PossessedHand: Techniques for Controlling Human Hands using Electrical Muscles Stimuli

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ABSTRACT
If a device can control human hands, the device can be useful for HCI and tangible application's output. To aid the controlling of finger movement, we present PossessedHand, a device with a forearm belt that can inform when and which fingers should be moved. PossessedHand controls the user's fingers by applying electrical stimulus to the muscles around the forearm. Each muscle is stimulated via 28 electrode pads. Muscles at different depths in the forearm can be selected for simulation by varying the stimulation level. PossessedHand can automatically calibrate the system for individuals. The automatic calibration system estimates relations between each electrode pad, stimulation level and muscle movement. Experiments show that PossessedHand can control the motion of 16 joints in the hand. Further, we also discuss an application based on this device to aid in playing a musical instrument.

Author Keywords
EMS, FES, Electric Stimulation, Hand Gesture, Musical Performance

ACM Classification Keywords
H.5 Information interfaces and presentation: [HCI]

General Terms
Design, Experimentation, Human Factors

INTRODUCTION
HCI and tangible devices use many actuators as outputs. On the other hand, human beings have many actuators such as their muscles in their body. In particular, human hands have the dexterous fingers which are used to output for communications, playing, touching and so on. However, human actuators have not been adapted to HCI and tangible devices. If a device can control human hands, the device would lead the next generation of HCI and tangle applications.

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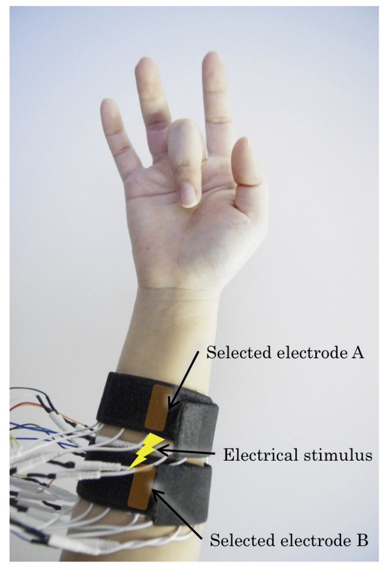

Figure 1. Our concept. PossessedHand controls user's finger.

In this paper, we introduce PossessedHand, a device with a forearm belt (Figure. 1) that can control several hand gestures and inform their timing; this device achieves this by providing electrical stimulus to the muscles in the forearm. However, a controlling the muscles requires special knowledge for the system setting because positions of the stimulation, the stimulation level and timing differ greatly in individuals. We also introduce an automatic calibration system of PossessedHand. On this calibration system, user can use PossessedHand without any special knowledge. Finally, we discuss applications of PossessedHand.

RELATED WORK
Many devices and systems that directly stimulate a user's fingers have been researched [14, 16]. However, users prefer to avoid wearing devices on area A, shown in Figure. 2, because this area is used to touch, hold, and pinch real objects. The skin on this area is important sensor for communication, touching, playing musical instruments or in other

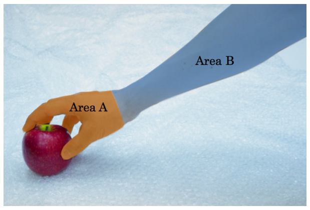

Figure 2. Area A: This area is involved in pinching, gripping, and holding motions. Area B: Electrical stimuli are provided to this area.

performing arts. Glove-type devices that dynamically and mechanically control a user's hand are available [29]. Such devices cover most of area A. Although a device that can be worn on the forearm has been developed, it is too large to be comfortably used for daily uses.

To solve these problems, we develop a small device, PossessedHand, that can control a user's hand without covering area A. PossessedHand can be used for controlling finger-joint movements; it operates by applying an electrical stimulus to the muscles in the forearm with noninvasive electrode pads. The muscles involved in finger motions are clustered in the forearm [23]. PossessedHand has electrode pads that are fastened to the forearm to stimulate these muscles. The tendons that are connected to the muscles move the finger joints. To date, there have been no research on controlling the position of the hand solely through electrical stimulation to the forearm. The electrical stimulation by PossessedHand is similar to *Electrical Muscle Stimulation*(EMS) [5, 6, 11] and *Functional Electrical Stimulation*(FES) [22, 9, 11, 17, 7, 26].

