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Experimental evaluation of the flexion and extension movement characteristics of toes in a position operation task and a comparison with fingers

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ABSTRACT

Toes are expected to perform various tasks by bending and stretching movements. However, to our knowledge, few studies have examined toe movement for operation. In particular, the characteristics of toe movements when used for operation have not been clarified. To investigate these characteristics, we proposed a new experimental evaluation system using wire displacement sensors. In this system, operators can move a marker shown on a PC screen by toe flexion and extension movements. In the experiment, 16 different operation patterns were considered, and the time required to finish the operation with one or two toes was measured and evaluated based on the average operation time. A comparison between toe flexors and extensors in operation time indicated that toe movements with a large angle were easier than those with a small angle if only one toe was used, but became more difficult if two toes were used. These results suggest that the ease or difficulty of toe movements differed depending on whether one or two toes are used. These results were then compared with those of additional evaluation experiments we conducted using fingers. The results indicated that toe operation requires 3.51 times more time than finger operation if two toes or fingers are used.

1. Introduction

In general, lower limbs in human are mainly used for walking; they are rarely used for manipulating objects, which is one of the main uses of the upper limbs. However, since the lower limbs have multiple degrees of freedom, similar to the upper limbs, they are considered to be capable of manipulating objects using an operation device. Therefore, to expand human functions, the lower limbs could be expected to play a new role. Some studies have researched and developed operation devices that utilize the lower limbs. Matsuda et al. developed a projection-type I/O interface in which the screen, which is projected onto the floor from a projector fixed on the operator's chest, can be operated by the feet [1]. Fukahori et al. developed an operation device using gravity and pressure applied on specific positions of the soles [2]. Yamamoto et al. proposed an operation device that tracks the foot movements of a jogger through sensors attached to the shoes and generates four different operation commands [3]. In recent years, some studies have been conducted on recognition methods for whole foot gestures such as kicking and striking [4], and PC operation devices utilizing such gestures have been developed [5]. In addition, some operation methods using a motion capture system to measure ankle angles have been proposed [6]. Komori et al. clarified experimentally the characteristics of foot movement during operation and proposed methods for machine operation [7]. Some research on computer mouse operation using the lower limbs has also been reported, including a study by Kume et al. that evaluated the accuracy and efficiency of pointing operations using a double-foot-type mouse [8].

As toes are part of the lower limbs, operation methods using toes are also considered to be valid. However, research on operation methods using toe movements has rarely been reported. Especially, the characteristics of toe movements during operation have not been clarified. Since toes are not as dexterous as fingers, each toe is considered to have easy and difficult movements. Additionally, when two toes are operated at the same time, the movement of one toe can affect that of the other. To realize high toe operability, it is therefore important to gain a better understanding of the characteristics of toe movements for consideration in terms of operation methods.

Since fingers are used on a daily basis to finish complicated tasks by

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flexion and extension movements, they have been the subject of numerous studies, including research on the characteristics of finger movements in the medical field [9,10] and movement analyses of finger joints in the engineering field [11,12]. On the other hand, some research focusing on toes has shown that toes play an important role in maintaining balance and preventing falls during walking [13,14]. Medical studies on toes include investigations about joint range of motion and flexor muscle force during full extension [15,16], the joint motion characteristics and contact surface of the great toe [17], and the location and principles of toe movements based on electroencephalograms [18,19]. Moreover, studies in the nursing field have compared toe grip strength in dominant and non-dominant feet [20], and the relations between gait speed, step length, and toe training [21,22]. And Sun et al. (2018) also clarified that different walking speeds had different effect on foot inter-segment kinematics, ground reaction forces, and lower limb joint moments [23]. However, in these studies toe operation methods have not been investigated. Although a computer mouse operated by the toes has been reported [24], the characteristics of toe movements have not been evaluated. In addition, a device appropriate for measuring toe movements has yet to be developed.

To solve these problems, we developed a new measuring device for toes that can assess flexion and extension movements in small-sized toes with a small range of motion. This device allows the characteristics of toe movements in position operation tasks to be evaluated. In this study, we used our newly developed system to investigate and illustrate experimentally the movement characteristics of the great (first) and long (second) toes. In addition, we clarified the differences between flexion and extension movements, great and long toes, and one- and two-toe operations. Finally, we compared experimentally and discussed toes and fingers movements.

2. Musculoskeletal structure and flexion/extension movement of toes

Before discussing our investigation of movement characteristics, we present a brief description of the anatomical structure of toes. Kai et al. compared the maximum gripping force and the time required to reach this maximum force between dominant and non-dominant feet and observed no significant difference [20], which suggested that toes in dominant and non-dominant feet have the same operability. Then, this paper focuses on the right human foot, and carries out a comparison with the right hand. The investigation targets the great and long toes (first and second toes from the left when the sole is facing downward) and the index and middle fingers (second and third fingers from the left when the palm is facing downward). We also consider flexion, defined as when the toe or finger is bending downward, and extension, defined as when the toe or finger is stretching upward. The configurations of the bones and joints of each finger and toe considered in this paper are shown in Figs. 1 and 2. The great toe has three phalanges: the distal phalange, proximal phalange, and metatarsal bone (in order from the tip of great toe). The joint between the distal and proximal phalanges and that between the proximal phalange and metatarsal bone are known as the proximal interphalangeal (PIP) and metacarpophalangeal (MP) joints, respectively. The long toe has four phalanges, including an additional phalange between the distal and proximal phalanges known as the middle phalange. The joint between the distal and middle phalanges, and that between the middle and proximal phalanges are known as the distal interphalangeal (DIP) and PIP joints, respectively. The index and middle fingers also have four phalanges and three joints with the same names as those in the long toe.

Next, we give a brief introduction of the extensor and flexor muscles affecting extension and flexion movements. Fig. 3 shows the three main muscles from the back of foot that affect toe extension movements [25]. The extensor halluces longus (EHL) muscle extends from the fibula to the tip of the great toe, four extensor digitorum longus (EDL) muscles, which belong to the same muscle group, extend from the tibia to the tips of the toes, excluding the great toe, and extensor digitorum brevis (EDB) and extensor hallucis brevis (EHB) muscles, which belong to the same muscle group, extend from the ankle to the tips of the toes, excluding the little toe. The MP and PIP joints in the great toe are stretched by the EHB and EHL muscles, respectively, while the DIP, PIP, and MP joints in the long toe are all stretched by the EDL and EDB muscles. The five main muscles acting on the bending movements of the toes, which are distributed in three layers (the shallow, middle, and deep layers), are shown from the sole of the foot in Fig. 4. Four flexor digitorum brevis (FDB) muscles, which belong to the same muscle group, extend from the calcaneus to the PIP joints of the toes, excluding the great toe, and act on the flexion movement of the PIP and MIP joints in the long toe. In the middle layer, the flexor hallucis longus (FHL) muscle extends from the fibula to the tip of the great toe and acts on the flexion movement of the PIP joint in the great toe. Four flexor digitorum longus (FDL) muscles, which belong to the same muscle group, extend from the fibula to the toes, excluding the great toe, and act on the flexion movement of the DIP, PIP, and MP joints. The flexor hallucis brevis (FHB) muscle extends from the lower surface of the cuboid bone to the MP joint in the great toe and acts on its bending movement. Moreover, four lumbrical muscles in the deep layer, which belong to the same muscle group, extend from the inside of the FDL muscle and adhere to the tips of the toes, excluding the great toe, and act on the flexion movement of the MP joint in the long toe. The quadratus plantae and interossei muscles also assist the flexion movement of the toes.

As shown above, the great toe is considered to be able to bend or stretch relatively easily since it has its own extensor and flexor muscles. Conversely, it is considered difficult for the long toe to move separately from the other toes since their extensor and flexor muscles belong to the same muscle group. It is also known that the long toe has fewer muscles for extension than for flexion, and that the flexor muscle has a larger physiological cross-sectional area than the extensor muscle in the great toe [25]. In addition, toes are frequently bent to maintain stability

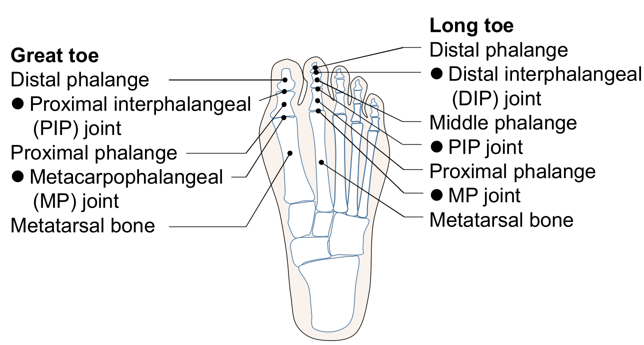

Fig. 1. Bones and joints in the foot.

