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Development of Hand Rehabilitation System for Paralysis Patient – Universal Design Using Wire-Driven Mechanism –

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***Abstract*— We have developed a hand rehabilitation system for patients suffering from paralysis or contracture. It consists of two components: a hand rehabilitation machine, which moves human finger joints with motors, and a data glove, which provides control of the movement of finger joints attached to the rehabilitation machine. The machine is based on the arm structure type of hand rehabilitation machine; a motor indirectly moves a finger joint via a closed four-link mechanism. We employ a wire-driven mechanism and develop a compact design that can control all three joints (i.e., PIP, DIP and MP) of a finger and that offers a wider range of joint motion than conventional systems. Furthermore, we demonstrate the hand rehabilitation process, finger joints of the left hand attached to the machine are controlled by the finger joints of the right hand wearing the data glove.**

I. INTRODUCTION

Recently, advanced technology has contributed to significantly developments in the medical field. Physical rehabilitation, which requires long-term recurrent movement, is expected to be performed by machines instead of humans. For example, hand rehabilitation is an important issue because hand movement is one of the most basic actions in daily life. Generally, hand paralysis or contracture is treated with the assistance of a physical therapist. The therapist holds and repeatedly moves the fingers affected by paralysis or contracture through the maximum range of its joint angle, as shown in Fig.1. It takes a few months to improve the range through which the finger can move. Thus, in general, hand rehabilitation is expensive and time consuming. Furthermore, the unavailability of physical therapists underscores the requirement for engineering solutions for physical rehabilitation. Therefore, we aim to develop a hand rehabilitation machine that can act as a substitute for physical therapists.

Conventional hand rehabilitation machines are mechanically categorized on the basis of their structures as follows: the joint structure, arch structure, and arm structure, as shown in Fig.2. The joint structure is characterized by actuators set along the fingers. It has high controllability because the actuators directly move the paralyzed finger joint. However, the joint structure placed on the sides of the finger and it is available for only the 1st, 2nd, and 5th fingers; that is, it is impossible to place this machine between fingers. Sankai et al. developed a power-assist glove based on the joint structure[1]. It uses motors and wire-driven mechanisms as drive sources; it is light weight and has high drive. Then, for the rehabilitation of the 3rd and 4th fingers, which could not be attached to the machine the 3rd,4th, and 5th fingers are coupled. The arch structure is characterized by an arc slider placed on the finger joint; the finger is moved by actuating the slider. Because the slider is placed on the finger, the machine can be used on all fingers (i.e., the arch structure resolves the problem of the joint structure). Wang et al. developed a hand rehabilitation machine with the arch structure and were able to successfully control 4 joints of a single finger[2]. Abovementioned examples show that machines can possibly substitute for physical therapists because they can suitably control finger movement.

A disadvantage of both the joint and the arch structures is the difficulty involved in attaching them to fingers. That is, these structures are required to match the rotational centers of their joints to that of the finger joint. Moreover, each finger has a different length; hence, the structure of the machine must be suitably modified for each user and finger. One of the solutions to this problem involving the arm structure was proposed by Wang et al.[3]. They developed an arm structure that consists of a closed four-link mechanism: 4 links (i.e., 2 metal links and 2 human finger links) and 4 joints (1 actuated joint, 2 free joints, and 1 human finger joint). The finger joint is not directly controlled by the actuated joint. The geometry of the links indirectly controls the finger. In the closed four-link mechanism, the distance between Base1 and Base2, shown in Fig.2(c), is adjustable because of the free joints. Thus, this structure can be adjusted to suit any user without any design modification, thus enhancing its practical usability. However, the closed four-link mechanism has two structural problems: (1)There are two possible configurations of the finger joint for an angle of the actuated joint. Thus it becomes necessary to avoid some range of angles of actuated joint; i.e., this mechanism limits the range of joint motion and (2) its mechanism overloads the finger joint when the finger joint bends more than 90 [°] This is because the free joints cannot generate rotational torques; and instead, they apply shear forces to the finger joint. This too limits the range of the joint angle. In this study, we develop a new hand rehabilitation machine that is based on the arm structure. We aim to improve the range of joint motion by employing a wire-driven mechanism. Further, we propose a hand rehabilitation system in which fingers affected by paralysis can be moved with the proposed hand rehabilitation machine, and the finger joints are controlled by a data glove worn on the healthy hand.