EMS has several applications. EMS is widely used in low-frequency therapeutic equipment and in devices used for ergotherapy [2, 33]. EMS allows in 15 min of continuous uses[2]. Akamatsu et al. used EMS in performing arts [19, 25]. EMS is similar to FES [8, 21, 31, 30, 32]. In FES, electrical currents are used to activate nerves innervating extremities that are affected by paralysis resulting from a stroke or other neurological disorders and spinal cord or head injuries. FES can be used to treat people with disabilities [34].

Watanabe et al. and Kruijff et al. presented a technique in which a user's wrist can be controlled with two degrees of freedom by stimulating four muscles [15, 30]. They observed that they could control wrist motion by electrically stimulating a muscle, which resulted in the motion of the tendon connected to the wrist. However, they did not consider the motion of finger-joints, which is important for controlling the position of the hand. Moreover, they used invasive electrodes embedded in the skin. Such electrodes are not suitable for playing musical instruments.

It is necessary to use noninvasive electrodes and to avoid fastening electrodes to the hands or fingers because the hands and fingers are used to hold or touch real objects. The haptic drum kit is developed by Simon et al [12]. This kit signals when a drum should be struck while playing drums by using vibrations. However, it is not effective for playing musical instruments other than drums such as piano and koto, because it cannot signal which finger should be moved.

We presented a designe of PossessedHand[28]. The paper shows that PossessedHand needs seven electrodes to control 16 finger joint angles of user's hand. Electrode pads, which is noninvasive electrodes, are set on user's forearm. However, a location setting of the pas took many time and required knowledges about muscle locations in forearm. We must make a personal belt for each user because the size of user's forearm differs widely in individuals. For widely uses, PossessedHand should have automatically calibration system.

PHASE OF DEVELOPMENT

There are four phases to control hand gestures as outputs of HCI and tangible applications. The applications are suggested on each phases. In this research, we identify three phases in which PossessedHand can be used.

Phase 1: Although the user cannot visually confirm the hand motion, he/she feels the motion owing to his/her somatic sense. (e.g., providing feedback for recognizing virtual objects)

Phase. 2: The user visually confirms the motion. The user's fingers are dependently controlled. (e.g., systems used in performing arts).

Phase 3: The user's fingers are independently controlled to perform grasping and opening motions (e.g., support systems for musical performances and sport activities, navigation systems, and sensory substitution systems for the visually impaired and the hearing impaired).

Phase 4: The user's hand is controlled to perform dexterous and powerful motions such as pinching by using the thumb and index finger (e.g., learning systems for finger languages and for making handicrafts)

OUR PLAN AND GOAL OF AN APPLICATION

Our goal of an application is to develop a support system for playing musical instruments with PossessedHand, that can teach the appropriate hand gestures and timing to a beginner playing a musical instrument. Beginners must devote considerable time to learning because it is difficult to simply observe a skillful performance and imitate the required hand gestures and their timing. This type of learning in which beginners compare their performance with a skillful performance leads to over fatigue. Skillful playing can be achieved if the appropriate hand gestures and timing can be taught to a beginner while he or she is playing a musical instrument.

First, we describe an experiment conducted to identify which and how finger-joints can be controlled by several stimulation levels. Second, we select the electric pads for daily uses. Third, we develop PossessedHand device and calibration systems about the location of the pads, the stimulation level, and stimulation timing. Forth, we verify that the each joint can be controlled, and users can correctly feel each joint movement induced by PossessedHand. In addition, we also discuss the results on the basis of the four phases discussed above. Finally, we will discuss a support system based on PossessedHand for playing musical instruments.