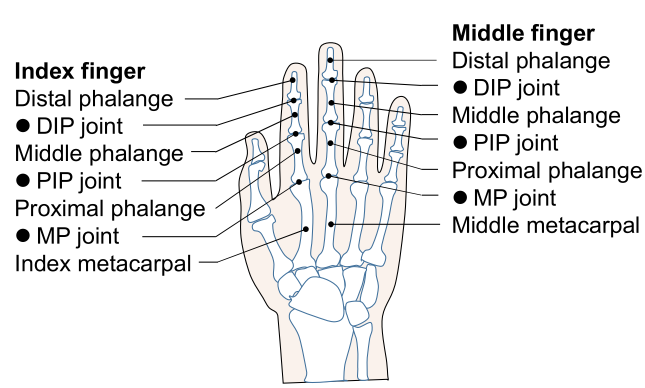

Fig. 2. Bones and joints in the hand.

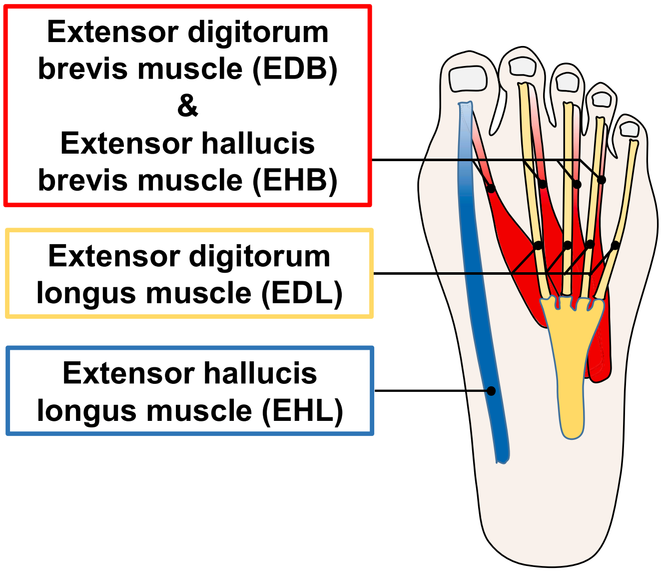

Fig. 3. The extensor muscles in the foot.

during walking, whereas stretching movements are rarely used in daily life [26]. From this, it is expected that flexion movements are easier and more accurate than extension movements in the toes. Based on this expectation, with a focus on the flexion and extension movements of the great and long toes, we conducted experiments to examine and compare the differences between flexion and extension movements, the great and long toes, and fingers and toes. The purpose of these experiments was to illustrate quantitatively how quickly toes and fingers operate, as well as differences in their operability.

3. Development of a measurement device and evaluation experiments for single toe movements

In this section, we describe our evaluation of the accuracy and speed of movement of a single toe or finger when bent or stretched at a specific angle. To conduct this evaluation, we developed a new system that involved a device to measure and compare differences in the flexion and extension movements of a single toe or finger. For the purpose of the present study, we specifically measured the flexion and extension movements of the MP joints of the right foot and hand.

3.1. Development of a measurement device for toe and finger movements

We developed a new device for measuring the flexion and extension movements of the toes and fingers. It is more difficult to measure toe than finger movements because toes are smaller than fingers. To our knowledge, few studies have involved devices for measuring toe movements, so the development of such a device was a focus of this study.

Some studies in the medical field have used dynamometers or strain gauges to measure toe movements or toe gripping force during flexion [27,28]. However, few studies have been conducted on the development of a measurement device for toe flexion and extension. Mita et al. investigated changes in the angle of the MP joint in the great toe during walking using a potentiometer-type rotation angle sensor [29]. However, it is difficult to measure flexion and extension angles in the other toes with this device because it cannot be fixed on toes other than the great toe.

On the other hand, many studies have been conducted on measurement methods for finger movements. In particular, measurement devices using optical systems have frequently been used, such as extracting the outlines of fingers from imaging information on finger movements [30], as have detection methods for markers on the hands using cameras [31–33]. Using these optical methods makes it possible to measure the movements of multiple fingers. However, finger movements sometimes cannot be measured using these methods because of interference involving the markers fixed on the fingers, and this is considered to be even more problematic when measuring toes owing to their smaller size.

To solve these problems, we decided to use contact-type sensors instead of optical methods to measure toe movements. The measurement device we developed to measure toe movements is shown in Fig. 5 (a). We used a wire-type magnetic displacement sensor (Wire-in Pulse Coder, LEVEX Corp., Kyoto, Japan) that consists of a wire fixed on the

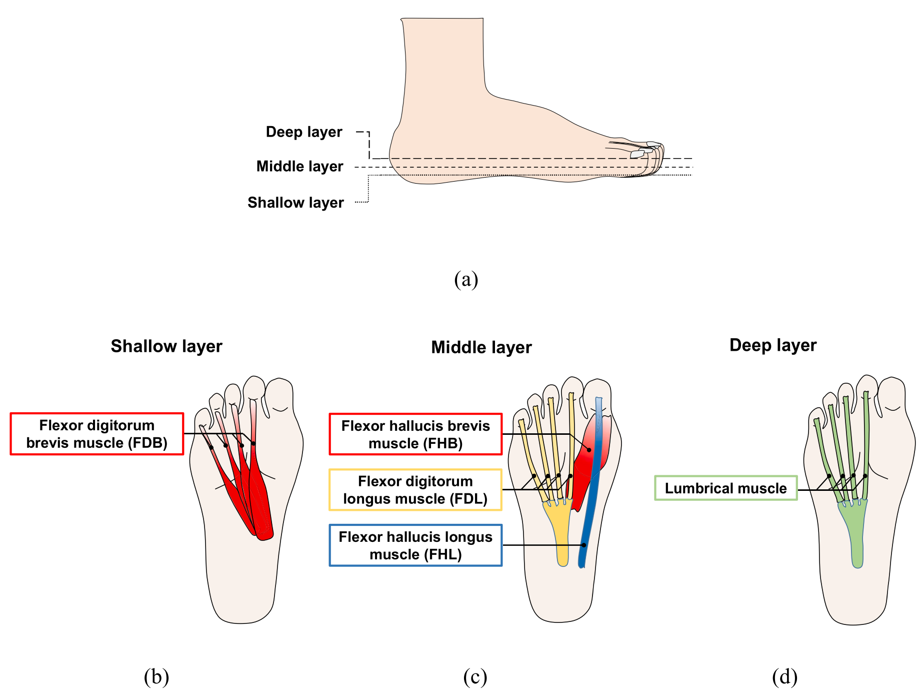

Fig. 4. The flexor muscles in the foot: (a) The three layers of the foot with flexor muscles. (b) Shallow layer. (c) Middle layer. (d) Deep layer.

toe and a metal tube fixed on the back of the foot. This sensor outputs a voltage according to the amount of wire ejected from and inserted into the metal tube when the toe is bent and stretched, respectively. Variations in the measured voltage indicate changes in the angle of the toe. The linearity of this sensor is ±2%/F.S, so the repeat accuracy is within this range. This method has the following merits: 1) it is easy to fix the sensor on small toes since the wire is thin (φ0.2 mm); 2) the flexion movements of the toe can be tracked by this wire because of its softness; 3) the sensor is so light that the burden on the body is small; and 4) the same measurement device can also be applied to fingers, as shown in Fig. 5(b).

The measured flexion amount of toes Y is calculated as follows:

$$Y = 100 \times \frac{2V - V_{\max} - V_{\min}}{V_{\max} - V_{\min}} \tag{1}$$

where V is the voltage of the sensor, $V_{\min}$ is the voltage of the sensor when the toe is fully bent, and $V_{\max}$ is the voltage of the sensor when the toe is fully stretched. When V is $V_{\min} \le V \le V_{\max}$, the value of Y is $-100 \le Y \le 100$. Thus, the closer Y is to 100, the larger the toe stretching angle, whereas the closer Y is to -100, the larger the toe bending angle. In addition, when the toe flexion is about $Y = 0$ (i.e., $V = (V_{\max} + V_{\min})/2$), it is considered to indicate a relaxed position for the flexor and extensor muscles [34]. Although the range of toe flexion and extension varies with each individual, these values can be expressed relatively based on the value of Y as defined by (1), which makes it possible to provide examinees with roughly equivalent operation conditions.

