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Hand Rehabilitation Device System (HRDS) for Therapeutic Applications

Mohd Nor Azmi Ab Patar, Takashi Komeda, Takashi Mori, Takaya Seki, Yukio Saito,
Jamaluddin Mahmud, Cheng Yee Low

Abstract — **The hand rehabilitation approach for people who are affected by cerebral apoplexy has been a long-standing issue with researchers worldwide. Currently, scientific research has discovered a way to recover the motor function. Moreover, the sensory function can be recovered by neuroplasticity. Previously, the conventional hand rehabilitation approach only focused on the motor function. Therefore, there is a need to develop an effective hand rehabilitation device to recover both the motor and sensory functions. This research embarked on the configuration setup and evaluation of new hand rehabilitation devices using a mechanical stimulation system. The system has directly led to the stimulation of tactile senses, which can later be used to help patients who lack motor and sensory functions. The work was carried out in four stages comprising the development of a programming algorithm, the design and fabrication of the device and finally, an evaluation of the product and its functions. The objective to develop and fabricate a new robust tactile grasping type stimulator for a hand rehabilitation device has been achieved successfully. The preliminary evaluation on a healthy volunteer was carried out to identify the safety factor in the implementation of hardware and software before targeted patients are used.**

I. Introduction

The ability to move the hand is necessary for the performance of the basic Activities of Daily Living (ADL). The inability to have hand movements and to sense an object while grasping or touching it will significantly reduce the quality of life [1]. Nowadays, there are many approaches to recover the motor function of the hand, for example, by orthosis, Functional Electrical Stimulation (FES), and physiotherapy [2]. Many studies in neuroscience have mentioned that the recovery of the motor function in the brain can be improved by doing repetitive activities [3]. These activities will train and improve the strength of the hand muscles [4]. Today, many patients have realized that through the use of prehension orthosis for the flexion of the fingers, they are able to move their fingers with sufficient force to grasp an object. However, intensive repetition of motor coordination activities will place a heavy load on the physiotherapists who are assisting the patients [5].

Most of the literature reviews on hand rehabilitation robotic devices focus on the recovery of motor functions, specifically the extension and flexion movements of the hand. However, there are no established approaches or publications available on the recovery of the sensory functions of the hand. In other words, the recovery of the sensory functions of the hand has yet to be explored by scientific researchers. Therefore, improvements to the sensory functions of the hand are just as crucial to the recovery of the motor functions of the hand.

The main aim of this study is to develop a Hand Rehabilitation Device System (HRDS) using a mechanical stimulation system. The system will stimulate the sensory receptors of the hand. Then, it will excite the nerve impulses and transmit these to the sensory function of the brain, which will react accordingly via visual sensations, motor functions and pressure sensations. Sensory receptors in the skin consist of an independent neural mechanism that consists of four types of sensations, namely pressure, pain, heat, and cold. Figure 1 illustrates the distribution of sensory points in 1 cm^2 of skin area. The current research however is a pilot study to enhance research on the rehabilitation of the hand and fingers. It starts with a mechanical design of the HRDS. The main idea of the design is to stimulate the tactile sensors in the hand and fingers based on mechanisms that can transmit the force from the actuators and exert pressure on the palm.

This paper presents a new hand rehabilitation approach to recover the sensory and motor functions of the hand. The design concept determined by these specifications is described in Section II. The choice of materials, the actuation system, and the implemented control schemes are described in Section III. Experiments were conducted with the interface to evaluate its performance (Section IV).

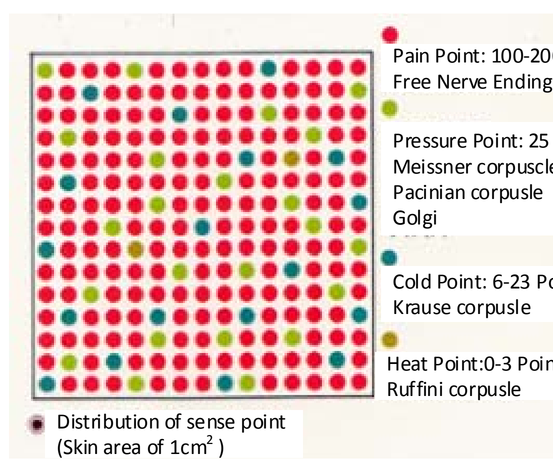

Figure 1. Distribution of four types of sense points of touch, pain, heat and cold in 1cm^2 of skin area