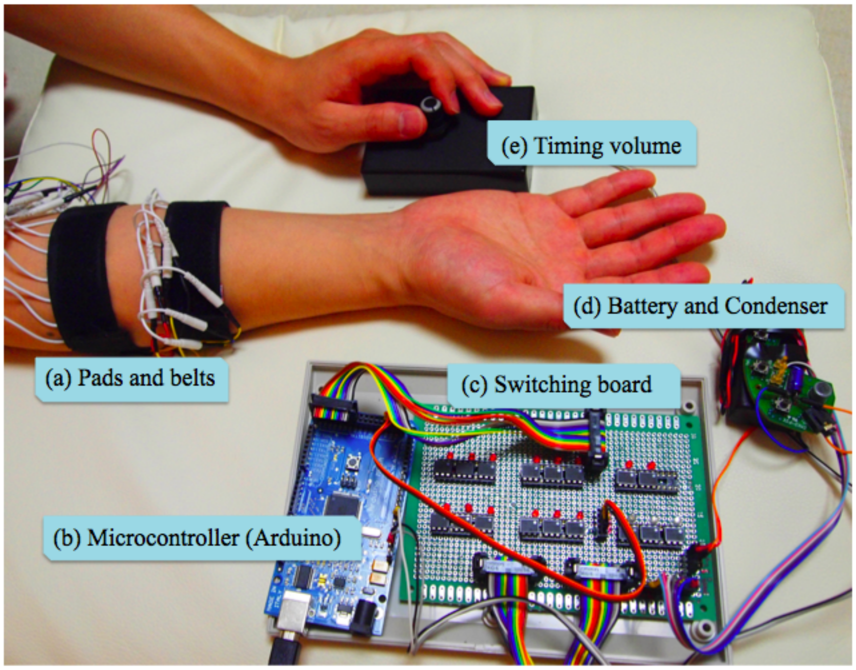

Figure 3. A prototype of PossessedHand.

SOLUTIONS

Muscles and stimulations for making hand postures

We use electrical pulses, 14 channels, and three levels of electrical stimulations to control the user's hand. The impulses generated by PossessedHand are transmitted to the muscles that are to be stimulated through electrode pads fastened to the skin. PossessedHand uses EMS to achieve its desired output energy and maintain a compact size [13, 27]. An electrical stimulus from PossessedHand is applied to the user's forearm because most of the muscles that control the fingers and the wrist are located the forearm. For this purpose, a forearm belt is used along with PossessedHand. The electrical stimuli are generated by an electronic pulse generator and transmitted via the electrode pads. The pads are arranged on the upper and lower parts of the user's forearm (Figure. 3-(a)). At least, five channels are needed to stimulate the muscles that are used to bend finger-joints, and two additional channels are needed to stimulate the muscles that are used to bend finger extensions and cause wrist flexions. PossessedHand stimulates seven muscles (the superficial flexor muscle, deep flexor muscle, long flexor muscle of the thumb, common digital extensor muscle, flexor carpi radialis muscle, long palmar muscle, and flexor carpi ulnaris muscle). These muscles are located in area B in Figure. 2. We can select a channel between a pad on the upper portion of the forearm and one on the lower portion of the forearm.

Stimulation levels and the pulse of electrical stimulation

PossessedHand selects the depth of the muscle by the stimulation levels. The flexor digitorum superficialis muscle is connected to the *proximal interphalangeal*(PIP) joint, the second joint in each finger. The flexor digitorum profundus muscle is connected to the *distal interphalangeal*(DIP) joint, the third joint in each finger. These muscles are located at the same position, however these muscle are at different depths in the user's forearm [3]. The existing electrical pads cannot be used to select muscles at different depths because the pads do not contact the muscles directly. Therefore, invasive needles are used when fine control of finger-joints is required. However, as previously described, controlling fingers by needles is difficult in daily life.

We tried to select the stimulated muscle by regulating voltages of stimulation. Moreover, we tried to stimulate both the flexor digitorum superficialis muscle and the flexor digitorum profundus muscle by applying higher voltages of stimulation. We conducted an experiment with various stimulation levels to see which muscle was selected. Figure. 5 shows the result of the experiment. The vertical axis indicates the joint angle. The horizontal axis shows voltages of the applied current generated by PossessedHand. In this experiment, subjects wore PossessedHand and were told to relax their muscles. We set the back of subjects' hand touched the flat of a desk. We measured joint angles starting from zero (when the finger is completely straight). Then, we raised the voltage by one volt and measured the joint angles.