3.2. Construction of the evaluation system and game

Fig. 6(a) shows the constructed evaluation system. The examinee wears one sock or glove on the right foot or hand, onto which the developed measurement device is attached. The examinee then sits on a chair facing a PC monitor. The foot is placed on a platform on the floor so that the toes can move freely, as shown in Fig. 6(b). The inclination angle of the platform is 20°. The right hand is placed on the armrest of the chair with the palm facing downward so that the fingers can also move freely.

The PC monitor displays a blue circular marker, a green circular target, and a rectangular frame surrounding these circles, as shown in Fig. 7. The vertical positions of the marker and target within the rectangular frame vary. As shown in Fig. 8, the coordinate value of the top, center, and bottom positions of the rectangular frame are +100, 0, and −100, respectively. The coordinate value of the marker corresponds to the value of Y, which makes it possible to move the marker vertically using toe flexion and extension. The examinee is expected to move the marker to the target position. In these experiments, the examinee moves his or her toes to clear the target appearing in various positions, and the toe movements are measured and evaluated.

The evaluation game is implemented using the evaluation system described above. In this game, examinees are required to operate the marker using a specified toe or finger from among the great and long toes and index and middle fingers. When the position of the marker matches the position of the target, the target is cleared and the next one is displayed at a different position. The game ends when this operation is repeated and a certain number of targets are cleared.

Regarding the setting of the target position, firstly, within the range from −100 to 100 shown in Fig. 8, the positions where targets may appear are set to as A (+80), B (+40), C(0), D (−40), or E (−80), as shown in Fig. 9. The position of the first target in the game is C, and that of the second is selected from one of the other four positions (A, B, D, or E). Next, the position of the third target is selected from three remaining positions, and that of the fourth is selected from the remaining two. These four targets comprise one target set, and the game consists of ${}_4P_3 = 24$ sorts of target sets in total. In this evaluation game, all 24 target sets are displayed in random order for each examinee. However, examinees may become aware that the fourth target in one target set always appears at position C, which can adversely affect the fairness of the experiments. Therefore, cases in which the marker moves from other positions to C were not considered and the experimental data for these cases were excluded. Therefore, 16 types of operation patterns were considered in this evaluation game (Fig. 10). These patterns are named based on the starting and finishing marker positions; for example, the pattern in which the marker is moved from C to A is named pattern CA. The moving distance of the marker (flexion amount of the toe) for each operation pattern is shown in Table 1.

Regarding the conditions for determining the match between the marker and the target in this evaluation game, examinees move the marker up and down to approach the target using toe movements. The range of the marker's movement is −100 to 100, as shown in Fig. 8, and match status is achieved when the position of the marker is within ±2.5 of the position of the target. If this match status lasts for 1 s, which is called the holding time, the target is cleared and disappears from the monitor. Then, the next target appears at a new position. In this experiment, the repeat accuracy of the measurement device described in 3.1 was not considered to affect the experimental results directly. The examinees always moved their toes or fingers just to make the marker match the target according to the visual feedback, which implies that the examinees compensated the repeat errors without the intension even if such errors occurred in the evaluation game.

3.3. Experimental outline

Experiments using the developed evaluation system were conducted on 10 male adult examinees (mean age ± standard deviation, 22.4 ± 0.92 years) without disability or toe or finger injury. In these experiments, the time intervals from the moment when one target was cleared to the moment when the next target was cleared were measured and referred to as the clearing time; this was used as the main evaluation index. The holding time of 1 s required to clear a target was subtracted from the clearing time. The examinees were required to clear all targets as soon as possible. It was considered that the shorter the clearing time, the higher the operability. All experiments conducted in this study were

(a) (b)

Fig. 5. Placement of the wire displacement sensor on the foot and hand: (a) Measurement device for the toes. (b) Measurement device for the fingers.

(a) (b)

Fig. 6. Experimental setup: (a) Examinee and experimental setup. (b) Platform for the foot.

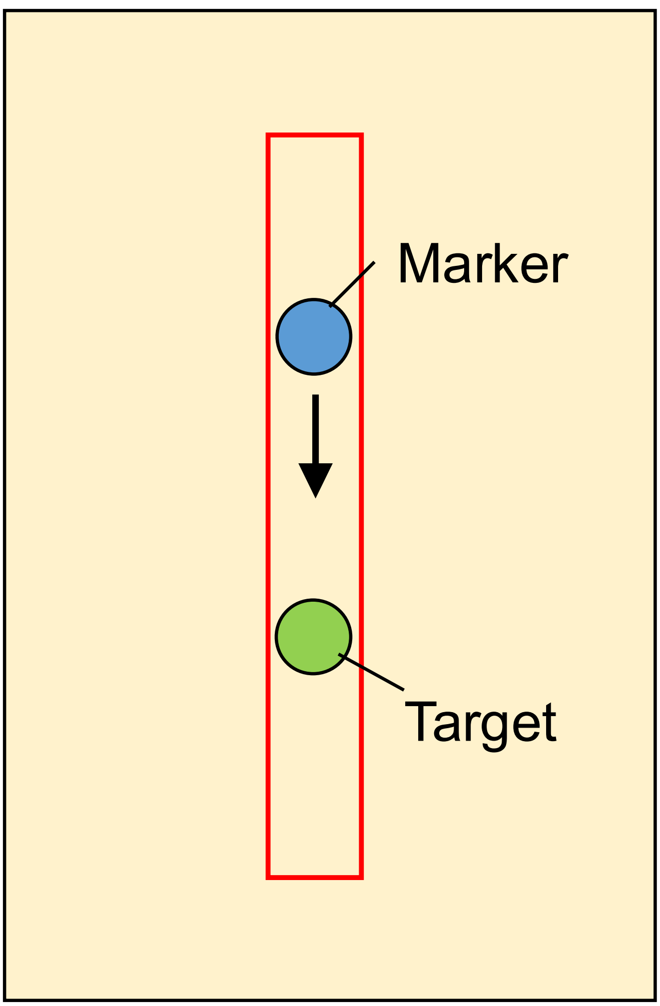

Fig. 7. Evaluation game as displayed on the monitor.

approved by the Kyoto University Graduate School of Engineering Ethics Committee.

Before the evaluation games, a practice game was conducted so that each examinee could become familiar how to operate the marker. In total, 25 targets, which consisted of six target sets with 24 targets and a single target appearing at position C at the end of the game, comprised a game set. In the practice game, one game set was performed. After the practice game, a test game with four game sets, which consisted of 100 targets for each toe or finger, was started, with a 1-min break between each game set. Additionally to the 1-min break, the examinees were asked to take a break if they felt fatigued or uncomfortable, even just a little. Therefore, the fatigue of toes was considered to be so limited that it had no significant effect on the experimental results.

3.4. Experimental results and discussion

Fig. 11 shows the experimental results of the average clearing times for the great and long toes and the index and middle fingers. In this figure, the error bars indicate the confidence interval (CI) at a 5% significance level. Grubbs' method was used to reject the outliers observed in the experimental data for the same toe/finger and the same operation pattern in all examinees. As shown in the figure, the average clearing time increased in the order of the index finger, middle finger, great toe, and long toe. The average clearing time of the middle finger was about 1.03 times longer than that of the index finger, the average clearing time of the great toe was about 1.43 times longer than that of the index finger, and the average clearing time of the long toe was about 1.55 times longer than that of the index finger. Fig. 11 also shows the test results of the differences in average values using Welch's *t*-test at a 5% significance level. Although no significant differences were observed between the average clearing time of the index and middle fingers, significant differences were observed for all other cases.

The results from this experiment are discussed here. First, regarding a comparison between the fingers and toes, the toes showed lower operability, which was predicted before the experiments began. The average clearing time of the toes was 1.45 times longer than that for the fingers, which suggests that the operation speed of the toes is about 69% that of the fingers. A comparison of the results for the two toes indicated that the great toe had a better operability than the long toe. This result agrees with the discussion of the musculoskeletal structure presented in Section 2. The average clearing time for the great toe was 0.92 times shorter than that of the long toe, which suggests that the operation speed of the great toe is about 109% that of the long toe. The great toe was considered to have substantially better operability than the long toe because unlike the long toe, the great toe has its own individual flexor and extensor muscles. However, the difference in operation speed between these two toes was small, at only 9%. The result also indicated that the operability of the index and middle fingers was equivalent since no difference was observed. To our knowledge, such quantitative results have not been reported in previous studies.

