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Development of Smart Gloves based on Knitted Strain Sensor for Finger Rehabilitation Training

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Abstract **- Effective rehabilitation training to restore motor function of the hand requires the patient's continuous and active participation, so the development of smart gloves that can increase the effectiveness of rehabilitation treatment through correct training movements is necessary. Accordingly, knitted strain sensors of three lengths were manufactured and repeated bending experiments were conducted for each sensor length, rpm, and angle. The excellence of the sensor was confirmed through sensitivity, repeatability, and responsivity, and a smart gloves was developed that can check the exact motion and joint angle of finger rehabilitation training in real time based on the verified sensor.The accuracy and reliability were verified by evaluating the real-time motion recognition performance of the smart gloves developed for 4 subjects. A smartphone application was developed and the industrialization of smart gloves for finger rehabilitation training was suggested.**

Index Terms **- knitted strain sensor, smart gloves, rehabilitation training, finger rehabilitation, motion recognition, application**

Introduction

The hand is one of the parts frequently used in daily life, and if physical damage or functional loss occurs in the fingers that require numerous movements, it causes discomfort in daily life and reduces the overall quality of life [1].Among them, finger joints have a problem where function deteriorates and contractures or degenerative changes occur if continuous movement does not occur, so rapid rehabilitation is recommended after injury diagnosis.However, there is a problem that the number of patients who can receive rehabilitation treatment is limited because the number of therapists is small compared to the number of patients who need rehabilitation training [2].Research to solve this problem includes rehabilitation robots and armored equipment, but these equipment are generally heavy or bulky and are limited to locations, making continuous rehabilitation difficult [3], [4].Therefore, the purpose of this paper is to create a lightweight and flexible knitted strain sensor to develop a finger recycling training smart glove that can be used anywhere without restriction.

In addition, five finger rehabilitation training movements were extracted and the performance of the smart gloves was evaluated. Textile sensors are sensors manufactured to suit the clothing environment based on textiles in the form of fibers, threads, and fabrics [5]. It is used for weaving, knitting, embroidery, etc. using yarn with electrical functions, non-woven fabrics, etc. [6]. Among the manufacturing methods, the plain knitted strain sensor manufacturing method, which uses a combination of conductive yarn and regular yarn, is manufactured in a loop shape and exhibits relatively high elasticity in the structure itself. In addition, based on its high sensitivity and excellent elasticity, it is especially useful for rehabilitation that requires real-time motion monitoring [7], and is comfortable to wear and does not affect finger movements [8], making it suitable for smart gloves.As these knitted strain sensors stretch, the distance between the conductive yarn and adjacent loops increases and the contact area between the conductive yarns decreases. As the contact pressure increases, the contact resistance decreases [9]. When evaluating electrical characteristics, they can be analyzed in terms of sensitivity, repeatability, and responsivity. Sensitivity is an important factor in evaluating the performance of a sensor and represents the change in capacitance or electrical resistance compared to the rate of change in strain caused by mechanical stimulation of the sensor [10]. In particular, smart rehabilitation gloves must accurately recognize movements and angles through real-time monitoring during rehabilitation training, and high sensitivity of the sensor is essential to be able to measure even minute angles such as finger bending. As rehabilitation training progresses steadily, sensor values must be reliably and accurately measured even after repeated bending for a long time. Repeatability, which is an indicator for verifying the stability of the sensor, can be verified through Vp-p (Vpeak-to-peak) baseline uniformity of repeated bending experiment data, and is an important parameter to evaluate the electrical/mechanical dynamic performance of the sensor [11].

In addition, the responsivity of the sensor is important in order to recognize movements in real time during rehabilitation training, and this can be verified by the speed at which the strain sensor responds to the bending movement and the time required to return to the extension movement.

