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Design and Development of the Wearable Hand Exoskeleton System for Rehabilitation of Hand Impaired Patients

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***Abstract* — In the past decade, the population of disability grew rapidly and became one of main problems in our society. The significant amounts of impaired patients include not only lower limb but also upper limb impairment such as the motor function of arm and hand. However, physical therapy requires high personal expenses and takes long time to complete the rehabilitation. In order to solve the problem mentioned above, a wearable hand exoskeleton system was developed in this paper. The hand exoskeleton system typically designed to accomplish the requirements for rehabilitation. Figure 1 shows the prototype of hand exoskeleton system which can be easily worn on human hand. The developed exoskeleton finger can provide bi-directional movements in bending and extension motion for all joints of the finger through cable transmission. The kinematic relations between the fingertip and metacarpal was derived and verified. Moreover, the construction of control system is presented in this paper. The preliminary experiment results for finger's position control have demonstrated that the proposed device is capable of accommodating to the aforementioned variables.**

I. INTRODUCTION

As we know, typical motor function of hand is crucial for everyday life. However, human hands are likely to be injured from common results such as accidents, especially occupational accidents has the highest accident rate. Additionally, diseases, stroke, and musculoskeletal disorders for instance, are also one of the main causes result in disability. Rehabilitation is essential for patients to regain previous dexterity after hand surgery. However, hand function may not fully recover after an intensive rehabilitation process. There were several previous studies indicated that up to 66% of hemiplegic stroke patients have not regained the function of the paretic arm when measured 6 months after suffering from stroke, while only 5% to 20% of patients show complete functional recovery [1] [2] [3]. Those studies revealed the difficulty of recovery through rehabilitation process. From the viewpoint of rehabilitation, the main purpose is to strengthen the motor function through an intensive, repeatable, and continuous therapeutic exercise [4] [5]. Nonetheless, the conventional therapy requires manual interaction with physical therapists is not only difficult to evaluate the patient's performance and progress but also inefficient. The efforts to overcome the inefficiency of conventional therapy have been achieved by robotic rehabilitation. It has been shown that robotics can provide repetitive movement training which might be a more effective treatment for rehabilitation [6]. Also, robotic rehabilitation system can record the performance and progress simultaneously. These benefits allow the use of hand exoskeleton for rehabilitation applications to be more practicable in the following development. More and more recent researches focus on the development of hand exoskeleton. Many types of currently developed hand exoskeletons in other researches are developed base on the purposes of the application, such as rehabilitation or assistance [7] [8]. Due to the extremely complicated structure of human hands, most of the investigated exoskeleton systems are also complicated in order to achieve all needs in finger motion of human hand [9]. It is obviously to observe that the currently developed exoskeleton system always requires a large space for mechanical structures and extra space for actuator units. Consequently, exoskeleton system becomes non-portable and has to be operated in certain workplace such as hospitals and home. On the other hand, the exoskeleton system developed in this paper eliminates this inconvenience. The exoskeleton system presented in this paper is a portable and light weighted system which is integrated with mechanical structures and actuator units.

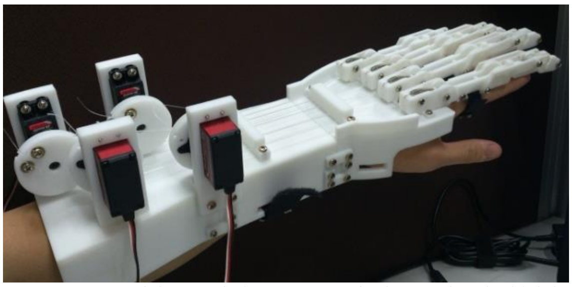

Figure 1. Prototype of the exoskeleton system for human hand which is attached to author's hand.