The 16 operation patterns shown in Fig. 10 were considered. The average clearing time and CIs at a 5% significance level for the toes and fingers for each operation pattern are shown in Fig. 12. We tested the differences of these mean values using Welch's *t*-test at a significance level of 5%. The test results are shown in Table 2. Among the 16

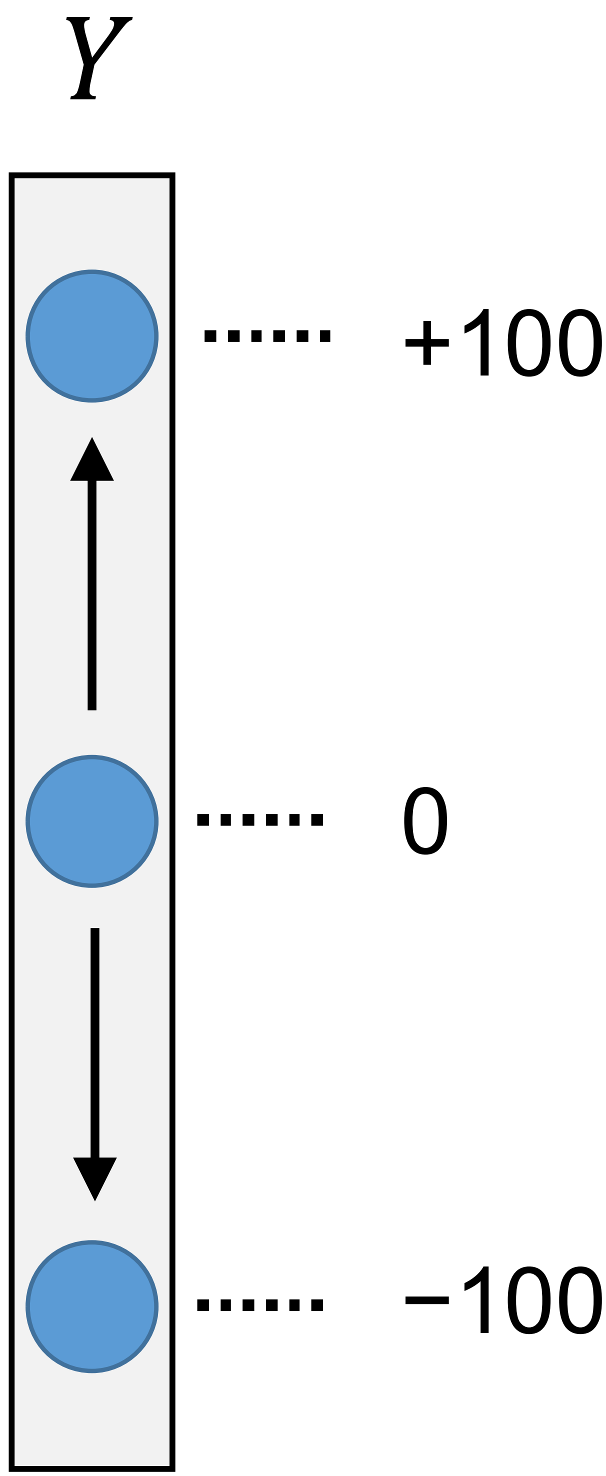

Fig. 8. Range of marker movement.

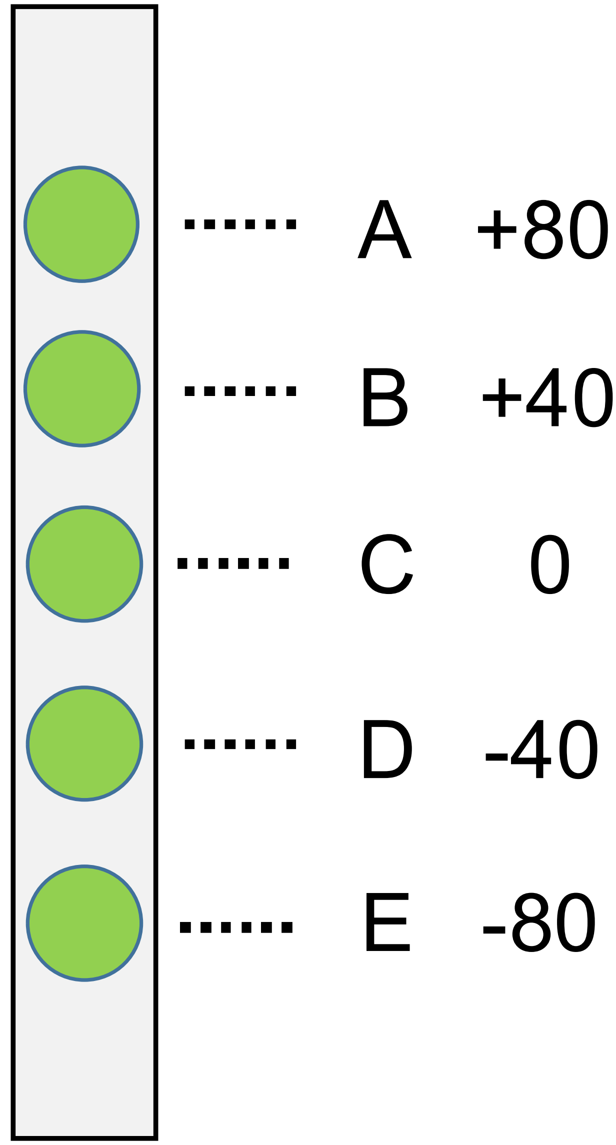

Fig. 9. Appearance positions of the target.

patterns, significant differences between toes and fingers were observed in 12: CA, AB, CB, DB, EB, AD, BD, CD, ED, AE, BE, and CE. These results indicated that the operability of the toes was significantly lower than that of the fingers for these patterns. Although no significant differences between toes and fingers were observed for some comparisons of the other four patterns (BA, DA, EA, and DE), it was confirmed that average clearing time of the toes was longer than that of the fingers for almost all patterns. Among these four patterns, the marker was moved from lower positions to the A position in patterns BA, DA, and EA. This suggests that differences in operability between the toes and fingers are unlikely to occur when substantial extension is required. Moreover, according to the result of a comparison between the two toes, no significant differences in the average clearing time were observed for operation patterns BA, CA, DA, AB, DB, EB, CD, BE, or CE, whereas significant differences were observed for patterns EA, CB, AD, BD, ED, AE, and DE. The operability of great toe was significantly better than that of the long toe for patterns AD, BD, ED, and AE, whereas the operability of the long toe was significantly better for patterns EA, CB, and DE. Regarding the comparison between the two fingers, significant differences in the average clearing time were observed for patterns BA and BD, whereas no significant differences were seen in the other most patterns. This indicates that there were no differences in operability between the index and middle fingers.

Next, the flexion and extension of the toes were considered. We focus on the following operation patterns pairs in which the marker has the same moving distance and opposite moving directions: AB and BA, AD and DA, AE and EA, BD and DA, BE and EB, and DE and ED. Because of having the same moving distance, only the influence of the movement direction, that is, flexion and extension, could be analyzed. The results of the comparison of average clearing times based on Welch's *t*-test are

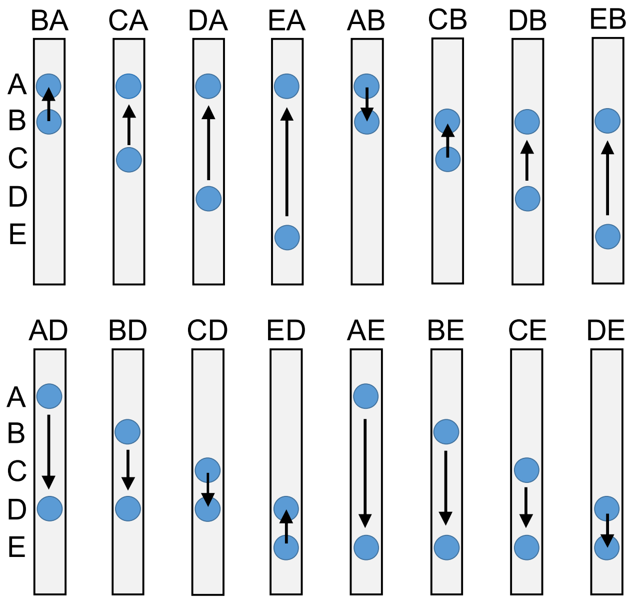

Fig. 10. The 16 operation patterns used in the evaluation game.

Table 1
Displacement of the marker for each operation pattern.