EXPERIMENTAL METHODS

2.1. Materials

To enable mass production, Stoll's computer knitting machine (CMS 330 HP W) was used to manufacture sensors. When producing smart gloves, we explored the possibility of industrialization by applying whole garments that knit the sensor part and the front of the gloves together. The conductive yarn used to fabricate the sensor is Amann's silver-plated conductive yarn and has a resistance of <530Ω/m. The lead wire, which acts as a wire connecting the sensor and MCU (micro controller unit), was made of Amann's silver-plated conductive yarn with a resistance of <85Ω/m. High-resistance silver-plated conductive yarn was used to maximize the difference in resistance values when stretching the sensor. For knit gloves that need to pass over joints such as fingers or wrists, silver thread is suitable as it does not affect the measured distance[12]. The sensor part was manufactured as two combinations using one conductive yarn and one mixed yarn, and the other parts were used only as one mixed yarn (AW) mixed yarn with a 1:1 ratio. The sensor is made with a plain stitch structure, a basic form of knitting, and has excellent elasticity.

2.2. Preparation of Knitted Strain Sensors

For excellent motion recognition performance of smart gloves using knitted strain sensors, the gloves must adhere as closely as possible to the user's body surface. Due to the structure of the body, each finger has a different length, so to increase the accuracy of motion recognition, the length of the sensor must be designed differently depending on the length of the finger. Among 2 adult females, the length of the joint was measured based on the hand of a woman similar to the average hand dimension measurement and was identified as thumb 30mm, index finger 60mm, middle finger 70mm, ring finger 65mm, and possession 50mm. In this study, five knitted strain sensor lengths were designed for smart glove customization. The length of the sensor is designed to be 50mm of thumb, 80mm of index finger, 90mm of middle finger, 85mm of ring finger, and 70mm of small finger by adding 10mm above and below the joint so that it can be closely adhered by wrapping the joint during bending operation.

Since the finger is cylindrical, the width of the sensor was designed to be the same for all sensors at 20 mm so that it can adhere closely to the finger and cover the joint even when bent. In order to check the sensing performance according to the length, the shortest length of 50mm, the middle length of 70mm, and the longest length of 90mm among the five sensors were manufactured. Figure 1(A) and (B) are test specimens of a knitted strain sensor manufactured for electrical property analysis, and the sensor length is 90 mm. The lead wire was sewn with zigzag stitches that were more durable than straight stitches. Smart gloves that perform repetitive bending also require high elasticity; zigzag stitches are designed at 3mm intervals because smaller stitches break conductive yarns at higher elongation [13]. A fastener interconnecting system was implemented by fastening a spring snap button at the end of the lead wire to be connected to the MCU.

2.3. Measurement of electromechanical properties

In order to examine the resistance change and sensing electrical characteristics according to the bending angle of the manufactured strain sensor, a repeated bending experiment was conducted using CKS' textile folding tester (CKFT-T400) as shown in Figure 1(C). All strain sensors must undergo a stretching process in advance to maintain stable electrical properties [14]. Therefore, before this experiment, pre-stretching was performed five times for each specimen to measure stable data. Rehabilitation training to return the damaged area to its original state is carried out in a repetitive motion, and it is important to continue at a constant speed because if the patient moves at a high speed, he or she may feel pain or secondary damage. In addition, the speed of operation varies depending on the user or the degree of damage, but the sensor value must be able to be measured consistently. Therefore, the bending rate was tested at two speeds of 10rpm and 30rpm to confirm the difference in sensor values for the bending rate based on rpm (revolution per minute). To confirm the possibility of motion recognition for the minute bending angles of finger joints and to consider differences in resistance depending on the angle, an experiment was conducted at three angles: 30˚, 60˚, and 90˚. As for the number of bends, 100 experiments were conducted for each experiment to confirm the performance of the sensor value for long-term repetitive bending. The MCU used in the experiment used an Arduino-based ESP 32-PICO, and in connection with the Arduino program, data was set to be output every 0.1 seconds, and 100 repetitive bending experiments were performed.