The applied stimulation pulse frequency was set to $40\,Hz$, and the pulse width was $0.2\,ms$, and the pulse height (voltage) was in the range of 17 - $29\,V$ (Figure. 4). The pulse reported is that which gives the user no pain, because it is similar to the human impulse to move muscles [5, 6, 11].
From this experiment, we found that the depth of the stimulated muscle could be selected by regulating voltages. The movement of each joint (PIP, DIP, and MP joints) was selected by different voltages. The PIP joint moved independently at $17\,V$. The PIP joint also moved at $19\,V$. Therefore,

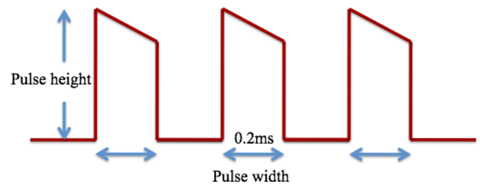

Figure 4. Pulse of electric stimulation by PossessedHand. The Pulse height is adjusted for the voltage. Pulse width is set 0.2ms to be similar to nervous signals in human muscles.

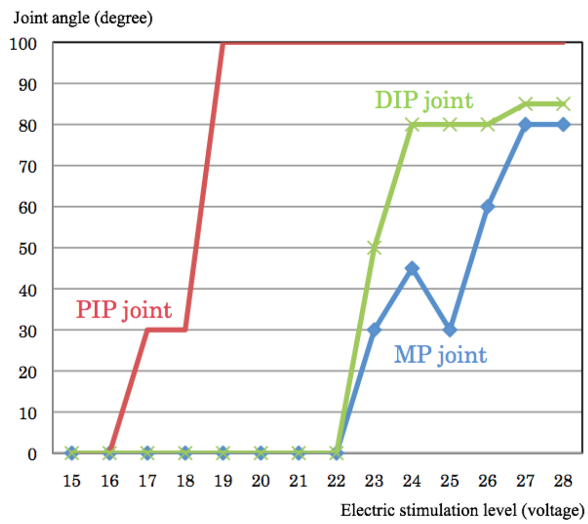

Figure 5. An example of the selected muscle depth and movement by the electric stimulation levels (voltage). Blue line with Diamond makers: MP joint movement. Red line: PIP joint movement. Green line with times makers: DIP joint movement.

we concluded that the voltage from 17 to $19\,V$ stimulates the flexor digitorum superficialis muscle selectively. Voltages higher than $23\,V$ also stimulated the flexor digitorum profundus muscle, resulting in the movement of the DIP joint and MP joint.

Operable joints

Our previous paper/,[28] reported that PossessedHand could control the motion of 16 joints in the hand. We conducted an experiment to confirm whether the finger-joints can be appropriately moved to achieve desired hand postures. We selected an anode from the seven electrodes placed on the upper arm and a ground electrode from the seven electrodes placed on the hand. We tested $7-by-7$ patterns of the electronic paths corresponding to each of three peak values of the pulse ($17\,V$, $23\,V$, and $29\,V$); in other words, we performed 147 stimulations. We asked the subjects to eliminate strain in the hand. We confirmed that PossessedHand could control 5 independent and 11 linked joints, 16 joints in total. We also found that a clasped hand could be opened by stimulating a common digital extensor muscle. Further, users could recognize the motion of their hands even when their eyes were closed. These results suggest that PossessedHand can control hand postures in phases 1, 2, and 3, as discussed above.

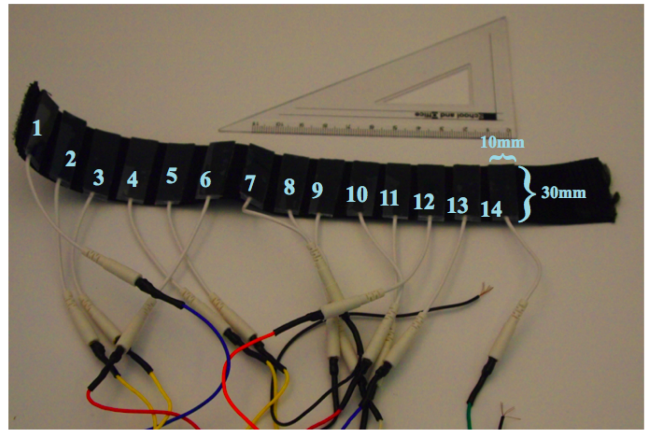

Figure 6. A belt and pads.

