation environment.

In the device positions, Wagner et al. [14] investigated the time and accuracy for touching targets on 18 body locations. This research showed that touching targets on the lower legs was slow and unappealing socially, and doing so on the dominant arm was prone to errors. Based on these results, for the position of the device, we selected those areas of the body that users could touch without changing their postures even if they were standing and sitting. In accordance with the societal norm, we eliminated those areas of touching that caused discomfort to other people. We selected seven areas of the human body (the forearm, upper arm, shoulder, abdomen, side, front thigh, and outside thigh) (Figure 7).

5.3.1. *Participant and procedure*

Participants were four of the males who had finished the experiment in Section 5.1 and we started the test in a sitting posture. They wore the clothes in which the input device was mounted and sat on a chair in front of the desk where a PC located. We asked them to provide the input following the indication on the PC screen without looking at the input device. They performed the same set of trials as in Section 5.1 three times subsequently in

Fig. 7. Device positions

each device position, and the position was changed after finishing three sets. When they had finished tasks on all the positions in the sitting posture, they changed the posture to standing. They stood in front of the desk and performed three sets in each position. After finishing tasks in the standing posture, they performed tasks during walking. They walked on a treadmill at a speed of 4 km/h which was an average walking speed and performed the three sets in each position. Finally, they performed tasks on a train after finishing tasks during walking. They stood in holding a strap on a train and performed three sets in each position. In the sitting and the standing posture, the indication of the targeted wrinkle was shown on the PC screen, and when walking, the application gave the voice instruction showing the input method and target in addition to that. For the train experiment, we changed a wireless communicator to a BLE Nano from an XBee and implemented the evaluation application for a smartphone. In this device, the Arduino Nano recognizes an input to a wrinkle and sends the recognition result to the iPod touch running the application. The application gives the audio instruction providing the set of an input method and targeted wrinkle. The order of the position was random in each environment.

5.3.2. *Result*

Figure 8 depicts the average input accuracy of each input method in all combinations of operating environments and device positions. We calculated the input accuracy out of the total number of successes when each participant has touched the targeted wrinkle in all the three sets. The long press touch achieved an average accuracy of 90% or more on all combination of environments and positions. The input on the upper arm and the shoulder achieved a high average accuracy of 95% or more in all environments because these positions were stable independently of environments. The input on the side when sitting achieved the lowest average accuracy of 91.1% and the largest standard deviation of 8.67 of all results of the long press touch. The double touch achieved an average accuracy of 90% or more on the forearm, the upper arm, the shoulder, and the abdomen in all environments. The input on the thigh achieved an average accuracy of 90% or more except for when walking. The input on the thigh achieved the low performance when walking due to the movement of the thigh, and the average accuracies on the front and outside thigh when walking were 85.7% and 84.3% respectively. The input on the abdomen when sitting achieved the highest standard deviation of 11.6 because the performance of one participant was a low accuracy of 71.1%. The narrowing-down selection achieved an average accuracy of 90% or more in all environments, except for the input on the side. The input on the side achieved the low performance in environments except for when riding a train, and the average accuracy

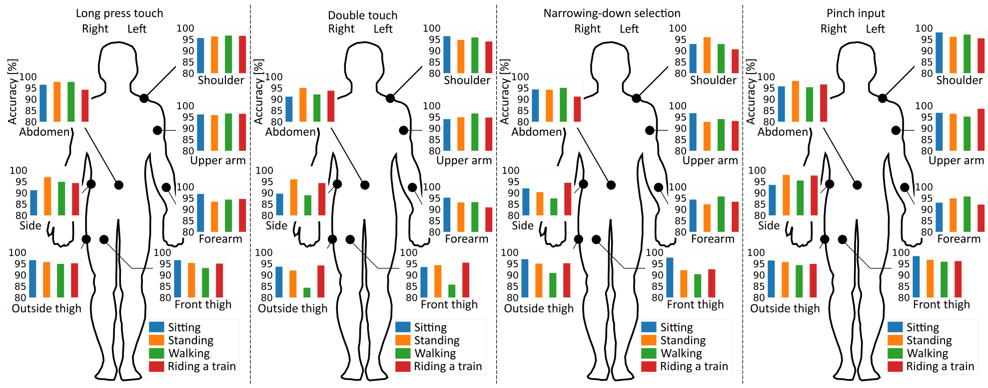

Fig. 8. Average input accuracy in all combinations of input methods, device positions, and operation environments