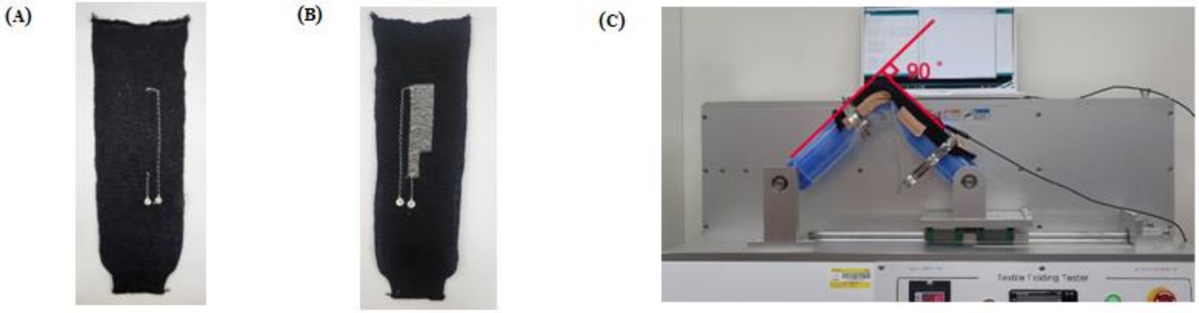

FIGURE1 (A) FRONT OF A SAMPLE WITH A SENSOR LENGTH OF 90MM. (B) BACK OF A SAMPLE WITH A SENSOR LENGTH OF 90MM. (C) 90˚ OF TEXTILE FOLDING TESTER.

RESULTS AND DISCUSSION

3.1. Sensing characteristics of knitted strain sensors

In order to confirm the possibility of motion recognition of the manufactured knitted strain sensor, the performance of electrical characteristics was evaluated based on sensitivity, repeatability, and responsivity. The voltage scale of the Arduino used in the experiment is 0~3.3V, and is measured in the range of 0~4095 on the serial monitor. The sensor value extracted from the bending experiment was converted to the actual voltage value by substituting it in equation (1) [15].

$$V_B = \frac{output\ (sensor\ value) \times 3.3}{4095} \tag{1}$$

$$V_A = 3.3 - V_B[V]$$

$$I_A = \frac{V_A}{R_A}$$

$$R_B = \frac{V_B}{I_A}$$

In terms of sensitivity, as the bending angle increased as shown in Figure 2(A), the gauge factor (GF), which represents the sensor's typical characteristics, and the resistance change rate increased. 90mm, the longest sensor length, had the highest sensitivity, so the difference between 30 ˚s and 90 ˚s was about three times or more. As a result, a difference in the voltage value for the angle appeared, and through this, the high sensitivity of the sensor was confirmed.In terms of repeatability, repeatability was evaluated and analyzed based on the uniformity of the baseline and signal size of Vp-p according to 100 repetitive operations, and the uniformity of Vp-p within the same cycle. As shown in Figure 2(B), all specimens were uniform and stable. Textile motion sensors have limitations where hysteresis occurs. At this time, the constant baseline means that the resilience and repeatability of the knitted strain sensor are excellent during bending and stretching, so the excellent repeatability of the sensor produced in this paper was confirmed.

In addition, as shown in Figure 2(C) the average value of the bending voltage value was obtained and the difference between the voltage values for the three angles was compared. The initial voltage values were located in a similar range at all angles, and similar values were derived for continuous elongation. On the other hand, the bending voltage value increased as the angle increased, and most of them showed a difference of 20 to 38%, confirming the difference in the voltage value for the angle. In terms of responsivity, 30 rpm is bent faster than 10 rpm, which is suitable for confirming reactivity, so it was confirmed based on this. In general, 30rpm takes about 2 seconds to return to its initial state, and looking at Figure 2(D), it took less than 2 seconds for the knitted strain sensor produced in this paper to bend and unfold, confirming the quick responsiveness to the operation. Therefore, through repeated bending experiments, we verified the excellence of the knitted strain sensor produced in this study and confirmed the possibility of real-time motion and angle recognition of smart finger rehabilitation training gloves.