SYSTEM CONFIGURATION

Prototype of the device

We built a prototype of PossessedHand that consists of a battery, a condenser, a timing volume, a switching board (Photo-MOS Relays Series AQV221), a microcontroller, and 24 electrode pads on two belts(Figure. 3, Figure. 6). These devices are controlled by a graphical user interface (GUI) on a PC (Figure. 7). The microcontroller is connected to the PC via a USB cable. The dimensions of PossessedHand are $10.0\,cm \times 7.0\,cm \times 8.0\,cm$, which are portable and suitable for daily uses and playing musical instruments. The pulse width is $0.2\,ms$, and the voltage is in the range of 17 - $29\,V$. For safety reasons, the electric are charged in the condenser that is limited.

Electric pads and pain

We used solid gel type electrodes (electrical pads) of sizes $10 \times 10\,mm$ or larger to prevent electric stimulations from causing pain. There are three types of noninvasive electrodes.

Dry type electric pads

These pads are made of metallic sheets. These pads are used to get galvanic skin response (GSR) values. The pads cause pain when the contact area is small.

Liquid gel type electric pads

Liquid gel type electric pads have a sponge base. The user must put some liquid gel on the base before placing the pad on the user's skin. The pads cause pain when the human skin becomes dry because the contact area becomes small with moisture conditions of the pads.

Solid gel type electric pads

Solid gel type electric pads include conductive gel on thin metallic sheets. User cause relatively little pain, because the pads attach to the skin surface with certainly, and the contact area does not decrease. *Self Stick Tyco gel Carbon Electrodes* [1] are adapted to PossessedHand.

Figure 7. Screenshot of the PossessedHand GUI.

We also confirmed that users felt no pain from electrical stimulation ($33\,V$, $100\,mA$, the pulse width = $0.2\,ms$) with the $10 \times 10\,mm$ pads. In our experiments, we had ten subjects who wore an eye mask. We adopted solid gel type electric pads that were bigger than $10 \times 10\,mm$ in size. In this work, $10 \times 30\,mm$ pads are used on the belts of PossessedHand. We cut the pads into pieces the same height size as the height of the belt.

Calibration system for individual variation

We suggest an automatic calibration system for PossessedHand that can calibrate the pads' positions and the electrical stimulation levels according to individual variations. It is difficult to fasten the seven pads and set the stimulation levels correctly on a user's forearm. To solve this problem, we include as many pads as possible on the belts. 14 pads can be set on a belt. PossessedHand has two belts, and 28 pads. The calibration system identifies the pads that are used to stimulate a user's muscles. The system also selects three optimal stimulation levels to move each joint from twelve stimulation levels. It works by software base. The calibration steps are given below:

STEP 1. Wear PossessedHand. Start the auto calibration system. (Figure. 7-(e) Auto-calibration button to calibrate pads' positions and stimulation levels)

STEP 2. The auto-calibration system gives 168 stimulation patterns that include 14 paths (via electric pads on the belts) and 12 stimulation levels.

STEP 3. Push the joint button on the GUI when the joints are moved. (Figure. 7-(c) Stimulation buttons for each joint)

STEP 4. The system checks the pads that can be used to move each joint.

STEP 5. The system also selects three optimal stimulation levels from twelve stimulation levels for use in moving each joint.

Calibration system for stimulation timing

It is also important that the timings for appropriate musical instruments are correctly set. We built a calibration system of stimulation timing on PossessedHand. A user can calibrate the stimulation timing by using a timing volume (Figure. 3-(e) Timing volume). There is always a lag between the sound timing and the stimulation timing because it takes some time to generate the electrical stimulations and for the stimulations to be felt. To synchronize the timing, we introduce a calibration system. The system gives sound and stimulation at the same time. A user can then adjust the timing using the timing volume (Figure. 3(e) Timing volume), (Figure. 7-(d) Timing calibration button, (g) Indicator of timing volume). For eight subjects, the average time lag was 0.34 s. The standard error was 0.16 s. In our experiments, all the subjects could adjust the timing.