Operation pattern	Marker displacement (toe bending amount Y)
CB, CD, AB, BA, DE, ED	40
CA, CE, BD, DB	80
AD, BE, DA, EB	120
AE, EA	160

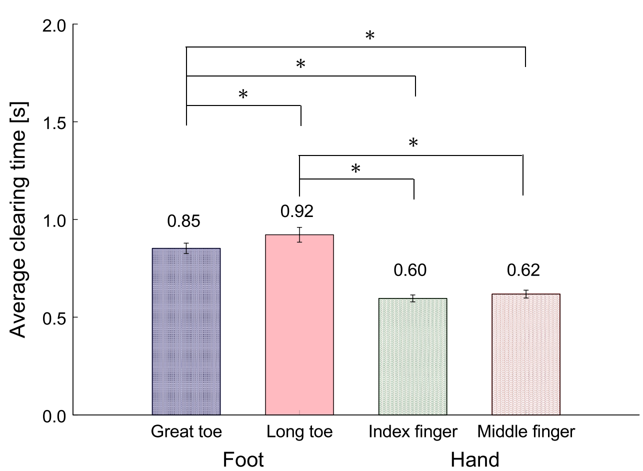

Fig. 11. Average clearing time of each toe and finger in the operation experiments (*: $p \leq 0.05$).

shown in Fig. 13. Patterns AB, AD, AE, BD, BE, and DE are flexion movements, in which the extensor muscles of the toes relax and the flexor muscles become tense, whereas patterns BA, DA, EA, DB, EB, and ED are extension movements, in which the extensor muscles become tense and the flexor muscles relax. In patterns AB, AD, BD, DB, EB, and ED, which are marked with a ● in Fig. 13, the toe or finger must be bent or stretched toward the center position C since the target appears at position B or D. By contrast, in patterns BA, DA, AE, EA, BE, and DE, without a ●, the toe or finger is required to be bent or stretched toward the end of the operating range since the target appears at positon A or E.

To compare the results between these movements, first, the average clearing times of the great toe were tested for all patterns. A significant difference was observed for patterns DE and ED, and the average clearing time for DE was longer than that for ED. On the other hand, no significant difference in average clearing time was observed for any other pattern pairs. Therefore, the operability in terms of the flexion and extension of the great toe was considered to be equivalent. As discussed in Section 2, toe flexion is used more frequently than toe extension in daily life, so flexion was predicted to have better operability than extension. However, the experimental results contrasted with this prediction. In addition, the average clearing time for the long toe when the target appeared at position A or E (patterns BA, DA, BE, and DE in Fig. 13) was shorter than that when the target appeared at position B or D (AB, AD, EB, and ED). Especially significant differences were observed for pattern pairs BE and EB, and DE and ED. In other words, the results suggested that the operability of the long toe was higher when it was moved toward the end of the operating range compared with the center position in both flexion and extension. When the target appeared at position A or E, the flexor or extensor muscles became tense, since the long toe had to be moved around the boundary of the movable range, whereas it was not necessary to exert the flexor or extensor muscles strongly when the target appeared at positon B or D. Therefore, it was predicted that the long toe could be operated with ease if the target appeared at positon B or D. However, the experimental results gave the opposite conclusion. When the target appeared at position B or D, it was necessary to stop the movement of the long toe at a specific position near the center of the movable range. However, such delicate movement is difficult for the long toe. As described above, no significant characteristics were seen in the operation patterns of the great toe, while some significant characteristics were seen in those of the long toe.

Next, we analyzed the experimental results for the fingers. As shown in Fig. 13, the average clearing times for patterns with target position A or E (BA, DA, BE, and DE) was significantly longer than those with target position B or D (AB, AD, EB, and ED) for the index finger. The same results were also seen for the middle finger. These findings suggest that the operability of the fingers was lower when bent or stretched toward the end of the movable range compared with the center position, which is the opposite of the results of the long toe. One reason for this difference may be that fingers are frequently used around the center position of the movable range in daily life, so they are considered to be accustomed to subtle movements in this range. In addition, the average clearing time of the fingers was significantly longer for pattern EA than for pattern AE, which suggests that the operability of the fingers when bent at a large angle is substantially better than when stretched at a large angle. One reason for this may be that humans always grasp objects using flexion, so flexion movements are easier than extension movements. On the other hand, no significant differences were seen between patterns BD and DB. Therefore, when the bending or stretching angles of the fingers are small, no differences in the operability of flexion and extension movements are apparent.

4. Evaluation experiments for the movement of two toes

In the evaluation experiments described in the previous section, when a specific toe was in operation, the adjacent toe could be moved freely. The conclusion in the previous section are valid if only one toe is used for operation; whether the conclusions are also valid when two toes are used at the same time remains unclear. It is therefore necessary to gain an understanding of the influence of the interaction of two adjacent toes during two-toe operation. In particular, since some of the flexor and extensor muscles of the great and long toes belong to the same muscle group, the movements of one toe may affect those of the other. Hence, in this section, we describe our investigation of the operation of two adjacent toes.

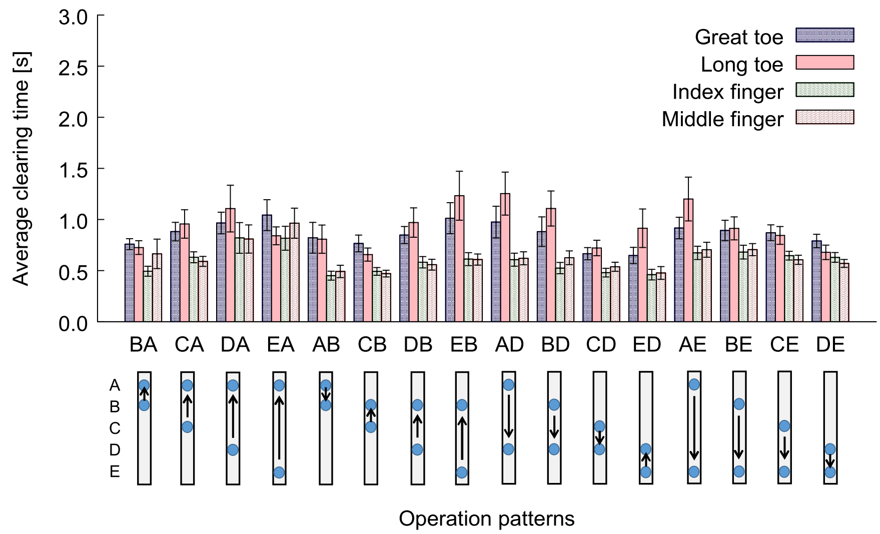

Fig. 12. Average clearing time of each toe and finger in the operation experiments (*: $p \leq 0.05$).

Table 2
Result of Welch's *t*-test for the toes or fingers for all operation patterns (*: Significantly different; No: Not significantly different).

Operation pattern		Long toe	Index finger	Middle finger	Operation pattern		Long toe	Index finger	Middle finger
CA, AB, DB, EB, CD, BE, CE	Great toe	No	*	*	DA	Great toe	No	No	No
	Long toe		*	*		Long toe		*	*
	Index finger			No		Index finger			No
CB, AD, ED, AE	Great toe	*	*	*	EA	Great toe	*	*	No
	Long toe		*	*		Long toe		No	No
	Index finger			No		Index finger			No
BD	Great toe	*	*	*	DE	Great toe	*	*	*
	Long toe		*	*		Long toe		No	*
	Index finger			*		Index finger			No
BA	Great toe	No	*	No					
	Long toe		*	No					
	Index finger			*					

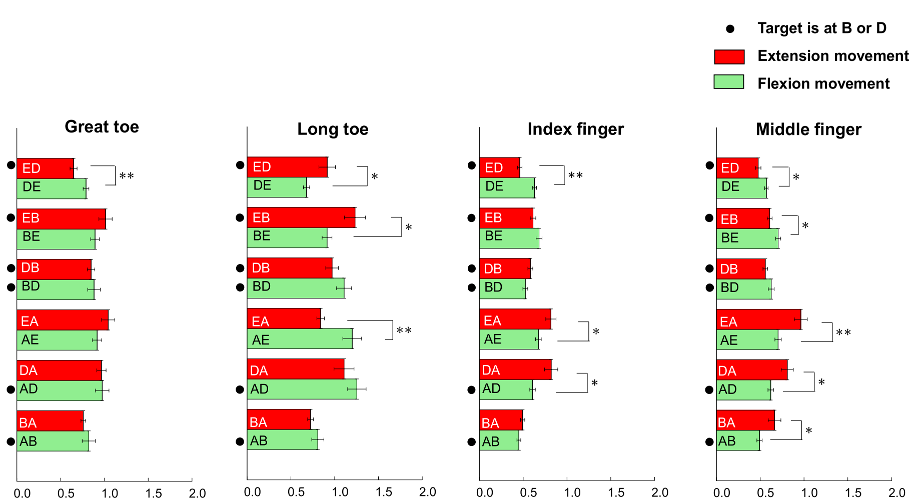

Fig. 13. Comparison of clearing times of operation patterns with the same movement distance and opposite movement direction (*: $p \leq 0.05$; **: $p \leq 0.01$).