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Mohd Nor Azmi Ab Patar, Takashi Komeda, Takashi Mori, Takaya Seki and Yukio Saito are with the Research Organization for Advance Engineering, Shibaura Institute of Technology, Saitama, Japan (e-mail of corresponding author: azmipatar@salam.uitm.edu.my).

Mohd Nor Azmi Ab Patar, Jamaluddin Mahmud and Cheng Yee Low are with the Centre of Excellence for Humanoid Robot and Bio-Sensing, Universiti Teknologi MARA, Shah Alam, Selangor, Malaysia.

II. METHOD

A. Sensory and Motor Pathway

When the HRDS is stimulated by a hand grasping motion, the muscles of the hand will contract and transmit the impulse to the motor cortex. The fibres from the motor cortex (corticospinal tract) will decussate in the medulla oblongata in the spinal cord. The contributions come from the supplementary motor area and the premotor cortex, which constitute 29% of the fibres, while the somatosensory cortex, parietal lobe and cingulate gyrus supply the rest [6]. A tactile stimulus activates the touch receptors in the fingers. Then, the potential action is activated in the afferent pathway, which propagates an impulse to the spinal cord. The spinal cord serves as the integrating centre for the stimulation of the afferent neurons [7]. The efferent nerve carries the nerve impulse away from the central nervous system to the effector muscles (Figure 2).

B. Design Concept and Implementation

Functional recovery can be promoted by giving pressure stimulation mechanically to the palm. Repeated grasping training will enhance the stimulation of the cerebral cortex [8]. The intensity of the stimulus to the palm can be modified according to the level of severity of the disease. Healthy subjects act as a control to obtain the grasping ability criteria for recovery. By performing visual feedback to the cerebral cortex, the intensity of the stimulus and level of the grasp can be displayed.

Figure 3 shows the theoretical concept of the implementation of the HRDS. The DC motor acts as an actuator to generate a continuous mechanical contact. The rotating shaft, consisting of 32 spur gear teeth arranged in a series (gearing system) and covered by a rubber tube, will provide the pressure stimulus when it is grasped by the disabled hand. The rotational speed of the stimulus is measured by a potentiometer, which is attached to the top of the Z-axis. The rubber tube is filled with oil, where the gripping force of the hand is measured by a pressure sensor. The force of the reaction to the palm is easily adjusted by using oil fillings with different viscosities and volumes. When a gripping force is exerted with continuous stimulation to the palm, the internal pressure in the tube will increase considerably. The gripping force is measured by the resistance force of the palm. The data detected is displayed on the external monitor as the parameters for the visual feedback.

In the first attempt on 9 healthy subjects, an evaluation experiment was conducted by accessing the distribution of sensory points in $1cm^2$ of skin area. The evaluation was classified according to seven stimulus levels: 1) Numbness; 2) Not clearly indicated whether felt touch or no touch; 3) Unknown localization of sensation; 4) Sensation is clearly felt; 5) Sense of pressure but not strong; 6) Clear sense of pressure; and 7) Pain

The level of stimulus was controlled by four major types of encapsulated mechanoreceptors, which were specialized to provide information to the central nervous system about touch, pressure, vibration, and cutaneous tension: Meissner's corpuscles, Pacinian corpuscles, Merkel's disks, and Ruffini's corpuscles [9].

Merkel's discs respond from a steady state to low frequencies of up to 15 Hz. Meissner's corpuscles are particularly efficient in transducing information about the relatively low-frequency vibrations (30–50 Hz) that occur when textured objects are moved across the skin. The Pacinian corpuscles act as a filter, in this case allowing only transient disturbances at high frequencies (250–350 Hz) to activate the nerve endings. Ruffini's corpuscles detect continuous tension.