3.2. Components of Smart Gloves

For patients requiring finger rehabilitation training, a knitted strain sensor with excellent elasticity and no obstruction to the flexion of the finger joint was used. The length of the sensor was customized to be located on all joints of the five fingers: 50mm for the thumb, 80mm for the index finger, 90mm for the middle finger, 85mm for the ring finger, and 70mm for the little finger. It was designed to recognize the bending of all joints when performing rehabilitation training movements. The location of the detachable/detached device with the built-in MCU is designed to be located directly above the wrist to minimize inconvenience during rehabilitation training operation. In order to check the motion recognition performance of smart gloves for rehabilitation training, an Arduino program was designed to output sensor values of five fingers according to motion every second through Bluetooth.The designed Arduino program was uploaded to an MCU with 5 channels for each finger, and the voltage value was measured by connecting it to the Bluetooth serial terminal program.

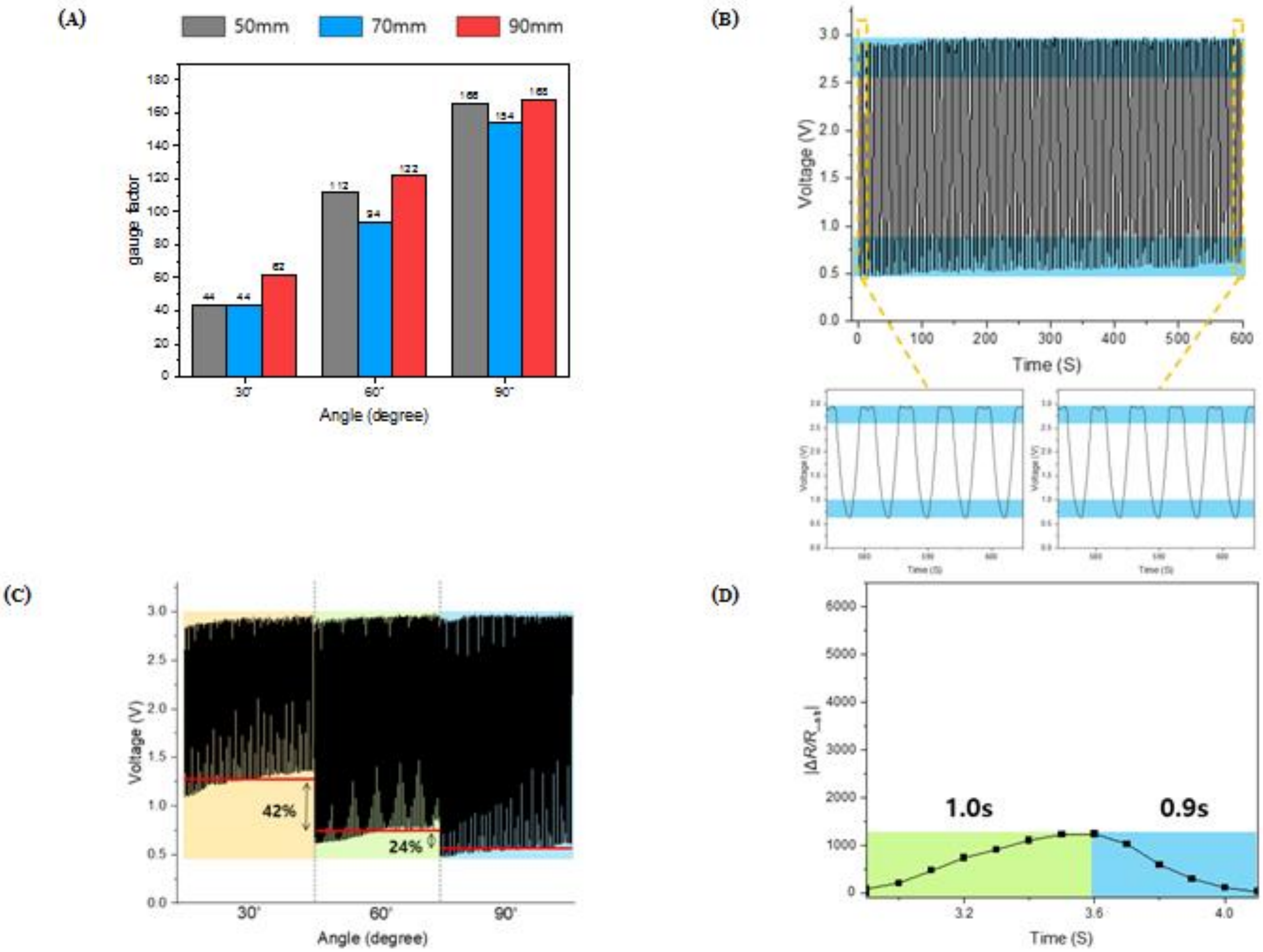

Figure 2 (A) Comparison of GF values by sensor length according to operating speed of 10rpm. (B) Baseline pattern according to operating speed of 10rpm when sample with sensor length of 50 mm is 90 ˚ of bending angle. (C) Average value of voltage for each angle according to operating speed of 10rpm. (D) Reactivity with operating speed of 30 rpm for a sample with a sensor length of 70 mm with a bending angle of 30 ˚