EXPERIMENTS

Probability of each joint movement

We checked the probability of each joint movement by PossessedHand and the calibration systems. We had eight subjects. Table. 1 shows the results. We confirmed that PossessedHand could control 5 independent and 11 linked joints, 16 joints in total, with the calibration systems. Figure. 10 shows over half of the probability of each joint movement from Table 1. Figure. 8 shows that PossessedHand was controlling each of the user's finger-joints. The results indicate

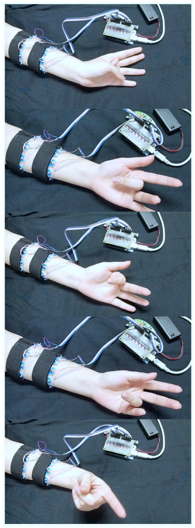

Figure 8. Examples of finger-joint movement by PossessedHand.

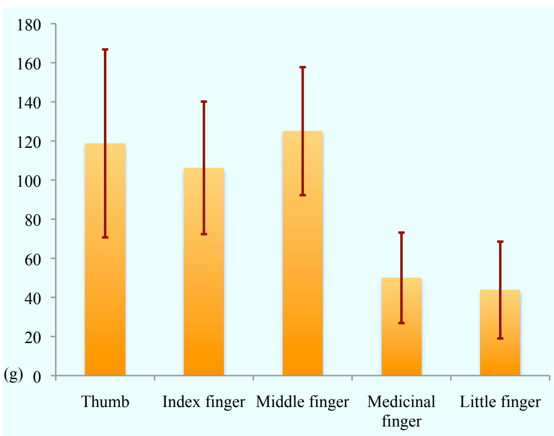

Figure 9. Measured forces for each finger.

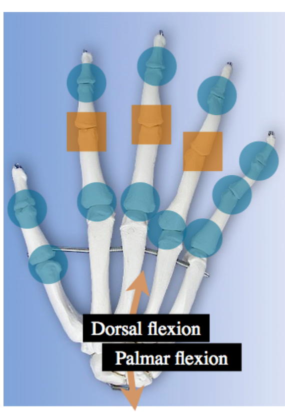

Figure 10. Operable joints. Squares indicate independently operable joints. Arrows and circles indicate ganed operable joints.

Table 1. Probability of each joint movement (%)

joint name	with other joints	independently
MP(Index finger)	100	0
MP(Middle finger)	100	0
MP(Medicinal finger)	100	0
MP(Littile finger)	100	0
PIP(IP) (Thumb)	100	0
PIP(Index finger)	100	100
PIP(Middle finger)	100	100
PIP(Medicinal finger)	100	100
PIP(Littile finger)	100	12.5
DIP(Thumb)	100	12.5
DIP(Index finger)	100	0
DIP(Middle finger)	87.5	0
DIP(Medicinal finger)	75	0
DIP(Littile finger)	87.5	0
Palmar flexion	100	0
Dorsal flexion	100	0
Radial flexion	37.5	0
Ulnar flexion	0	0

that PossessedHand and the calibration systems can realize Phases 1, 2, and 3.

Force per finger

We measured the force generated by PossessedHand on each finger with a spring balance. The eight subjects took part in this experiment, and did not move their fingers by themselves. The stimulation levels were set to the maximum possible values that did not cause pain to the subjects. The limit of voltage was $42\,V$. The locations of the pads were identified by our calibration system. PossessedHand moved MP, PIP and DIP joints in each finger at the same time. The fingers turned in. The force of each finger were measured by a spring scale, which mounted on a table and a finger. We set the back of subjects' hand touched the flat of a desk. We noted maximum values of the force in the three seconds.

In this experiment, all forces were too weak to grap real objects and to play musical instruments. Figure. 9 shows the results. The horizontal axis indicates fingers, while the vertical axis represents the forces (g). The error bars denote the standard error values. The number of trials per finger was three, and the total number of trials was 120. The average force was $88.75\,g$. The forces were not sufficient to grap and to play musical instruments however were enough to point out the fingers to be moved.