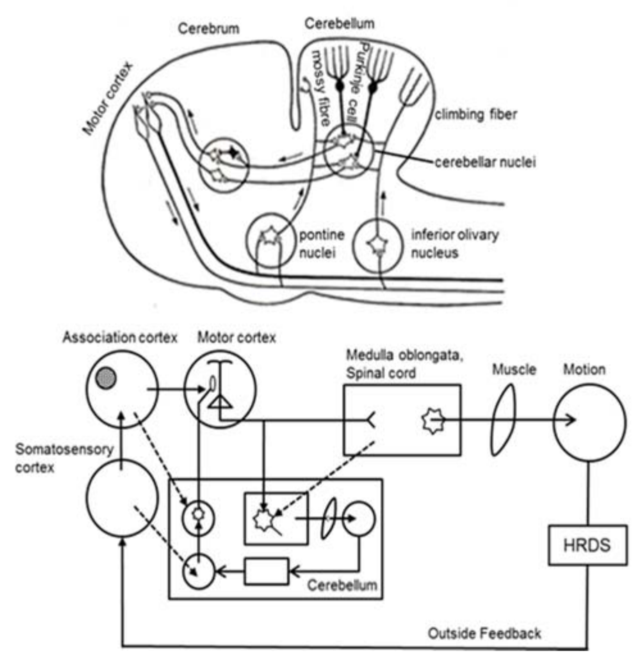


Figure 2. Afferent (sensory) and efferent (motor) pathway of muscle motion model of motor cortex and somatosensory cortex

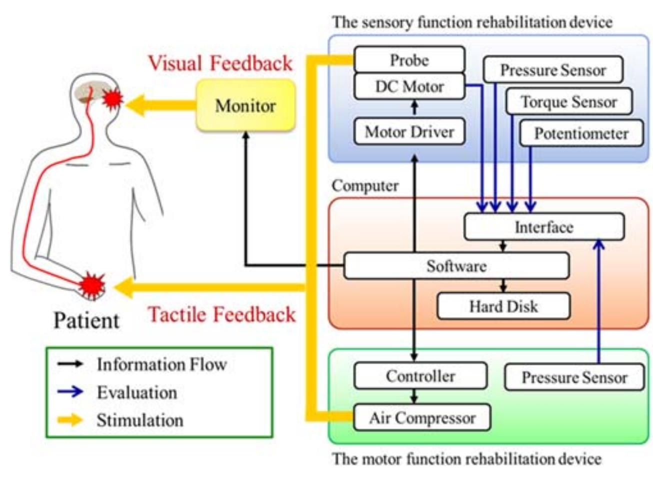


Figure 3. Implementation Concept of Hand Rehabilitation Device System (HRDS)

III. DEVICE STRUCTURE

A. Specifications

During the designing of the advanced Mechatronics system, it was compulsory to have a cross domain system model to assimilate all the elements of the mechanical, electrical and software engineering [10]. Therefore, a device was developed based on the semi-formal specification technique, which required effective and continuous cooperation within the same communication between developers from multiple disciplines during the whole development process, especially in the initial stage of the design phase (conceptual design) (Figure 4). The advantage of a semi-formal description was the exhausting of the creativity of the developers in the early stages of the development cycle [11]. Later on, the prepared models had to be formalized in order to carry the initial analysis of the logical or dynamic behaviour. By using the specification technique, the developers were able to prepare a first principle solution together [12].

The specification technique was used to describe the principle solution of a hand and finger device for rehabilitation. Aspects of the function and application scenario are discussed in the following sections.