II. HAND BIOMECHANICS

Since the mechanism of exoskeleton hand is closely coupled with human hand when it is worn, it requires a systematic understanding of hand anatomy and biomechanics to consider the degrees of freedom (DOF) and range of motion (ROM) of each joint. Hand is naturally grouped with the carpus, comprising of five fingers which are named as follows: thumb, index finger, middle finger, ring finger and little finger. There are 19 bones and 14 joints connected to the carpals, as shown in figure 2. Each finger is composed of one metacarpal and three phalanges, except for thumb which only has two phalanges. The first joint of each finger starts from the carpal bone is the metacarpophalangeal (MCP) joint which links the metacarpal bone to the proximal phalanx [10]. MCP joints are classified as ellipsoidal joints with two degrees of freedom which permit flexion, extension, abduction, and adduction movements. The proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints are found secondly and thirdly between the phalanges of each the four fingers from carpal bone; thumb only has one interphalangeal (IP) joint. The PIP and DIP joints are both bicondylar joints which provide one degree of freedom. Since IP joints only have one degree of freedom, we can assume it as a rotational joint with one single axis while we are designing the exoskeleton model.

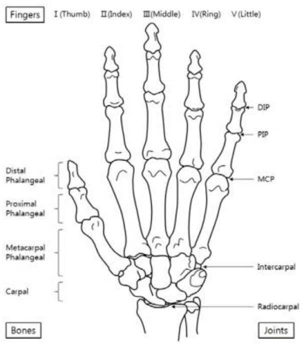

Figure 2. Bones and joints of human hand.

Many hand motions are subjected to several constraints which limit the range of the natural movements of human fingers [11]. However, the range of human finger motion can be indistinct because it is composed of many various factors, such as biomechanics of human hand and individual difference. Consequently, it is hard to express the movement range in the closed forms (i.e., equations). Additionally, how to model the constraints still requires further investigation. Nevertheless, it is obvious to understand that the dominate finger motions for grasping and releasing things are flexion and extension. These motions help human perform simply daily tasks such as holding, picking, and placing some light items. Therefore, trying to achieve the DOF for finger flexion and extension with non-complexity mechanical structure is the main goal we are focusing on in this paper.

III. Mechanical Design of the Exoskeleton and Integrated Sensors

As mentioned above, even though current exoskeleton rehabilitation devices do almost meet the needs of rehabilitation due to the complexity of hand structure, the exoskeleton system is huge and non-portable. Thus, the investigated exoskeleton rehabilitation device in this paper was designed to meet the following requirements:

- Bidirectional movements for finger's flexion and extension of each exoskeleton finger
- Motion decoupled for the MCP joint and PIP joint
- Safety design of the system through mechanical structure
- Light weight, low cost, and easy equipped for human hand

The developed system consists of four components: the mechanical structure, actuator unit, control unit, and sensor unit. The exoskeleton fingers are connected through cable wires to the actuating motors which are controlled by the control unit. The system will be used on human hand; therefore, safety factors must be taken into consideration.

A. Mechanical Construction

Figure 3 shows that the CAD model of exoskeleton finger and each segment is well-defined. It provides 1 DOF for each exoskeleton finger by the mechanical linkage system. The mechanical linkage system supports the independent flexion and extension of each exoskeleton finger in MCP and PIP joints. The PIP and DIP joints are coupled together through the linkage segments that result in certain relationship of angle range of motion for the PIP and DIP joints. In order to decouple the motion from MCP and PIP joints, an additional spring is implemented into the component that is located between the metacarpal and proximal phalanx. It becomes one of the constraints while the exoskeleton finger is actuated. This additional spring ensures the actuated sequence of two joint, starting with PIP joint and ending with MCP joint. Since the motion of MCP and PIP joint were decoupled, control of each exoskeleton finger is able to achieve by one motor.