on the side when walking was the lowest average accuracy of 87.5% of all results of the narrowing-down selection. The input on the forearm when walking achieved the highest standard deviation of 8.66 due to the low accuracy of one participant of 77.2%. The pinch input achieved an average accuracy of 90% or more on all combination of environments and positions. The input on the upper arm, the shoulder, the abdomen, and the front thigh achieved a high average accuracy of 95% or more in all environments. The input on the forearm except for when walking achieved the high standard deviation of around six.

From the above results, we found that the upper arm and the shoulder maintained a high accuracy of all input methods in all environments since these positions were affected a minimum impact by operating environments. The input on the side decreased performances of all methods since touching the upper part of the right side by the right hand was difficult especially when sitting and walking. The input on the thigh decreased the accuracy when walking since the input surface moved and the distance of that from the dominant arm changed, notably, the double touch and the narrowing-down selection decreased their performances largely when walking. The two input methods require floating the hand from the input surface once, which caused the large fall of their performance when walking. The three-way ANOVA showed a significant difference in the main effect of input methods ($F(3, 9) = 8.33, p < .01$). The Fisher's LSD test showed that the long press touch and the pinch input acquired higher accuracies than the double touch and the narrowing-down selection.

Figure 9 depicts the average input time of each input method in all combinations of operating environments and device positions. The input time of each participant is the average time between the output of the target and completion of the input in three sets of trials. The long press touch achieved the average time of around 2.5 seconds in all combination of operating environments and device positions. The average input time on the shoulder when sitting, standing, and riding a train was respectively the fastest of each environment of 2.35, 2.23, and 2.31 seconds. The input time on the forearm achieved the largest standard deviation of 0.57 of all results of the long press touch. The double touch achieved the fastest average time of 1.99 seconds on the thigh front when sitting, 2.01 seconds on the shoulder when standing, and 2.34 seconds on the abdomen when walking, and 1.82 seconds on the forearm when riding a train. The average input time on the side when walking was the

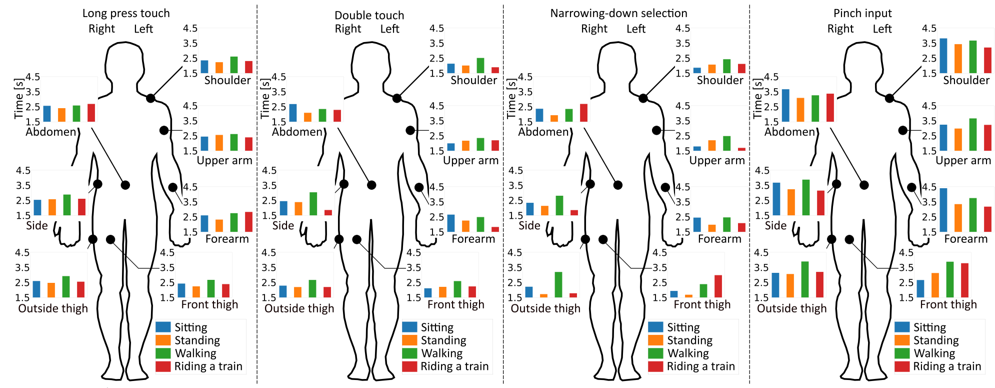

Fig. 9. Average input time in all combinations of input methods, device positions, and operation environments