The Controlling the amount is next step of this research. That is feasible system, if the system calibrate the relation between the electric stimulation level and the amount of bend in a joint. It is reported that the muscle controlling method is similar to motor controlling method(proportional integral derivative controller, PID controller), on the electric stimulation experiment by using needle. It will be useful to tell correct hand postures, strength and weakness. In present system of PossessedHand can not reach the Phase. 4.

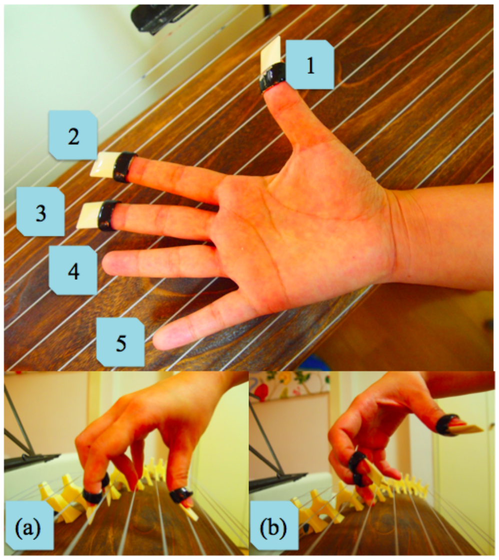

Figure 11. Playing styles of Koto. (a) one playing style using 1-3rd finger, (b) another playing style using 4 or 5th finger.

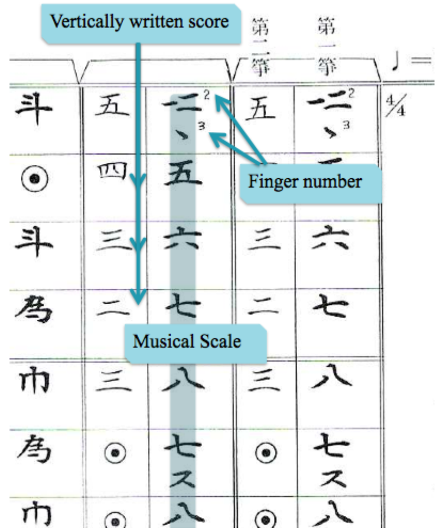

Figure 12. An example of koto score.

Somatesthesia

In this experiment, we confirmed that eight subjects could correctly feel each joint movement induced by PossessedHand. While wearing an eye mask, the subjects could correctly guess which joints were moved by PossessedHand. The stimulation levels and the locations of the pads were identified by our calibration system. For three seconds, PossessedHand moved MP, PIP and DIP joints in each finger. We conducted three trials for each fingers. The total number of the trials was 120. The results show that PossessedHand can teach which finger must be moved to output information and to play musical instruments.

SUPPORT SYSTEM FOR MUSICAL INSTRUMENTS

PossessedHand can be used to help a beginner how to play musical instruments. In musical instruments, koto, subtle differences in tones are achieved by fine finger movements.

In this study, we developed an example application: a support system for playing koto. The koto is a traditional Japanese stringed instrument. Kotos are about 180 centimeters wide and made from paulownia wood. Koto has 13 strings that are strung over 13 movable bridges along the width of the instrument. Players can adjust the string pitches by moving these bridges before playing. A koto player uses all fingers to pluck the strings. The player puts three different picks on the thumb, index finger, and middle finger, respectively (Figure. 1). In playing koto, it is important when and which finger should be moved because each finger produces different sound and has a different playing style (Figure. 11).

It is difficult for performers to use visual or sound guides for the support of the Koto performance, because the performers should read a Koto score and listen to their own performances during their performances. On the score, string numbers, timings and finger numbers are written. The finger numbers guide which finger should be moved. However, performers' view points are almost set on the string numbers of the score for their performances. It is hard to read the string numbers, timings and finger numbers at the same time. Then, PossessedHand directly tells the finger number and timing to the performers.