The knitted strain sensor produced in this study improves sensing performance by increasing the contact pressure according to the number of contact points of the conductive yarn when stretched [16].For this purpose, the sensor was structured in a vertical wale rather than a horizontal course where a loop is formed.The wrist part of the glove was designed with a 2X1rib structure, and the rest was knitted flat, the basic structure of the knit, and the possibility of whole garment was explored by knitting parts except for the thumb together.

The device, which must be used with smart gloves, has an MCU and battery built into the device so as not to interfere with rehabilitation training, and a battery switch and USB C-type hole for charging or data transfer were created.In addition, according to Figure 3(A), a schematic diagram of smart gloves, a spring snap button for a fastener interconnecting system is attached to increase the convenience of the device, so it can be attached and detached depending on the user's situation and purpose.

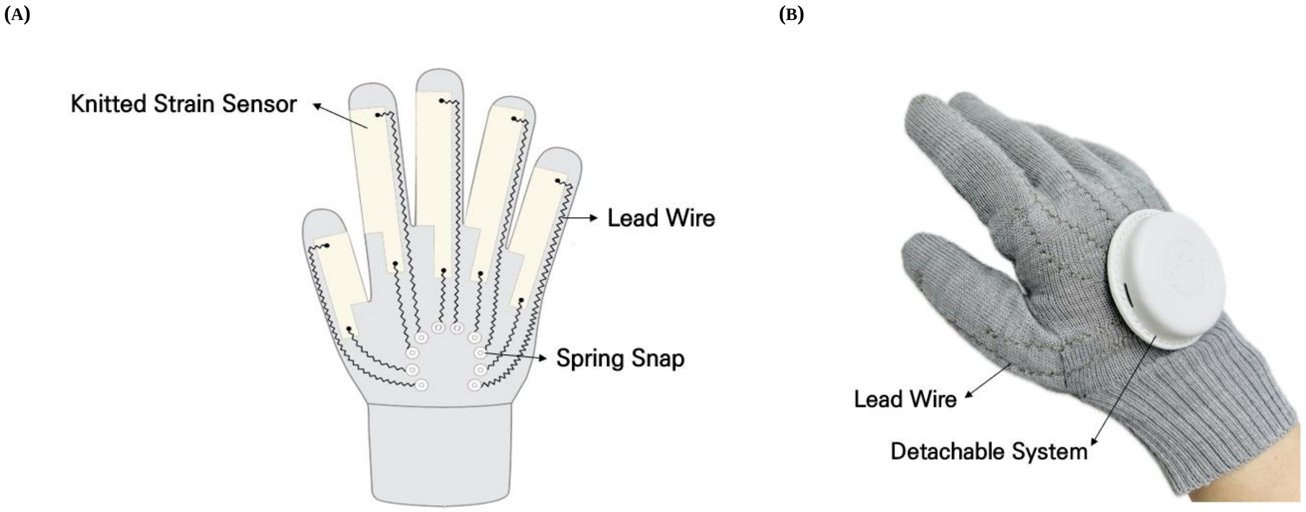

FIGURE 3 (A) SCHEMATIC OF SMART GLOVES.(B) DEVELOPED SMART GLOVES.

Figure 3(B) shows the smart gloves and devices developed in this study.