4.1. Evaluation system for the movement of two toes

A description of the evaluation system for the movements of two toes is shown in Fig. 14(a). The basic construction of this system is the same as that for one toe, except that two sets of markers, targets, and rectangular frames are displayed on the monitor. The left marker is operated by the movements of the great toe or index finger, whereas the right marker is operated by the movements of the long toe or middle finger. The examinees can see and operate these markers at the same time.

Next, the target position settings are explained. Fig. 14(a) shows the monitor when the long toe or middle finger is maintained at the center position and the great toe or index finger is moved. The target in the left frame is arranged in the same way as that in the experiments described in the previous section. The target in the right frame is always placed at position C within the frame. The examinees are required to move the left marker up and down while simultaneously maintaining the right marker at the center position C. A small rectangular frame with red lines that instructs the examinees to maintain the marker's position is displayed near the center position of the right rectangular frame. When the right marker deviates from the center position and touches the red lines (i.e., the value of Y exceeds $\pm$20), the game set is redone. Fig. 14(b) shows the monitor when the great toe or index finger is maintained at the center position and the long toe or middle finger is moved, with the frames for the movable and fixed toes placed on the right and left sides, respectively.

4.2. Experimental outline

The examinees in this experiment were the same 10 adult men as those in the previous experiment. In this experiment, the following four situations were considered: operating the long toe while fixing the great toe, operating the great toe while fixing the long toe, operating the middle finger while fixing the index finger, and operating the index finger while fixing the middle finger. Four game sets were carried out for each situation.

4.3. Experimental results and discussion

Fig. 15 shows the average clearing times and CIs for each toe and finger at a 5% significance level based on the experimental data, where the outliers were excluded using Grubbs' method. According to the results of Welch's t-test, no significant difference was found between the great and long toes or between the index and middle fingers. However, significant differences were observed between the toes and fingers. The average clearing time of each toe or finger in ascending order was the index finger, middle finger, great toe, and long toe. The average clearing time of the middle finger was 1.04 times longer than that of the index finger, that of the great toe was 3.57 times longer than that of the index finger, and that of the middle finger was 3.64 times longer than that of the index finger. The mean value of the two toes' average clearing time was about 3.51 times as long as that of the fingers, which illustrates quantitatively that the operation speed of the toes is about 28.5% that of the fingers. No significant difference was observed when comparing the great and long toes; therefore, the operability of the two toes was considered to be the same. We predicted that the great toe would have higher operability because of its individual flexor and extensor muscles. However, the experimental results did not agree with this prediction. The experimental results also indicated that the two fingers have equivalent operability.

A comparison between the experimental results for one toe shown in Fig. 11 and two toes is shown in Table 3. Although the average clearing

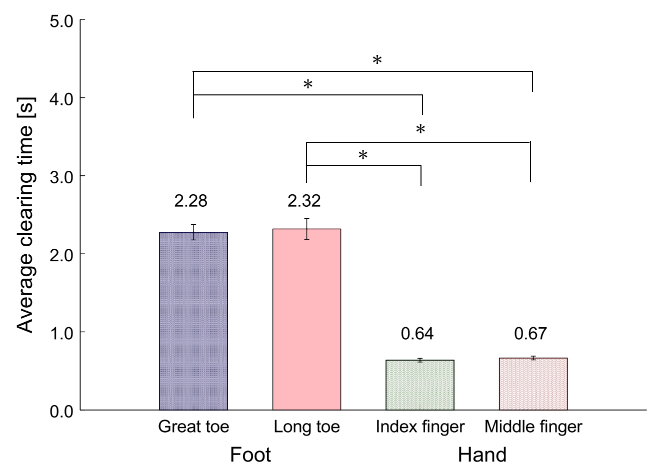

Fig. 15. Average clearing time for each toe and finger in the experiment using two-toe or two-finger operation (*: $p \leq 0.05$).

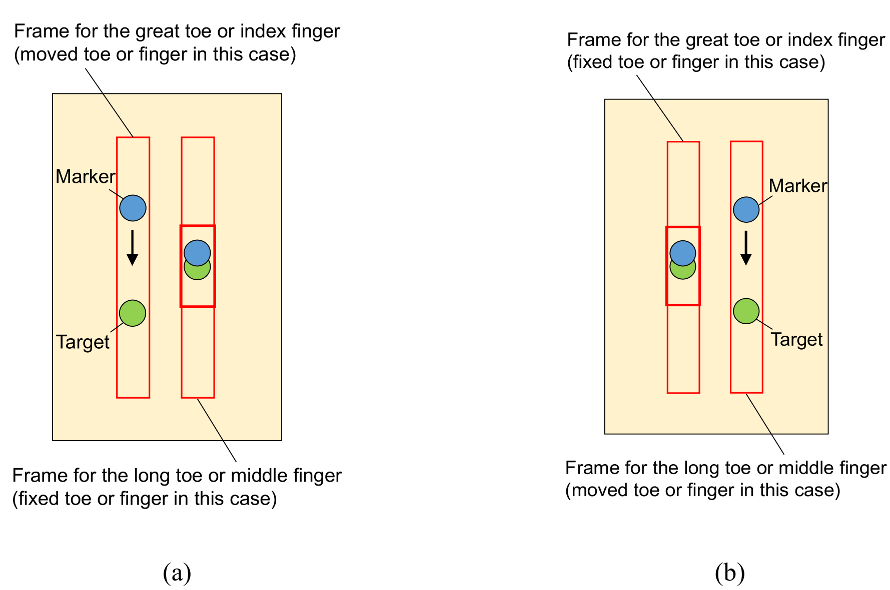

Fig. 14. Evaluation game displayed on the monitor to evaluate the motion of two toes or fingers: (a) Case in which the great toe or index finger is moved and the long toe or middle finger is fixed. (b) Case in which the great toe or index finger is fixed and the long toe or middle finger is moved.

time of movements using fingers increased slightly, it was still about 0.6 s, which means that the status of one finger did not significantly influence the movements of the other. Nevertheless, the average clearing time of two-toe movements increased significantly compared with that of a single toe (167.1% for the great toe and 151.5% for the long toe). This result confirmed quantitatively that when one toe is bent or stretched while the posture of the other is maintained, the operability of the toes is greatly deteriorated compared with simply bending or stretching one toe. The reason for this is considered to be the mutual interference between toes in flexion and extension movements. As mentioned in Section 2, many muscles that belong to the same muscle group are attached to each toe. For this reason, interaction between toes occurs, and when one toe is moved, the other is dragged. Regarding the comparison between the great and long toes, Fig. 11 shows that the great toe had a slightly but significantly shorter clearing time than the long toe. Conversely, the difference between two toes became small and not significant, as shown in Fig. 15. This finding indicates that the great toe has higher operability than the long toe when only a single toe is used, whereas the difference in operability for two toes becomes smaller if two toes are used for operation.

Fig. 16 shows the average clearing time for each operation pattern, and Table 4 shows the results of Welch's *t*-test. Regarding the comparison between the toes and fingers, significant differences in the average clearing time were observed for all patterns. These findings suggest that fingers are more operable than toes for all patterns. Regarding the comparison of the great and long toes, the average clearing time of the great toe was shorter in the case that the toe was stretched at a large angle, such as patterns BA, CA, DA, and EA. In particular, significant differences were observed for patterns BA, CA, and DA. On the other hand, for patterns in which the target appears at position D or E (patterns AD, BD, CD, ED, AE, BE, CE, and DE), the average clearing time of the long toe was shorter than that of the great toe, except for pattern AE. Highly significant differences were observed for the patterns that only involved positions C, D, and E, such as patterns CD, CE, DE, and ED. This finding suggests that the long toe is easier to operate than the great toe when the toe is moved on the bending side from the center position.