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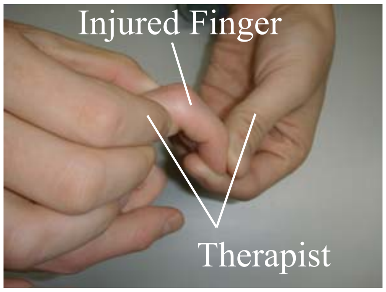
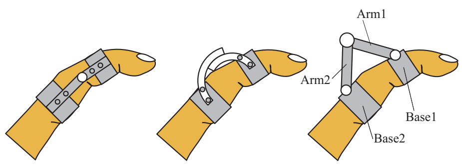


Fig. 1. Rehabilitation of Injured Finger.



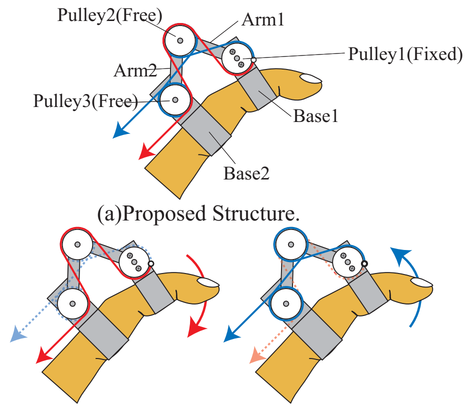
(a) Joint Stracture. (b) Arch Stracture. (c) Arm Stracture.

Fig. 2. Mechanism of Hand Exoskeleton.

II. Proposed Design

The arm structure type of hand rehabilitation machine has a closed four-link mechanism, and it can be attached to fingers of any length. To the best of our knowledge this is the most convenient hand rehabilitation machine at present. Thus, we focus on the arm structure and endeavor to improve its performance. Specifically, we aim to increase the range of joint motion and improve the control of finger movement. In order to achieve this, we propose a design that combines the closed four-link mechanism with the wire-driven mechanism. Our basic design is based on the arm structure, shown in Fig.2(c), which has three joints – a motor joint and two free joints – in the closed four-link mechanism. We substitute the motor joint with a free joint and attach three pulleys to the three free joints. The pulleys are connected by means of two wires, as shown in Fig.3(a); the red line represents a flexion wire, and the blue line represents an extension wire. One end of each wire is attached to the pulley on Base1, and the other end is attached to a motor. Fig.4 shows the conceptual diagram of the rehabilitation machine; it bends a finger when the flexion wire is pulled (Fig.3(b)) and extends the finger when the extension wire is pulled (Fig.3(c)).The wire-driven mechanism allows to spatially separate the drive from the actuator. In this mechanism the motor is not placed on the fingers thus reducing the weight of the machine on the finger. Further, since the space occupied by the motor on the finger is now freed, we are able to add three arm structures on a finger; thus affording multiple degrees of freedom (DOF). As a result of these two advantages, it is possible to use a higher drive motor, which is heavier. Therefore, our proposed design offers advantages of lighter weight, higher drive, and higher degree of freedom.

The combination of the wire-driven mechanism and closed four-link mechanism overcomes the limitations of the arm structure. In the original arm structure design, the motor cannot rotate when the three joints are in a straight line. However, in the proposed design, all three joints are coupled and actuated with one motor at the reduction rate 1. Therefore, even when the joints are in a straight line, The motor continues to rotate easily. In other words, the proposal design yields a wider range of joint motion than the original arm structure. To summarize, the proposed hand rehabilitation machine has been designed to be practically applicable. (1) Its light weight will enable patients to use it for long period. (2) It offers multiple DOF and high drive, which enhance the control of fingers and can therefore be used for a variety of rehabilitation plans.



(a)Proposed Structure.

(b)Flexion. (c)Extension.

Fig. 3. Proposed Design.

Fig. 4. Flexion and Extension Actuated by Single Motor.