longest time of 3.03 seconds of all results of the double touch because of the twist of the body when walking deformed the input surface. In the narrowing-down selection, the fastest input time of each environment was 1.76 seconds on the upper arm when sitting, 1.68 seconds on the front thigh when sitting, 2.34 seconds on the abdomen when walking, and 1.69 seconds on the upper arm when riding a train. This method achieved the fastest input time in each operating environment, and when the sitting and standing experiment, this method achieved the fastest input on all device positions. However, in the train experiment, the input time on the abdomen and the front thigh had the large standard deviation that was 1.55 and 2.01 respectively. One participant took 5.3 seconds on the abdomen and 6.3 seconds on the front thigh per input on average. He reported that it had been difficult to know whether or not touching all wrinkles and required feedback informing the success of touching all wrinkles. The pinch input achieved the fastest average time of 2.66 seconds on the front thigh when sitting, 2.98 seconds on the upper arm when standing, 3.25 seconds on the abdomen when walking, and 3.14 seconds on the side when riding a train. This method was slower than touch input methods in all combinations of environments and positions.

From these results, we found that the narrowing-down selection method achieved the fastest input speed of all input methods, while the pinch input did the slowest speed. The narrowing-down selection had no time construction and the selection method could confirm all wrinkles at once, which could input fast. The pinch input separated the selection and input behavior, and conductive threads for detecting pinch were narrow, which caused the slowest input speed. Users could input fast when standing in all input methods on almost positions because they easily touched their body parts in standing posture. On the other hand, the input during walking was slow due to the movement of the input surface. Some user felt difficult to sense whether touching all wrinkles in the narrowing-down selection on a train due to the shake. The three-way ANOVA showed a significant difference in an interaction of the input methods, postures, and device positions ($F(54, 162) = 1.44, p < .05$). The two-way ANOVA in each device positions showed significant differences of a main effect of input methods on the forearm, upper arm, shoulder, side, and front thigh (respectively $F(3, 9) = 6.51, 4.53, 6.68, 4.29, 4.12$, all $p < .05$). The Fisher's LSD test showed that the pinch input was the slowest input of all input methods.

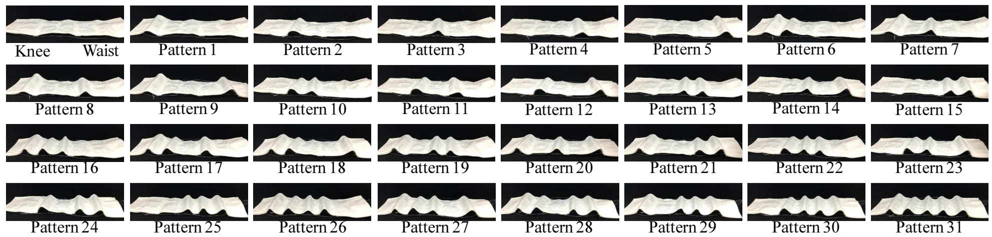

Fig. 10. All wrinkles patterns

5.4. *Recognition of wrinkle patterns*

We assumed that the generation of wrinkles of various patterns supplied information about the input to the user. To confirm whether he/she can recognize the shape and number of wrinkles when touching them, we evaluated the recognition of the generation pattern.

5.4.1. *Participant and procedure*

Participants wore the trousers where the output device as mounted and sat in a chair in front of a desk where we had put a PC. The device was not sewn with conductive threads and they were to use only the tactile for the wrinkles. Wrinkles shaping a pattern appeared on the device. The instruction asking participants to touch the device was shown on the PC screen when completion of generating the pattern. When they saw the instruction, they recognized the completion of the pattern generation. Then, they touched the wrinkles and chose the same pattern as it shaped by the wrinkles on the PC screen using a trackpad without looking at the device. The wrinkles on the device and the instruction on the PC disappeared after the selection, and the other shaped pattern appeared, and the instruction was shown on the PC when the generation completion. The prototype could generate up to 5 wrinkles and has 31 patterns of generated wrinkles excepted for the pattern that all wrinkles are not generated. Each test that each participant carried out consisted of all patterns of wrinkles and each pattern appeared randomly once in the test. Before the test started, participants carried out the learning phase once. The learning phase had the same content of the test and gave audio feedback of different sounds according to the correctness of the selection of the pattern the on the PC screen, and the test phase did not. 11 all-male, right-handed participants were recruited for this experiment. Figure 10 shows all the generation patterns of the wrinkles.