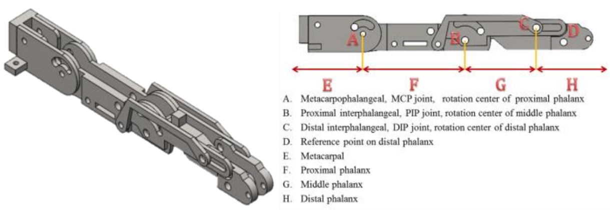

Figure 3. CAD model of exoskeleton finger and definitions of each segment

Safety can be observed in the mechanical linkage system of the exoskeleton finger. There is a circular slot in MCP and PIP joints. The slot's angle limits the range of motion for MCP and PIP joints which naturally become a safety for the exoskeleton finger. It can prevent the linkages from moving out of the demanding range of angle. This allowable range of angle motion is listed in table 1. The exoskeleton finger is equipped on the back of human hand. Velcro is used to fasten the hand exoskeleton and human hand together in proximal phalanx and middle phalanx of each finger and forearm module. Furthermore, the dimension of middle phalanx is variable which is to ensure that the human hand can be well-wrapped (shown in figure 4) by exoskeleton finger. Therefore, we put a sliding chute in the middle phalanx to adjust the length when PIP joint is actuated. The prototype made of ABS material instead metal is fabricated by a 3D printer which is weighted only 700 g including the mechanical structure and motors.

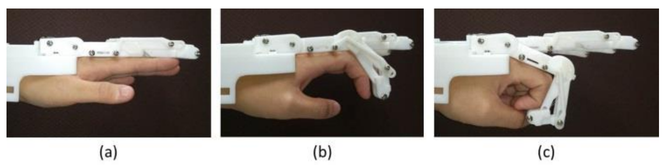

Figure 4. Side view of the exoskeleton motion when it is worn on human hand.: (a) Flat condition. (b) Flexion of PIP and DIP joints. (c) Flexion of MCP joint.

Table 1: Supported range of motion for finger joints. All angles are zero when the hand is flat. (Unit: degree)

Finger joint	Minimum angle	Maximum angle
MCP flexion/extension, θ_1	0	90
PIP flexion/extension, θ_2	0	80
DIP flexion/extension, θ_3	0	100

B. *Actuator Unit*

The device is designed to be portable; therefore, minimizing the number of motors is required since it is the heaviest component in the system. Thus, the actuator unit consists of only four RC servo motors. Each exoskeleton finger only require one RC servo motor to finish the motion of stretching and bending because the motion for the MCP joint and PIP joint are decoupled. Figure 5 shows the schematic connection between the motors and exoskeleton fingers. One end of cable wire is attached to the RC servo motor and the other at the middle phalanx of exoskeleton finger. The purpose of the cable guider is to adjust the entering and exiting angle of the cable from the motor to the exoskeleton. Motors are controlled by Arduino board (Arduino Mega 2560). By applying the PWM signal to motor, the motor can easily and precisely control the rotating angle. Thus, the angular position control of motor can indirectly control the exoskeleton finger through pulling and releasing the cable wire. The RC servo motors which are used in the system can provide maximum torque of 20kg-cm when the applied voltage is 6 volt.

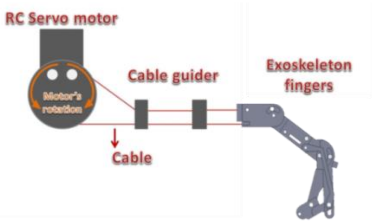

Figure 5. Schematic connection between the motors and exoskeleton fingers.

C. *Integrated Sensor Equipment*

For the sake of accurate position control of the exoskeleton fingers, flex sensor, variable resistor is required. The value of resistor varies with the different shapes of the finger. Due to the several advantages such as flexible, thin, and light, it is suitable to be attached on the human hand while the finger is in flexion and extension process. Therefore, the data from the flex sensor plays an important role to the monitor and confirms the motion of the exoskeleton finger. The value can also be used to calculate the joint angle of exoskeleton finger since the feature of motion decoupled for MCP and PIP joints are investigated. The flex sensor is embedded in the glove.