3.3. Electrical Performance Test

To evaluate the reliability of the finger rehabilitation training smart gloves, motion recognition tests were conducted on four subjects. Prior to this experiment, all subjects performed five fist-clenching and stretching motions to obtain stable data. Among the stop motion and finger rehabilitation training motion for comparison, four single and one continuous motion were performed. Among the single movements, the rest of the movements except for the intrinsic muscle movement are movements that bend one or two fingers, so four movements may be performed in the same way. The continuous operation was divided into 4 movements, resulting in a total of 18 movements.

The data from when four subjects performed the same movement was created into a graph to compare the aspects, and the accuracy of movement recognition was evaluated through the differences and changes in the initial voltage value and bending voltage value for the five fingers. In the stop motion, all fingers were stretched, so the voltage value did not fluctuate significantly, so the voltage value of 2.5~3.0V was maintained as shown in Figure 4(A). Since the intrinsic muscle exercise as shown in Figure 4(B) is a motion in which only the metacarpophalangeal joints of four fingers is bent at 90 degrees, the voltage value decreased from 3.5V to 2.5V even in the bending operation. As shown in Figure 4(C), the thumb range-of-motion exercise is a movement in which the thumb opposes one of the other four fingers. By contrasting the thumb and middle finger, the voltage value of the thumb decreased from 2.5V to 2.75V and that of the middle finger decreased from 3V to 1.5V, respectively. The proximal phalanx blocking exercise, such as in Figure 4(D), is an exercise that fixes the proximal phalanx and applies a bending force to the joint.

When the middle finger was bent, the voltage value decreased from 3V to 2V. During the bending process, the voltage values of the other four fingers also changed due to the extension and movement of the fingers, but all of them maintained a range of 2.5V or higher, confirming that the state was not curved. The Flexor digitorun superficialis exercise, such as in Figure 4(E), is an exercise in which the undamaged finger is kept stretched as much as possible and only the damaged finger is flexed. When the middle finger is bent, the voltage value of the middle finger is reduced from 3V to 2.25V or less, and the remaining fingers have voltage changes due to extension movement, but the value is maintained above 2.5V and the operation can be recognized through the pattern in which the voltage value fluctuation of the middle finger is the largest.During the continuous motion in Figure 4(F), tendon gliding exercise proceeds in the order of hook gripping, long gripping, and complete fist gripping, but in this study, the stop motion was completed after tendon gliding exercise was completed to confirm the voltage difference between bending and stretching. Although it is difficult to accurately distinguish the angle because it is a continuous movement, it was confirmed that recognition of the bending and extension movements was possible. Consequently, in the graphs of four single and one continuous motion, all four subjects showed differences in voltage values due to different finger length and thickness, flexibility, and extension movements due to bending motion, but the pattern of the motion graph of bending the finger joint was similar. In addition, the bendingvoltage value of the exercised finger decreased by the greatest difference, confirming the bending and stretching state of the motion. Therefore, it was verified that the movement can be recognized in real time during rehabilitation training through the strain sensor of the smart glove developed in this study.