Similarly, we focused on the pairs of operation patterns in which the marker had the same moving distance and opposite moving directions (AB and BA, AD and DA, AE and EA, BD and DB, BE and EB, DE and ED). The results of a comparison of average clearing times for these pattern pairs are shown in Fig. 17. The average clearing time when the target for the great toe appeared at position A or E (DE, BE, DA, and BA) was longer than that when it appeared at position B or D (ED, EB, AD, and AB). Similarly, based on the experimental results for the long toe, highly significant differences were observed when comparing DA and AD and BA and AB. In other words, when a toe was moved to clear a target that appeared close to the boundary of that toe's movable range, such as position A or E, the adjacent toe tended to drag. As a result, this movement became difficult. In the experiment for one-toe operation described in the previous section, no such tendency was observed for the great toe. As for the long toe, in one-toe operation, the average clearing time was shorter when the target was at A or E compared with at B or D. This means the tendency was opposite between the one- and two-toe experiments, and indicates that attention should be paid to this characteristic when toes are used for operation. In other words, whether movements are easy or difficult differs when one or two toes are used for operation. It is easy for operators to bend or stretch the toe at a large angle when only one toe is used, whereas it is easy for operators to bend or stretch one toe at a small angle when two adjacent toes are used. It is therefore desirable to understand this characteristic before constructing a toe-operating system. Fig. 18 shows the ratio of the average clearing times gained in the one- and two-toe experiments, and clarifies how much worse the two-toe experimental results were in comparison with the one-toe experiments. As shown in Fig. 18, the ratio for the long toe was larger in the patterns in which the target appeared at position A and the toe was greatly extended (BA, CA, DA, and EA), while that of the great toe was larger in the patterns in which the toe was bent (AD, BD, CD, BE, CE, and DE). This result suggests that if two toes are used for operation, extension of the long toe becomes more difficult compared with the great toe, whereas flexion of the great toe becomes more difficult compared with the long toe.

Table 3
Comparison between the experimental results using one toe or finger and two toes or fingers.

Toe/ finger	Average clearing time using one finger/toe [s]	Average clearing time using two fingers/toes [s]	Increase rate of average clearing time
Great toe	0.85	2.28	+167.1%
Long toe	0.92	2.32	+151.5%
Index finger	0.60	0.64	+6.9%
Middle finger	0.62	0.67	+7.6%

5. Conclusion

In this paper, which focused on operation by toe movements, a measurement device for toe flexion and extension characteristics was developed, and a new evaluation system using this device was constructed. Several experiments using this evaluation system were conducted to clarify the motion characteristics and operability of the great and long toes and index and middle fingers when used for operation. The following results were obtained:

- A device for measuring toe flexion and extension was developed using wire displacement sensors. This device can also be applied to fingers.
- An evaluation system was constructed to evaluate the flexion and extension movements of toes when used to operate a marker displayed on a PC monitor.
- The results of evaluation experiments involving operation with a single toe or finger were as follows: 1) a difference in the operability of the toes and fingers was confirmed quantitatively, in that the average clearing time of the toes was 1.45 times longer than that of the fingers; 2) the great toe showed higher operability than the long toe, and the difference in clearing time with two toes was approximately 9%; and 3) no significant difference was observed in the clearing time between the index and middle fingers.
- The results of comparisons of each operation pattern in the experiments with the single toe were as follows: 1) the operability of the long toe was higher when it was bent or stretched toward the boundary of its movable range than when it was moved toward the center position of this movable range; 2) no such characteristic was found in the experiments with the great toe, meaning that the great and long toes showed different characteristics; and 3) the operability of the fingers when moved toward the boundary of their movable range was lower than that when they were moved toward the center position, which disagreed with the experimental results for the long toe.
- The results of the evaluation experiments regarding operation with two toes or fingers were as follows: 1) the toes required a clearing time 3.51 times longer than that of the fingers; and 2) no significant difference was found when comparing the great and long toes or the index and middle fingers.
- A comparison of operation using one or two toes indicated that: 1) the clearing time of the great and long toes increased by 167.1% and 151.5%, respectively, which confirmed quantitatively that the operability of two toes was greatly deteriorated compared with a single toe; and 2) the operability of the fingers showed no apparent difference between one- and two-finger operations.

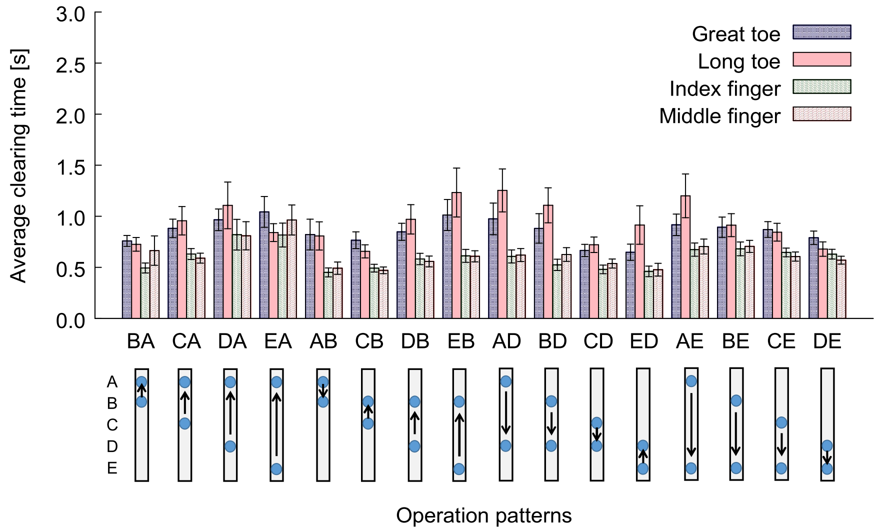

Fig. 16. Average clearing time for each operation pattern for each toe and finger in the experiments using two toes or fingers.

Table 4
Result of Welch's *t*-test for the toes and fingers for all operation patterns (*: Significantly different; No: Not significantly different).

Operation pattern		Long toe	Index finger	Middle finger	Operation pattern		Long toe	Index finger	Middle finger
BA	Great toe	*	*	*	CB	Great toe	No	*	*
	Long toe		*	*		Long toe		*	*
	Index finger			*		Index finger			*
CA, DA, EB, CD, ED, CE, DE	Great toe	*	*	*	EA, AB, DB, AD, BD, AE, BE	Great toe	No	*	*
	Long toe		*	*		Long toe		*	*
	Index finger			No		Index finger			No

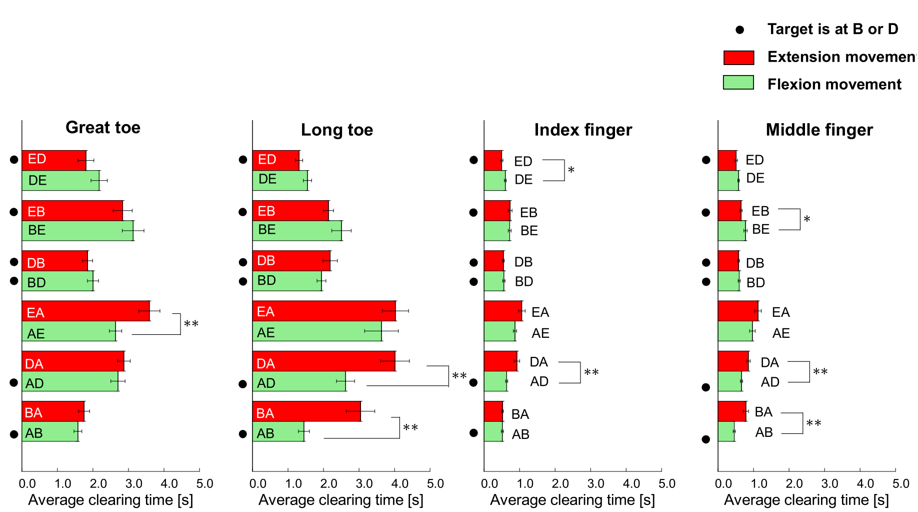

Fig. 17. Comparison of clearing times of operation patterns with the same movement distance and opposite movement direction (*: $p \leq 0.05$; **: $p \leq 0.01$).

- Similarly, the experimental results for each pattern analyzed for operation with two toes were as follows: 1) when toes were moved on the bending side from the center position, the long toe showed higher operability than the great toe; and 2) it was easier to operate toes around the center than around the boundary position of the movable range. In one-toe operation, the great toe showed no such tendency and the long toe showed the opposite tendency. This finding indicated that whether the movements of the toes were easy or difficult differed when operating with one or two toes.