IV. ANALYSIS

A. *Parameter Definition*

As the design concept mentioned above, each developed exoskeleton finger provides one DOF for flexion and extension. It can be regard as a plane motion when doing the kinematic analysis of exoskeleton finger. Symbols and definition of parameters are shown in figure 6 before exoskeleton finger is actuated. There is a reference fixed origin point which is named point O on the edge of metacarpal; point A, B, and C are MCP, PIP, and DIP joints; point D is the other reference point on the distal phalanx. The initial position relationship between each point is known. Knowing the fundamental information of each joint, we can apply the homogenous transformation matrix to describe the relation between the selected and origin point. The relations are composed of translation and rotation matrixes, represented as ${}^{u}Trans_v(x, y)$ and $Rot_p(\theta)$. The working trajectory of exoskeleton finger can be examined from the relations.

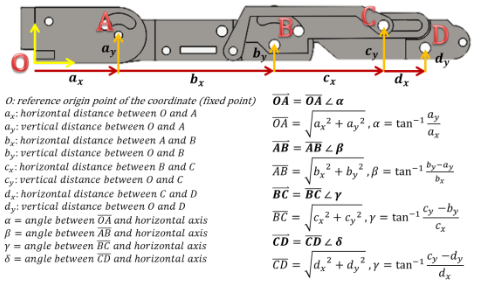

Figure 6. Symbols and definition of parameters on exoskeleton finger

B. *Kinematic Analysis*

As illustrated in figure 7, angles between the two phalanges are defined. θ_1, θ_2, and θ_3 represent the range of angle for MCP, PIP, and DIP joints respectively. The position relation equation when exoskeleton finger is actuated between the reference origin point O and the reference point D on the distal phalanx is shown as follow:

$$ {}^{O}\mathrm{D}(\mathrm{x}, \mathrm{y}) = {}^{D}\mathrm{Trans}_{O} \times \mathrm{O}(\mathrm{x}, \mathrm{y}) \qquad (1) $$

${}^{D}\mathrm{Trans}_{O}$ is the translation matrix from point O to point D. Since one of the design strategies for hand exoskeleton system is motion decoupled for the MCP and PIP joints, there is a typical actuated sequence for two joints: begin with PIP joints (θ_2), end up in MCP (θ_1) joint. As a consequence, the motion equation of θ_2 and θ_3 needs to be discussed first when deriving the numerical model of exoskeleton finger which has been established in this paper.

The relationship between θ_2 and θ_3 are derived by the linkage system structure as shown in Table 1, so point B is set as the reference point to observe the movement of point D while the PIP joint is actuated. Relations between θ_2 and θ_3 is shown as:

$$ \theta_3 = 1.2 \times \theta_2 \qquad (2) $$

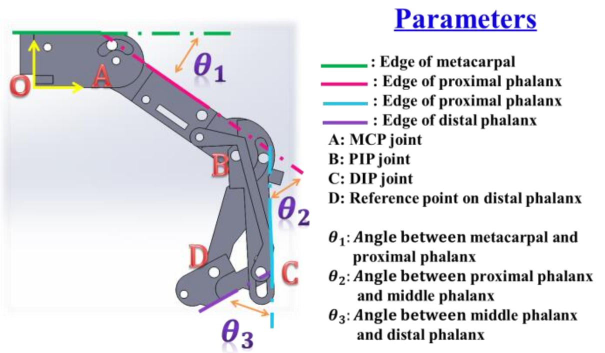

Figure 7. Definition of variables when exoskeleton is rotated.