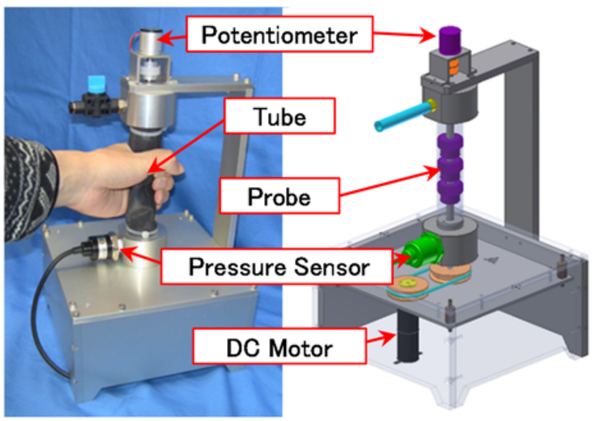


Figure 4. The conceptual design of HRDS

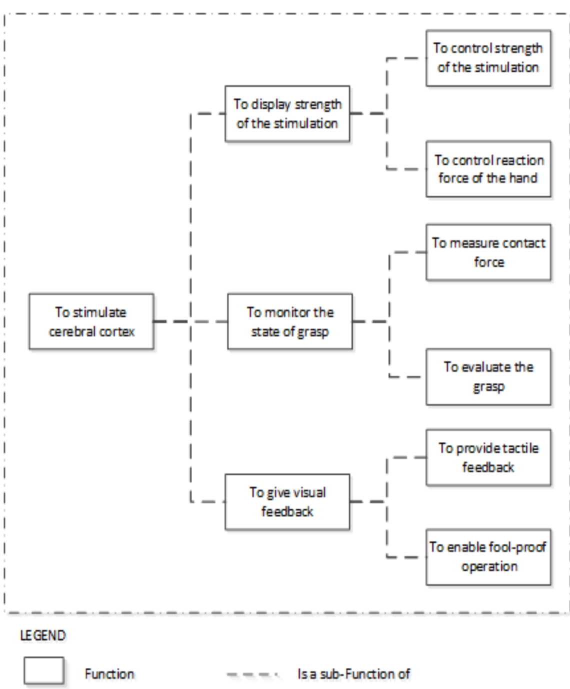


Figure 5. Function of Hand Rehabilitation Device System (HRDS)

B. *Functions*

This section describes the functions of the HRDS system. The main function of the hand rehabilitation system is to stimulate the cerebral cortex by applying the mechanical pressure contact stimulation probe to the palm continually and increasing simultaneously the strength of the stimulation. In supporting the main function of stimulating the cerebral cortex, three sub-functions are decomposed as shown in Figure 5.

C. *Prototype Development*

The development concept of the HRDS was based on the following requirements:

1. Ability to stimulate the motor function
2. Ability to stimulate the sensory function
3. The ability of assessment tools

D. *Rehabilitation device for the motor function*

Patients can grasp using five fingers. Thus, this approach is totally different compared to the conventional prehension orthosis, which uses the three-point support approach in the hand. This approach can give more effect to the hand in the rehabilitation process. The device uses an external hydraulic pressure source to produce the pressure around the grasping area. Thus, when patients grasp the tube, the grasping force will be detected as a grasping displacement.

E. *Rehabilitation device for the sensory function*

Patients grasp the rotating gear mechanism axle cover with the rubber tube by the affected hand. The axis in the tube will turn according to the DC motor rotation, which is controlled by a Pulse Width Modulation (PWM) control scheme [13]. The number of gear teeth at the rotating gear mechanism will stimulate the tactile area in the palm repetitively by using mechanical pressure contact stimulation. The device detects the internal pressure in the tube via a pressure sensor, while the angular velocity of the rotating gear mechanism and the rotational angle will be detected by a potentiometer when exposed to the repetitive stimulation to the palm. The axial rotary resistance is detected from the current value of the motor. The specifications for the device are listed in Table 1. The sensory function rehabilitation device is shown in Figure 6.

TABLE I. SPECIFICATION OF THE DEVICE FOR THE STIMULATION OF SENSORY FUNCTION

Parameter	Values
Size	196×204×355 mm
Grasping Tube (Material)	Rubber Tube
Tube length	125 mm
No. of Gear Teeth	32
Torque	1830 mNm
Engine Speed	121 RPM