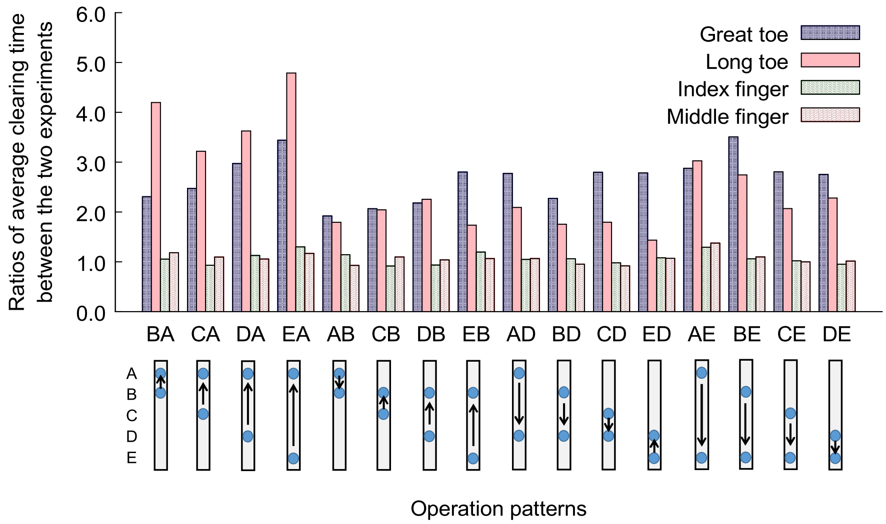

Fig. 18. Ratios of average clearing time of the evaluation experiments using one and two toes or fingers.

In the future, these research results are expected to be used for the development of a toe operation device. By using the results, the operability of the operation device can be improved.

References

[1] Matsuda D, Uemura K, Sakata N, Nishida S. 'Toe input' using wearable projector and depth camera (<special issue> real world imaging). Trans Virt Real Soc Jpn 2012;17(3):161–9.

[2] Fukahori K, Sakamoto D, Igarashi T. Exploring subtle foot plantar-based gestures using sock-style pressure sensors. Comput Software 2016;33(2):116–24.

[3] Yamamoto T, Tsukamoto M, Yoshihisa T. Foot-Step input method for operating information devices while jogging, 2008 International Symposium on Application and Internet. 2008. p. 173–6.

[4] Alexander J, Han T, Judd W, Irani P, Subramanian S. Putting your hand best foot forward: investigating real-world mapping for footed-based gestures. CHI 2012: 1229–38.

[5] Saunders W, Vogel D. Tap-kick-click: foot interaction for a standing desk. In: DIS 2016 proceedings of the 2016 ACM conference on designing interactive systems; 2016. p. 323–33.

[6] Scott J, Dearman D, Yatani K, Truong KN. Sensing foot gestures from the pocket. In: UIST '10 Proceedings of the 23nd annual ACM symposium on User interface software and technology; 2010. p. 199–208.

[7] Komori M, Miyauchi H. Position operation method by leg motion and characteristics of leg motion during operation. J Jpn Soc Des Eng 2018;53(7): 511–26.

[8] Kume Y, Inoue A. Feasibility of feet-operated pointing device. J Inst Image Inf Televis Eng 2000;54(6):871–4.

[9] Kamakura N, Ohmura M, Ishii H, Mitsuboshi F, Miura Y. Positional patterns for prehension in normal hands. Jpn J Rehabil Med 1978;15(2):65–82.

[10] Yasuda N, Murata S, Murata J. Relationship between hand function and finger muscle strength, sensation and reaction time in frail elderly women. Rigakuryoho Kagaku 2010;25(3):469–72.

[11] Ito H. Tsukamite no dousakinoukaiseki: junnougata hand no approach nitsuite, [The functional analysis of grasping hands: about the adaptable hand approach]. Biomechanisms 1975;3:145–54.

[12] Komori M, Kobayashi K, Tashiro T. Method of position command generation by index finger motion to mitigate influence of unintentional finger movements during operation. Precis Eng 2018;53:96–106.

[13] Kabe N, Kurosawa K, Nishida Y, Kishida A, Kobayashi S, Tanaka Y, Makizako H, Masuda Y, Watanabe M. The study of relationship between toe and dynamic postural control. Rigakuryoho Kagaku 2002;17(3):199–204.

[14] Handa S, Horiuchi K, Aoki K. A study on the measurement of toes grasping strength and effect of standing postural control. Jpn J Ergon 2004;40(3):139–47.

[15] Joseph J. Range of movement of the great toe in men. J Bone Jt Surg Br Vol 1954; 36-B(3):450–7.

[16] Allen RH, Gross MT. Toe flexors strength and passive extension range of motion of the first metatarsophalangeal joint in individuals with plantar fasciitis. J Orthop Sports Phys Ther 2003;33(8):468–78.

[17] Ahn TK, Kitaoka HB, Luo ZP, An KN. Kinematics and contact characteristics of the first metatarsophalangeal joint. Foot Ankle Int 1997;18(3):170–4.

[18] Boschert J, Hink RF, Deecke L. Finger movement versus toe movement-related potentials: further evidence for supplementary motor area (SMA) participation prior to voluntary action. Exp Brain Res 1983;52(1):73–80.

[19] Pfurtscheller G, Flotzinger D, Neuper C. Differentiation between finger, toe and tongue movement in man based on 40 Hz EEG. Electroencephalogr Clin Neurophysiol 1994;90(6):456–60.

[20] Kai Y, Murata S, Tanaka S. Comparison of foot-gripping strength and quadriceps femoris muscle strength of the dominant foot and non-dominant foot. Rigakuryoho Kagaku 2007;22(3):365–8.

[21] Fukuda I, Kobayashi R. The effect of the toes-grip training in healthy young adults. Phys Ther Jpn 2008;35(5):261–6.

[22] Soma M, Igarasi T, Kudou W, Nakae H, Abiko T. Influence of foot-gripping strength training to functional reach test and maximal step length, walking ability in healthy adults. Jpn J Health Promot Phys Ther 2012;2(2):59–63.

[23] Sun D, Fekete G, Mei Q, Gu Y. The effect of walking speed on the foot inter-segment kinematics, ground reaction forces and lower limb joint moments. PeerJ 2018;6: e5517.

[24] Tanaka N, Ueda T, Nakao M, Sato T, Minato K, Yoshida M, Kouketsu K. Evaluation of kinematic characteristics of the foot thumb for the development of a new input device. Trans Jpn Soc Med Biol Eng 2005;43(4):790–4.

[25] Arakawa H, Ishii N, Okuyama S. Soku kansetsu·sokushi no kin [Foot's joints and toes' muscles], Puro ga oshieru kinnikunoshikumi hataraki perfect jiten: all color, [The perfect encyclopedia of mechanism and work of muscle taught by professional: all color]. first ed. Natsume; 2012. p. 166–76.

[26] Kapandji I A, Sokubu [foot part], in Physiologie articulaire, schemas commentes de mecanique humaine: anatomie fonctionnelle II [Joint physiology, commented diagrams of human mechanics: functional anatomy II] 2010;Ishiyaku Publishers, lnc.(sixth ed.): 208-228.

[27] Ridge ST, Myrer JW, Olsen MT, Jurgensmeier K, Johnson AW. Reliability of doming and toe flexion testing to quantify foot muscle strength. J Foot Ankle Res 2017;10(55).

[28] Murata S, Kai Y, Tanaka S, Yamasaki S. Development of a strain gauge based foot-gripping force meter. Rigakuryoho Kagaku 2006;21(4):363–7.

[29] Mita T, Yamashita K, Koyama H, Kawasumi M. Evaluation of walking characteristics obtained by the measurement device of MP joint range of motion, LIFE2016. 2016. p. 663–6.

[30] Fujii N, Moriwaki T. A study on motion measurement of fingers based on image analysis. Jpn J Ergon 1991;27(3):151–7.

[31] Isaji S, Takano M, Sasaki K. Development of a measurement system for manipulative motion of human fingers. J Jpn Soc Precis Eng 1998;64(8):1127–31.

[32] Terado T, Fujiwara O. A method for recognizing state of finger flexure and extension. IEEJ Trans Electron Inf Syst 2004;124(12):2414–20.

[33] Lee KS, Jung MC. Flexion and extension angles of resting fingers and wrist. Int J Occup Saf Ergon 2014;20(1):91–101.

[34] Yonemoto K, Ishigami S, Kondo T. Kansetsu kadouikihyouji narabini sokuteihou [Joint movement range indication and measurement method]. Jpn J Rehabil Med 1995;32(4):207–17.