When PIP joint starts to rotate, the equation for the position relationship of D respect to B can be written as:

$$^{B}D'(x,y) = {}^{B}C'(x,y) + Rot_{B}(\theta_2) \times {}^{C'}D'(x,y) \quad (3)$$

$Rot_B(\theta_2)$ is the rotation matrix that rotates through an angle θ_2 about the point B. The MCP joint rotates after θ_2 is fully actuated. All segments in front of MCP joint rotated through an angle about the point A when θ_1 increased. The equation of position relationship for D respect to A can be written as:

$$^{A}D'(x,y) = Rot_{A}(\theta_1) \times {}^{A}B(x,y) \times {}^{B}D'(x,y) \quad (4)$$

$^{B}D'(x,y)$ is shown in (3) above. In addition, OA segment represents metacarpal which is fixed on the back side of human hand, the existing relation between point O and point A is translation. Therefore, the equation for D respect to reference origin point O can be written as:

$$^{O}D'(x,y) = {}^{O}Trans_{A}(a_x, a_y) \times {}^{A}D'(x,y) \quad (5)$$

$^{A}D'(x,y)$ is shown in (4). As the numerical model of the exoskeleton finger has been constructed, we can perform simulations to examine the model that we have constructed. The angular scopes of the MCP, PIP and DIP joints are shown in table 1 when the exoskeleton is fixed on the hand. Knowing the lengths of each phalange and the angles of each joint mentioned above, we can correctly calculate the trajectory of point D on exoskeleton which are indicated in (5) by using Matlab program. Moreover, not only package simulation program such Solid Motion is used to simulate the trajectory motion but Matlab image process system is also used to perform as an experiment to capture the real motion of the exoskeleton finger. Both results are compared to the simulation of the numerical model in order to verify the model.

V. CONTROL SYSTEM

A. System Construction

The control system shown in figure 8 is divided in two parts: a real-time controller and the computer running interface for the instructor. The real-time controller, Arduino Mega2560, is running as the real-time operation system and acquires sensor data. All control loops and data acquisition are performed in this controller as well. The computer running interface for the instructor allows the setting of desire motion and displays the sensor data including the angle information from the motors and flex sensor. By recognizing the sensor data, the motion of exoskeleton finger can be easily derive since its trajectory has been correctly examined before. In addition, the control system is programmable while the instructor tried to achieve certain conditions.

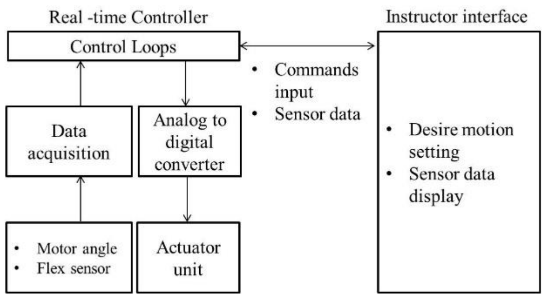

Figure 8. Diagram of the system The Real-Time controller samples the sensors data and controls the movement through the actuation unit of the hand exoskeleton worn by the patient.

B. Electrical Circuit Integration

For sensor reading, the concept of voltage divider is applied when the voltage form flex sensor varies with the different shapes of finger. It produces an output voltage (V_{out}) that is a fraction of its input voltage (V_{in}) which is varies between 2V and 3.5V. In order to improve the resolution of the flex sensor, we make electrical circuit interface to adjust and amplify the signal level. The integrated electrical circuit is shown in figure 9, and each flex sensor is connected to controller through this circuit. Differential amplifier and buffer amplifier circuits are used in the interface. Differential amplifier can adjust the lowest voltage level to 0V and amplify the variation range of sensor. The amplify gain can be calculated by using the equation as follow:

$$V_{out} = \frac{R_2}{R_1}(V_2 - V_1) \quad (5)$$

The purpose of using buffers is to prevent the second circuit from loading the first circuit unacceptably and interfering with its desired operation. Low pass filter also applied in this case. It has been added in two places of the electrical circuit. The cut-off frequencies for low pass filter are 15Hz and 1Hz. One is for flex sensor that the frequency is 15Hz; the other is for variable resistor which is to adjust the lowest voltage level to 0V for flex sensor.