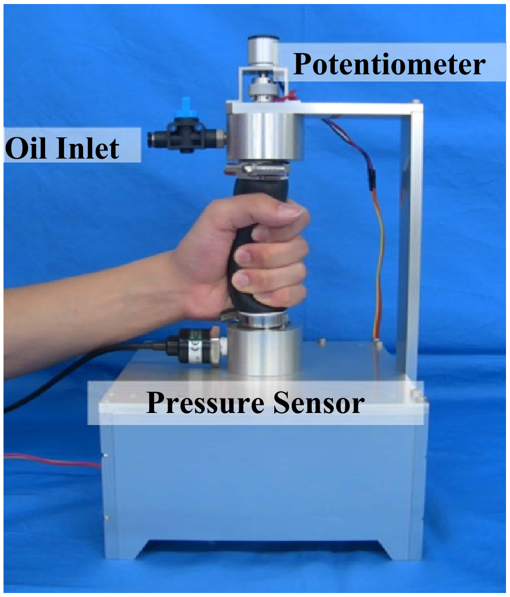


Figure 6. Rehabilitation device to stimulate the sensory function.

F. Monitoring system of Rehabilitation Device

Figure 7 illustrates the interface used in the data logger system for the assessment tools. The data logger and measurement system show the data and parameters involved in the experiment such as the grasping displacement, the internal pressure in the tube, the speed engine of the gear, the rotation angle, and the axial rotary resistance. The data displayed on the user interface program is for visual feedback.

Fig. 8 shows the variation results from the grasping pressure of 9 healthy subjects. The results illustrate the comparison of grasping pressure while gripping the rotating teeth of the gear mechanism at different rates of stimulation to the palm (50, 70 and 100 RPM). During the gripping, there were differences in terms of the grasping force of the healthy subjects although they were exposed to the same rate (50 RPM) of stimulation (Figure 9).

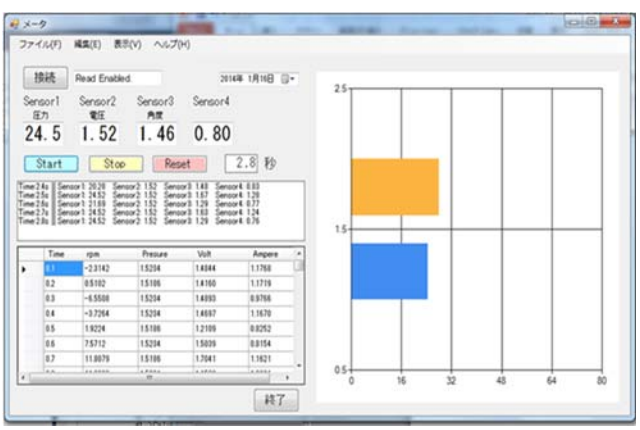


Figure 7. Interface of data logger system for assessment tools

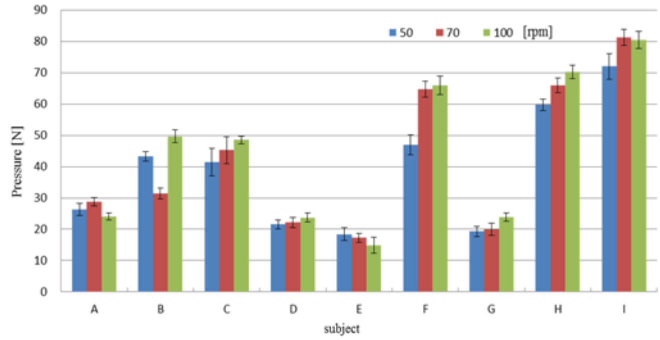


Figure 8. Grasping pressure for 9 healthy subjects while gripping the rotational shaft which stimulate the palm at stimulation rates of 50,70 and 100 RPM

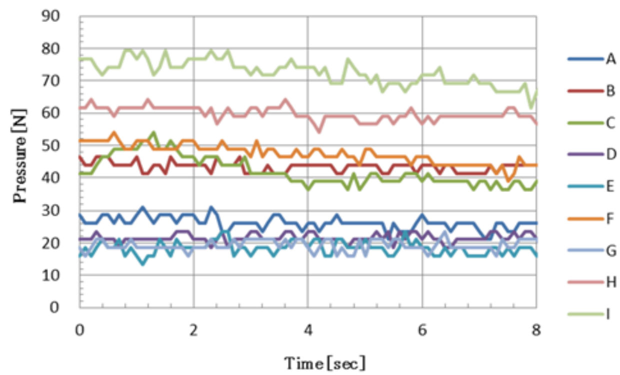


Figure 9. Grasping pressure variation for 9 healthy subjects while gripping the rotational shaft which stimulates the palm at a rate of stimulation of 50 RPM

IV. Evaluation Performance

A. Evaluation of Tactile Area Experiment

There are sensory receptors on the skin with a somatic sensation, which are very sensitive to pressure and touch stimulation.