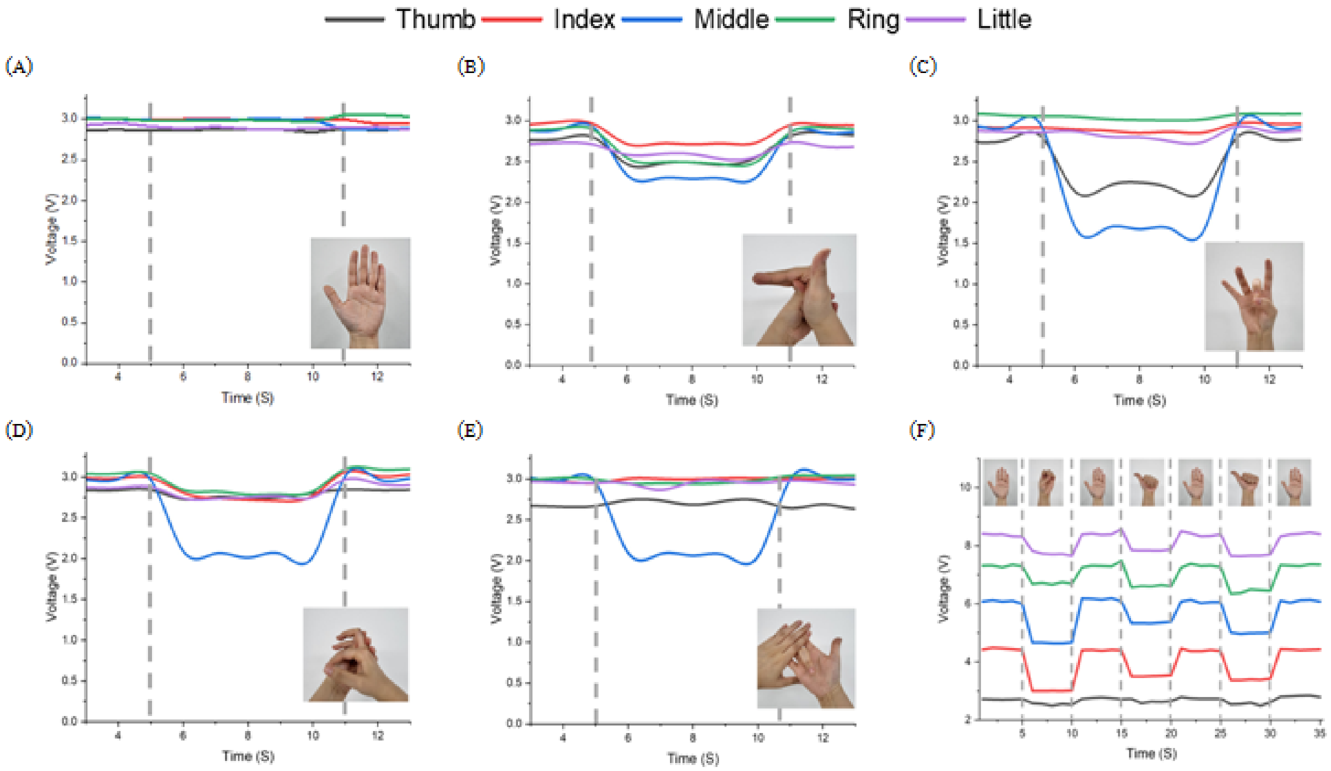

FIGURE 4 (A) Voltage value of stop motion. (B) Voltage values of intrinsic muscle exercise . (C) Voltage values of the thumb range-of-motion exercise. (D)Voltage values of the proximal phalanx blocking exercise. (E)Voltage values of the Flexor digitorun superficialis exercise.(F)Voltage values of tendon gliding exercise.

3.4. Demonstration of the wearable rehabilitation training

A smartphone application was developed to verify the possibility of recognizing the real-time rehabilitation training motion of the developed smart gloves for rehabilitation training. It is designed to link the device and the application using the Bluetooth function, touch the image to select the desired exercise as shown in Figure 5(A), and notify success and fail according to the correct motion and angle when the corresponding operation proceeds. In the single motion for verification, the motion of the thumb range-of-motion exercise in which the index and middle fingers were opposed, the motion of the proximal phalanx blocking exercise of the index finger, and the motion of the the Flexor digitorun superficialis exercise of the middle finger were selected. Since each exercise bends at a similar angle and shows similar patterns in the graph, the possibility can be confirmed with just one finger, so only one finger was used for each movement.

In the continuous motion a full fist clenching was selected during the tendon gliding exercise. Since a complete fist flexes all the joints of all fingers except the thumb, it is suitable for checking the possibility of recognizing flexion and extension through a sensor. Therefore, the motion recognition evaluation of smart gloves was conducted using the four selected motions. Figure 5(B) and (C) show the rehabilitation training operation using the developed smart gloves and applications.

If you perform the correct movement for the selected exercise, success is displayed as shown in the application screen in Figure 5(B). If you perform an exercise other than the selected exercise or do not perform the correct movement, fail is displayed as in the application screen in Figure 5(C). The video for the actual demonstration process and 10-time repetition reliability verification can be viewed through the QR code in Figure5(D). As a result of the demonstration, it was verified that the developed smart gloves were capable of accurate motion recognition in real time even after 10 consecutive experiments.