For a sample of perfect performances, we transcribe Japanese koto scores to PossessedHand scores. The Japanese koto scores included information on when and which fingers should be moved (Figure. 12). Two beginners (subjects) tried to play koto by wearing PossessedHand. In this experiment, we checked that beginners could get the rhythm and make fewer mistakes by wearing PossessedHand. We used a score, which was named "Usagi" [18]. The subject played 8-bar in quadruple time. For eight times, the subject alternated between normal playing and supported playing by wearing PossessedHand. The arm located by user-self. The result is shown in Table 2. It attests that PossessedHand supports beginners' playing. Furthermore, PossessedHand will help beginners move fingers appropriately when playing musical instruments.

DISCUSSION AND COMMENTS

In Table. 3, We list the comments of the subjects, who contributed to our experiments. Regarding the first comment, almost all subjects are not used to electric stimulation by PossessedHand. We must be careful to consider the feeling of terror. In our future work, PossessedHand's appearance will be improved to lessen the feeling of terror.

Table 2. The results of the experiment about the musical performance.

	supported	normal
mistakes about finger	3	4
timing errors	4	13

Table 3. Comments from the subjects.

subject's number	comment
1	Scary... just scary...
2	I felt like my forearm was pushed by someone.
3	I felt like when I got a cramp in my arm.
4	A kind of new sense!
5	I want to be controlled remotely.
6	It would be possible that I can do difficult task (such as driving helicopter) without training.
7	It will be useful when playing other instruments such as Piano or Sax other than koto.
8	I felt like my body was hacked.

As for the second comment, the current could stimulate not only muscles, however also sensory organs. In this case, pressure sensory organs in the surface of the skin were stimulated. This is unavoidable. However, selecting which ones to stimulate might be possible in the future by changing the stimulation frequency or controlling the stimulation depth.

As for the third comment, PossessedHand now applies current only to two points in one muscle. More elaborated application of current, such as adding current application points, would prevent cramp-like feeling.

As for the fourth and eighth comments, people believed their body was totally "under control", However PossessedHand raises questions about their control or "free will".

As for the sixth comment, PossessedHand now controls only the hand to enhance musical experiences. In the future, difficult tasks such as flying a helicopter might be possible. Applying current to the shoulder should be studied in the future. Moreover, combining PossessedHand with other technology such as context-recognition should be necessary.

As for the seventh comment, PossessedHand can be used to play any musical instruments. In this study, the koto was selected as the musical instrument in experiments because it was the only instrument with which the author was familiar.

We also feel that the use of PossessedHand can be extended to sports, learning finger languages, performing arts, and making handicrafts. To extend the use of PossessedHand, we have to consider reaction rates, accuracy, and muscle fatigue [4, 10, 24].

CONCLUSION

PossessedHand can inform the appropriate hand gestures and the timing of these gestures to a beginner playing a musical instrument. We used electric pulses, 14 channels, and three levels of electrical stimulations. The system stimulates the user's forearm muscles that are connected to each finger-joint. Auto-Calibration systems have been introduced to set pads' locations, levels of electrical stimulations and the timing. The calibration system gave 168 stimulation patterns that included 14 paths (via electric pads on the belts) and 12 stimulation levels. Than, the system selected the pad's locations and the levels of electrical stimulations from feedback of finger motions. To synchronize the timing, the system gave sounds and stimulations at the same time. The user can adjusted the timing by using a timing volume of PossessedHand.

PossessedHand can selectively apply simulations to muscles at different depths according to three levels of electrical stimulations, and it can control 5 independent and 11 linked joints, 16 joints in total, with our auto-calibration systems. In our experiments, subjects could correctly feel each joint movement induced by PossessedHand. We also measured the force generated by PossessedHand for each finger. The average force was $88.75\,g$. The forces were not sufficient to grap a real object and to play musical instruments were enough to indicate the fingers that needed to be moved.

We discussed a support system based on PossessedHand for playing koto, which is a traditional Japanese musical instrument. About the support system of the Koto performance, we are in the first stage. We must consider effective feedbacks, the controlling the amount of bend, motivations[20] and so on. In this paper, we confirmed that PossessedHand could tell a user which finger should be moved at which timing. When using PossessedHand, the subjects could maintain a correct rhythm and made fewer mistakes in finger selection.

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