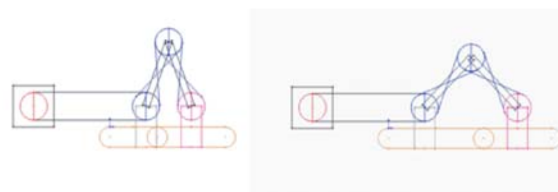


Fig. 5. Adjustment of Apparatus to Various Hand Sizes.

III. Mathmatical Model

In order to analyze the range of joint angles achievable using our proposed design, we construct a mathematical model of the proposed machine as shown Fig.6. It consists of 3 pulleys, 2 links, and 2 wires. A wire runs from Pulley1 to Pulley3. Point A on Pulley1 indicates the starting point of the wire and point B on Pulley3 indicates its end point. The length l_{AB} of the wire between the two pulleys is given by Equation (1).

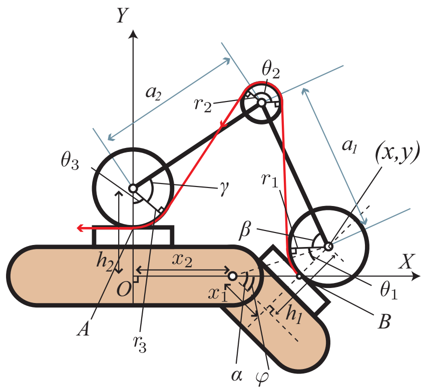


Fig. 6. Adjustment of Apparatus to Various Hand Sizes.

$$l_{AB} = r_1\theta_1 + r_2\theta_2 + r_3\theta_3 + \sqrt{a_1{}^2 - (r_1+r_2)^2} + \sqrt{a_2{}^2 - (r_2+r_3)^2} \quad (1)$$

The point (x, y) is expressed as shown in Equation (2) and (3).

$$\begin{aligned} x &= x_2 + L\cos(\alpha - \varphi) \\ &= a_2\sin(\theta_3 + \gamma) - a_1\sin(\theta_2 - \theta_3 + \beta) \quad (2) \\ y &= L\sin(\alpha - \varphi) \\ &= h_2 - a_2\cos(\theta_3 + \gamma) + a_1\cos(\theta_2 - \theta_3 + \beta) \quad (3) \end{aligned}$$

L,α,β and γ are presented as follows:

$$L = \sqrt{x_1{}^2 + h_1{}^2}, \alpha = \arctan\frac{h_1}{x_1}$$

$$\beta = \arccos\frac{r_1 + r_2}{a_1}, \gamma = \arccos\frac{r_2 + r_3}{a_2}$$

Then, the geometrical relation yields the following equation.

$$\varphi = \pi - \theta_1 + \theta_2 - \theta_3 \quad (4)$$

The relation between l_{AB} and φ is obtained by removing θ_1, θ_2, and θ_3,in Equations (1)-(4). That is, the result indicates that the traction distance of the wire controls the human finger joint.

IV. Actual Hand Rehabilitation Machine

Fig.7 and Fig.8 show a CAD image and a photograph, respectively, of the proposed rehabilitation machine. The machine is designed such that there are three arm structures for the MP, PIP, and DIP joints. The wire used is made of polyethylene, and it is connected to a motor through a metal spring tube. The motor is an RC Servo (GWS Micro2BBMG,torque 5.4[kg/cm], 28[g], $28 \times 30 \times 14$[mm^3]). The weight of the arm structure is 160[g]. It has three arm structures, and two of the three structures – for the PIP and DIP joints – are coupled. The mechanism of the arm structure is similar to the mechanism of relationship between human

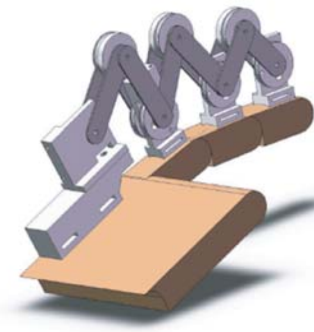


Fig. 7. CAD Image of Exoskeleton of Proposed Machine for One Finger.