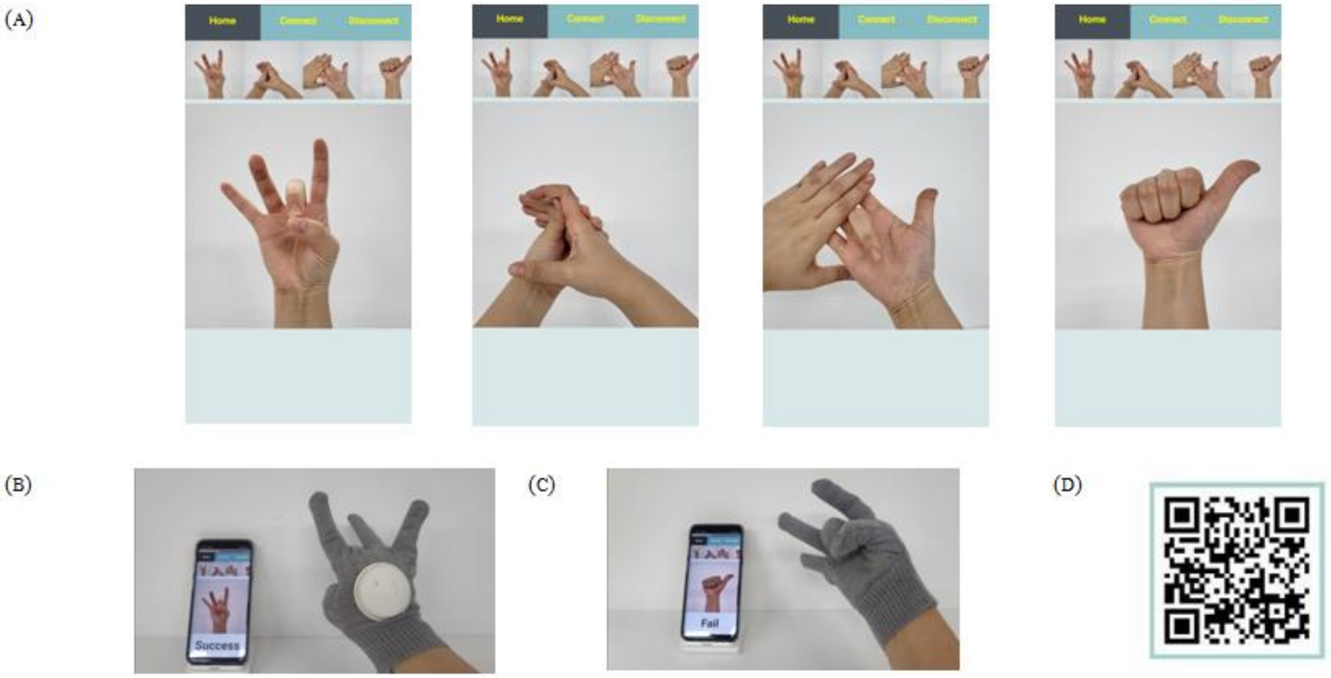

FIGURE 5 (A) SCREEN IMAGE OF THE APPLICATION. (B) WHEN MOTION IS SUCCESSFUL DURING A GLOVE PERFORMANCE TEST USING A SMARTPHONE APPLICATION. (C) WHEN MOTION FAILS DURING A GLOVE PERFORMANCE TEST USING A SMARTPHONE APPLICATION. (D) DEMONSTRATION VIDEO QR CODE.

Conclusion

In this study, to develop smart gloves for rehabilitation treatment, knitted strain sensors of 50mm, 70mm, and 90mm were manufactured to enable motion and angle recognition. Repeated bending experiments were conducted for each sensor length, rmp, and angle to confirm the sensor's excellence through sensitivity, repeatability, and responsivity. Using proven sensors, we developed smart gloves for finger rehabilitation training that can check the correct movements and joint angles of finger rehabilitation training in real time. A real-time motion recognition performance evaluation was conducted on 4 subjects to confirm the excellence of the motion recognition performance of smart gloves.

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