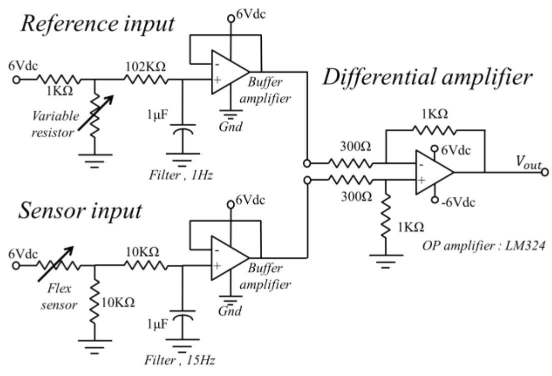

Figure 9. Integrated electrical circuit for flex sensor.

VI. RESULTS

A. Simulation Results

The angular scopes of the MCP, PIP, and DIP joints are shown in table 1. By knowing the lengths of each phalange and the angles of each joint mentioned above, we can correctly calculate the trajectory of point D. Figure 10 demonstrates the simulation result which was performed through Matlab program. First, the rotation of the PIP joints (θ_2) induced the DIP (θ_3) joint's rotation, and the relations was shown in (2). When PIP joint is completely actuated, the MCP (θ_1) joint continuously starts to move. That is the concept of motion decoupled for MCP and DIP joint. The blue line in the figure 10 is the trajectory of point D when MCP and PIP joints were fully rotated.

As illustrated in figure 11 and 12, the result of trajectory for point D is acquired by different methods. Package simulation program such as Solid Motion is used to simulate the motion trajectory of point D in figure 8; the results form Matlab image process system is in figure 9. The results are almost close to the same trajectory from using different methods, including numerical method, simulation method and experiment method. Therefore, it is indicated that not only the design purposes of exoskeleton finger is completed but also the numerical model we have derived is correct.

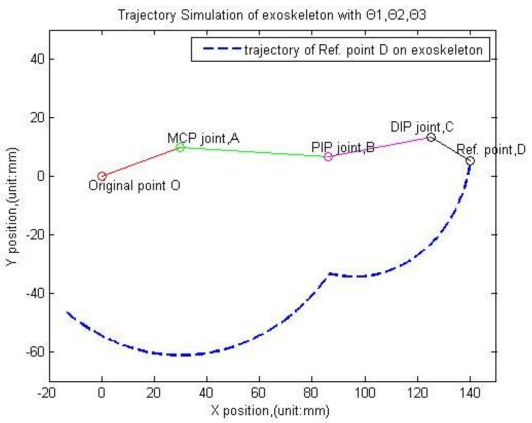

Figure 10. Numerical simulation result of trajectory for exoskeleton finger.

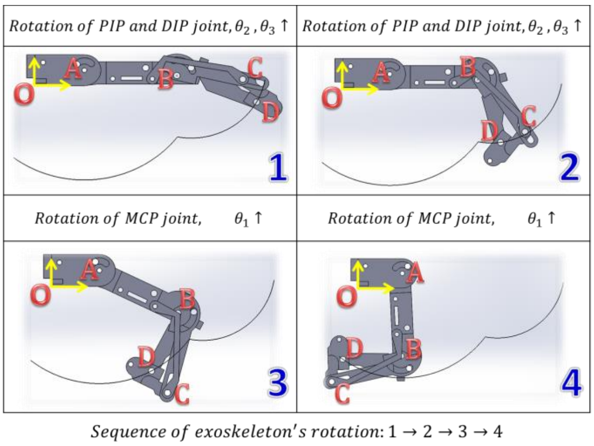

Figure 11. Trajectory simulation result performed by program Solid motion.