5.4.2. *Result*

This result achieved 89.4% (SD = 11.8) of an average recognition rate of all participants and approximately 17 seconds (SD = 6.46) of an average recognition time. We calculated each recognition rate from the number of times that the participant had succeeded in selecting the correct pattern in a 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 in a test. These results show that they can recognize the change in the shape of the clothes only by the tactile.

Figure 11 shows the confusion matrix indicating the number of times that participants

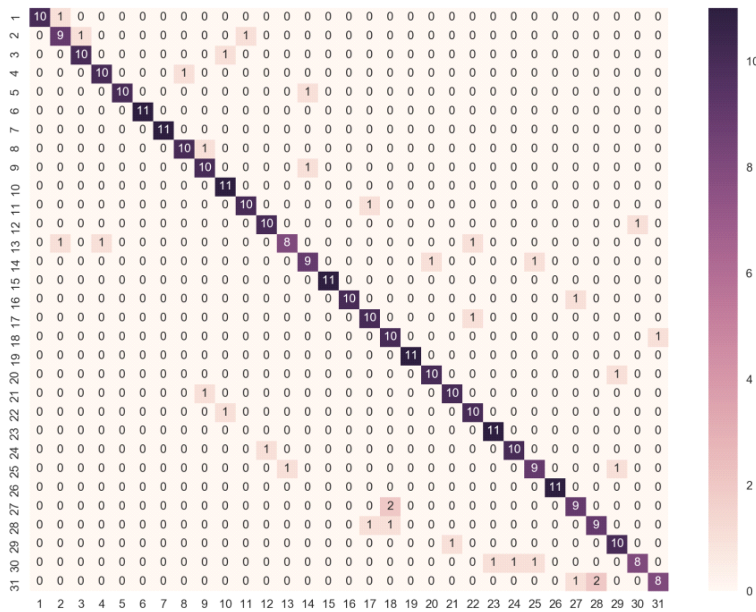

Fig. 11. Confusion matrix of result

recognized each pattern of wrinkles. We found a tendency to commit mistakes from this result. Participants tended to recognize that there were not three wrinkles on the waist side, although those had been actually generated. The above mistake occurred in the pattern 13, 21, 22, 24, 25, 27, 28, 29, 30, 31. Especially, when three or more wrinkles had been generated, the mistake was likely to occur. A common observation in all the participants was that they touched from the knee side in order. They also did not touch wrinkles at the same time. Furthermore, the central wrinkle was smaller than the others since it was pulled most muscularly from both sides in generating them. It was also hard to generate wrinkles of waist side since the amount of the cloth pulled up was increased. These factors would cause this tendency of mistakes. The recognition time included the selection of the pattern on the PC screen. The selection time on the PC screen took approximately five seconds on an average in all participants.

We divided 31 wrinkles patterns into 4 groups (group 1: pattern 1 - 5, group 2: pattern 6 - 15, group 3: pattern 16 - 25, group 4: pattern 26 - 31) depending on the number of wrinkles and calculated the recognition rate of each participant per groups. Although we conducted the ANOVA using the above accuracy, we did not find any significant differences.