The objective of the experiment was to evaluate the pressure sensation on the palm after grasping the mechanical stimulation (rotating teeth of the gear mechanism). Moreover, the experiment also identified and examined the distribution of the sensory points of tactile sense that exist on the palm.

The experiment was carried out on 10 mm × 10 mm square scales on the palm (Figure 10). Three different types of cylindrical brass rods (probes) with a diameter of 0.8 mm were used. The probe was pushed 100 times on the palm. This system is shown in Figure 11. The probe for the measurement system can move up or down due to the rotation of the DC motor. If the probe touches the palm, the movement will stop when the subject feels the stimulation.

The inclusion criteria for this study included (1) Healthy Subjects recruited from the Rehabilitation Robotics Lab, Shibaura Institute of Technology, Japan (Female; n = 4, Male; n = 5); (2) Velocity of Probe: constant voltage of motor speed (0.58 mm/s); (3) Factor Error: with or without glove; and (4) Shape of Probe : 3 different types.

The measurement was repeated three times in the same place, with the X-Y axis moving constantly. The evaluation of the measured data was optimized by using the Mahalanobis-Taguchi System (MTS). The MTS is a diagnostic and predictive tool for analysing patterns in multivariate cases.

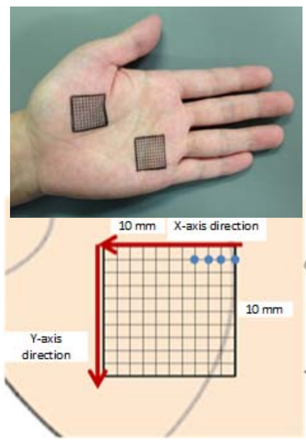
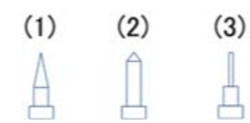


Figure 10. The tactile area subjected on the palm in the measurement.



No	Tip Angle	Rounded Tip	Diameter
1	15 °	R0.3	0.8
2	60 °	R0.3	0.8
3	D0.3	0.3mm	0.8

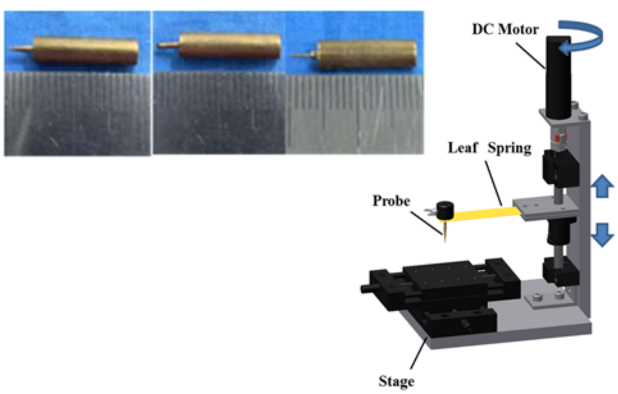


Figure 11. Measurement system used to evaluate the tactile area on the palm.

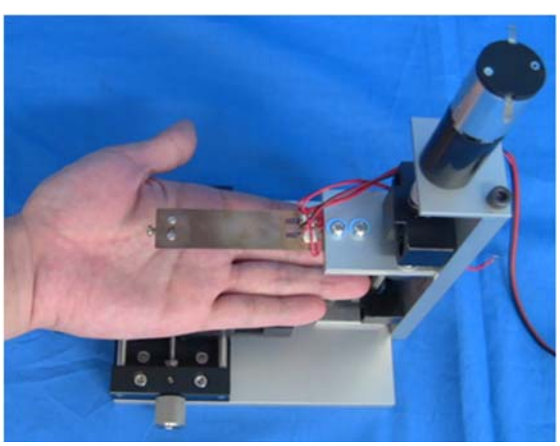


Figure 12. The experimental setup to evaluate the tactile area of the palm.