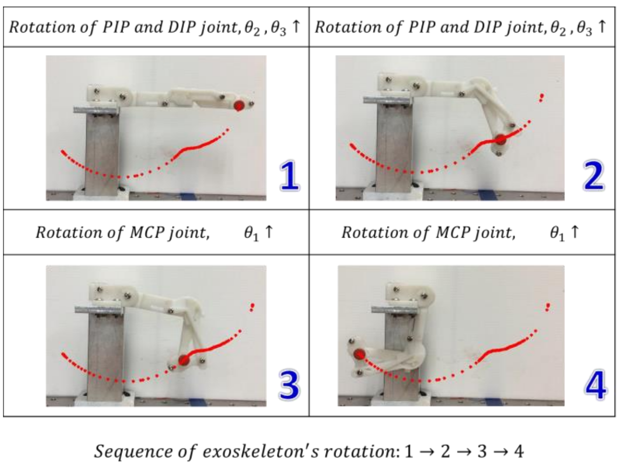

Figure 12 Trajectory result performed by Matlab image process system.

B. Experimental Results

The snapshots in table 2 show how the exoskeleton fingers are controlled. The glove which is embedded with flex sensors is worn by the instructor. When instructor's hand moves, the hand exoskeleton system follows the motion of the glove in the right side of the snapshots by sensing the voltage signal change from flex sensor. Both exoskeleton hand and instructor's hand are flat at starting position. The sequence of fingers starts with index finger, middle finger, ring finger, and finally small finger.

Signal change also was recorded and illustrated in figure 13. Huge jump of signal on each line represent the flexion and extension motion of each finger. When finger was performing the flexion motion, resistance in flex sensor increased so rapidly that caused the voltage signal to decrease. However, it is interesting to observe that when one finger is moving, the other three fingers will be affected a slightly. This phenomenon is the natural constraints of human hands. Each finger is interconnected by muscles, so that the motions of human hands for each finger cannot be completely separated. This feature of human hand inevitably results in the misdetection of the finger motion for controller. In order to avoid it, setting up the threshold for controller to differentiate the motion is necessary. Once added the program mentioned above into control system, the exoskeleton hand performed as fluent as a human hand and decreased the possibility of the misdetection.

Table 2: Snapshot of individual motion for each finger that is controlled by the glove worn on the instructor's hand. The sequence of finger motion starts from the 1 to 6.

1. Rest Condition	2. Motion of Index Finger
	
3. Motion of Middle Finger	4. Motion of Ring Finger
	
5. Motion of Small Finger	6. Rest Condition
	

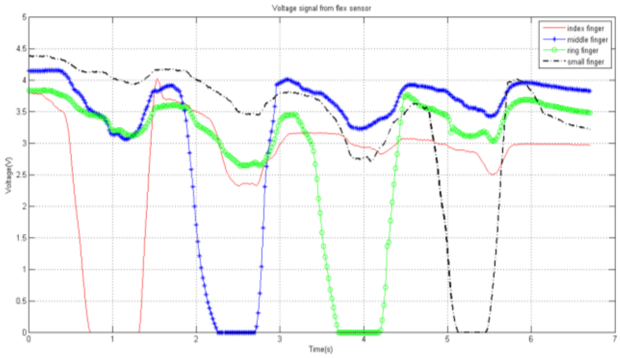

Figure 13. Variation of voltage signal form the flex sensor when exoskeleton hand performed as the Table 2

VII. CONCLUSIONS AND FUTURE WORKS

The presented work is a basis for future studies on the field of hand exoskeleton system. The prototype hand exoskeleton system in this paper was proposed to provide a more portable rehabilitation device than the existing works. Thus, prototype made of ABS material instead of metal weighted only 700 g including the mechanical structure and motors. Range of motion for the exoskeleton finger is investigated. The trajectory of exoskeleton is well clarified by simulations and experiments. Furthermore, the control system integrated with flex sensors was constructed in the paper. The integrated system allows instructors to successfully operate the exoskeleton for rehabilitation during the operation process. Subsequently, improving the mechanical structure is another field we have to investigate. Hand adduction and abduction motion will be added into exoskeleton system. Also, we are proposing to develop a measurement system integrated with exoskeleton hand which can diagnose the injury level of the user's hand automatically. This makes the progress of evaluation during rehabilitation becomes possible in the near future.

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