6. Discussion

6.1. *Input method*

The result reveals that the performance of the four input methods yielded an average accuracy of more than 97%, the highest of 98% being of the pinch input. The separation of the selection and decision behavior produced high input accuracy. The double touch that is similar to an operation on a touch screen achieved an accuracy of more than 85% on the first day with a small variance. The narrowing-down selection reached the fastest input time of 1.64 seconds on the last day. However, the selection method touching all the wrinkles requires long-term learning for mastery. The long press touch had a time constraint and would have the optimum time to maintain the input accuracy. The wrinkles on the input device have a structure that is hard to pinch and caused the slowest time, and the pinch input requires an improvement in them with appropriate interval and thickness of two conductive seams so that it would be easy to pinch. When comparing the effect of wrinkles on the input, they affect the input time in all input methods, which is especially accelerated in the pinch input.

From the results of evaluating the operating environments and device positions, the long press touch and the pinch input reached a high accuracy of 90% or more in all combinations of operating environments and device positions. These input methods enable users to input without floating their hand from the input surface, which realizes the high accurate operation regardless of the environments and positions. In the pinch input, however, the separation of the selection and the decision behaviors and the wrinkles having the difficulty of pinching caused the slow input speed of the pinch input. In the double touch and narrowing-down selection, the user takes his/her hands off a wrinkle during the selection and decision process, which drops the input accuracy on the thigh when walking. However, the selection method touching all wrinkles attains fast input operation since the user can confirm the position of all wrinkles at once. All input methods on the upper arm and the shoulder achieved a high accuracy independent on operating environments. Operating environments had a minimal effect on the input on these areas of the body. Touching the upper part of the right side by the right hand is difficult, which drops the performance of the input on the side during sitting and walking.

We summarize the property of each input method obtained from the evaluation experiment below. The long press touch and the pinch input which do not require the floating the user's hand from the input surface realize the accurate input operation. Also, the separation of the selection and decision behavior such as the pinch input helps to input accurately. The double touch and the narrowing-down selection achieve a fast input operation. Notably, the narrowing-down selection has the fast selection method of a targeted wrinkle. However, this method is easily affected by the operating environment and the user needs long-term learning to master it. We suggest the input on the upper arm and the shoulder where all input methods are hardly affected by operating environments. We have to find the structure of the wrinkle which makes it easy to pinch to improve the speed of the pinch input.

6.2. *Wrinkle recognition*

The interface using wrinkles generates several wrinkles corresponding to the input required in an application. The designer designs an application and the generation pattern of wrinkles simultaneously. The results of the evaluation indicate the guidelines of the design of the wrinkle pattern. The patterns consisting of three wrinkles had high accuracy. However, the recognition accuracy of patterns consisting of four or more wrinkles is low. Therefore, an eyes-free operation using this interface should be designed to have three or fewer commands. A complicated operation requiring four or more commands should be designed using a display. The wrinkle recognition time took 12 seconds. Actuators which drive faster than the artificial muscle reduce the wrinkle generation and erase time. We considered implementing the device by combining fabrics where a single wrinkle is generated. Combining small fabrics makes the amount of cloth pulled up a uniform and enable to generate various wrinkle having different textures, which increases the recognition accuracy and decreases the recognition time.

7. Conclusion

We evaluated the input using wrinkles, reviewed the input and designed three touch input methods and one pinch input method and implemented the input and output device using wrinkles and carried out four evaluations. From the results, it can be concluded that all the input methods have the learnability, and the performance of all the input methods reached an average accuracy of 95% or more, the highest being 98% of the pinch input. The narrowing-down selection reached the fastest input time of 1.87 seconds on the last day. When comparing these performances with the input using no wrinkles, it was found that wrinkles increase the input speed in all the input methods, especially, the pinch input method. The result of evaluating the input in the combination of four operating environments and seven device positions reveals that the long press touch and the pinch input reach a high accuracy of 90% or more in all combination of positions and environments. The performance of the double touch and the narrowing-down selection decrease largely on the thigh during walking. The upper arm and the shoulder are operating positions where the performance of each input method changes little if the operating environment changes. According to the result of the wrinkle recognition, users have a high accuracy of 89.4% of identification of wrinkles and recognize their shape in approximately 12 seconds.

Acknowledgements

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