B. Results and Discussion

Figure 13 demonstrates the model of the tactile area of the palm. Figure 14 shows the tactile area of the dorsal part of the hand. When the area of the palm was pressed, the red points indicate the area that reacted to the stimulus. The blue triangle indicates the area where there was no reaction to the stimulus. The palm is more sensitive to stimulus (100%) compared to the dorsal part of the hand (92%). The skin of the palm is glabrous (hairless) and more durable, yet sensitive to touch. There are more touch and pressure receptors (Meissner's corpuscles, Pacinian corpuscles, Merkel's disks, and Ruffini's corpuscles) under the skin of the palm than under the skin of the dorsal part of the hand (Figure 15).

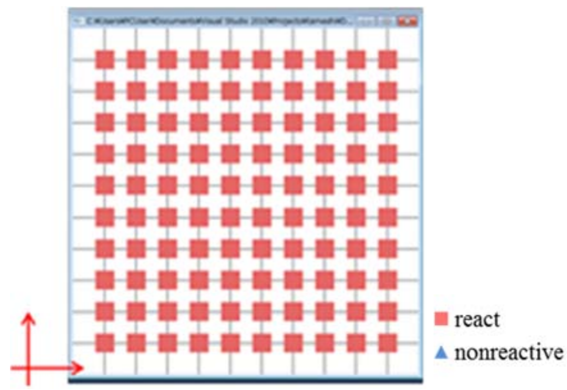


Figure 13. Experimental results of the evaluation of the tactile area of the palm.

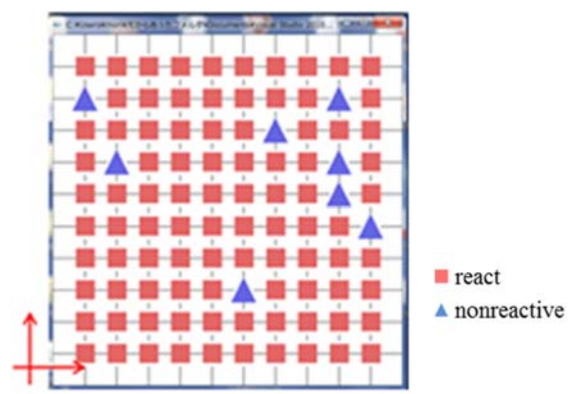


Figure 14. Experimental results to evaluate the tactile area of the dorsal part of the hand.

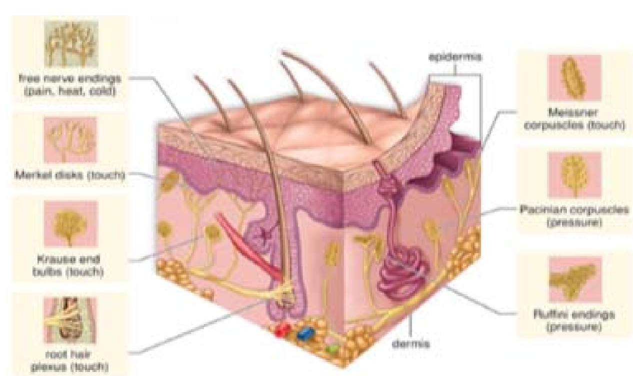


Figure 15. Overview of skin anatomy [14]

V. Conclusion

A new interface for hand and finger rehabilitation has been developed based on physiotherapy requirements in terms of the biomechatronics, safety factor, and comfort ability. An assessment of the grasping force (motor function) and sensory function of the hand will help physiotherapists to train the hand and fingers to function effectively. The HRDS has been designed to be adaptable to most hands and was tested with healthy subjects. However, the limitations of the study were the small sample size and the variation in the subject recruitment. This paper focused on the development of a hand rehabilitation device system that can improve the motor functions and sensory receptors of the hand. It used a different approach compared to conventional orthosis, which is a less effective method that can only be used to recover the motor functions of the hand. A potentiometer and force sensor allowed the patient's progress to be monitored during the training session.

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