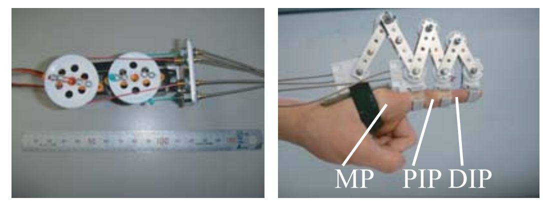


Fig. 8. Proto-type of the Exoskeleton for One Finger.

PIP and DIP joints. Consequently, this machine uses two RC servos to move three finger joints. Velcro tape is used to attach the arm structure to the fingers, because it is easy to attach and remove.

V. Demonstration: Hand Rehabilitation Machine

Fig.8 shows the hand rehabilitation machine attached to a hand. The machine is shown as being suitably attached to the 2nd finger (finger length: 69[mm]) in Fig.9(a)-1 and to the 5th finger (finger length: 58[mm]) in Fig.9(b)-1; it then moves these fingers. The time needed to adjust the arm structure to the finger length is within 1 min. Fig.9(a)-2 and Fig.9(b)-2 show that the machine could successfully bend the finger joints; the ranges are listed in Table 1. In both cases, the machine smoothly bent the DIP joints. Moreover, since three pulleys on one arm structure rotate simultaneously with the wire-driven mechanism, the user feels less load on the finger. Furthermore, the combined design of the closed four-link mechanism and the wire-driven mechanism results in a one-to-one positional relationship between the motor joint and the human finger joint, which offers better controllability than that provided by the original arm structure.

VI. Demonstration: Hand Rehabilitation System

Generally, hand paralysis does not affect both hands. Therefore, some hand rehabilitation systems involve the use of the unaffected healthy hand; This is known "self-motion control." For example, Kawasaki developed a hand rehabilitation system that acquires joint angle information from the healthy hand and thus controls the paralyzed hand with a machine corresponding to the joint information[4].

In this study, we apply the same concept to our hand rehabilitation system (Fig.10).The hand rehabilitation process

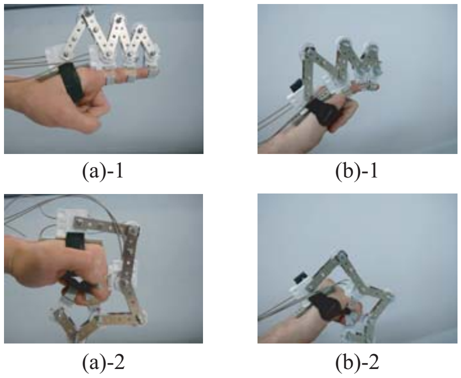


Fig. 9. Operation of the Little/Index Finger.

TABLE I
SUPPORTED RANGE OF MOTION FOR THE LITTLE/INDEX FINGER JOINTS.

	Little finger		Index finger	
	Extension	Flexion	Extension	Flexion
MP[°]	0	75	0	70
PIP[°]	0	80	0	80
DIP[°]	0	55	0	60

proceeds as follows. (1)The patient wears a data glove on the healthy hand, (2)The rehabilitation machine is attached to the target finger of the affected hand. (3)The machine is calibrated for the maximum flexion and extension of the finger in Fig.11. (4)The target finger joints are controlled by the finger joints on the data glove(i.e., mirror motion). In this manner hand rehabilitation is carried out without the help of a physical therapist. In addition , this system has a motion play back function by which carried out by the controller can be recorded and played back by a user. This function is useful for long-term rehabilitation.

VII. Conclusions

We have developed a hand rehabilitation system for patients affected by or contracture. It consist of two components: a hand rehabilitation machine, which moves human joints using motors, and a data glove, which provides control of the finger joints attached to the rehabilitation machine. The machine is based on the arm structure type of rehabilitation machine; a motor indirectly moves a finger joint via a closed four-link mechanism. We employ a wire-driven mechanism and develop a compact design that can control all three joints (i.e., PIP, DIP, and MP joints) of a finger; the design offers a wider range of joint motion than conventional systems. Furthermore, we have demonstrated the hand rehabilitation process, in which the finger joints of the left hand attached to the machine are controlled by the finger joints of the right hand wearing the data glove.

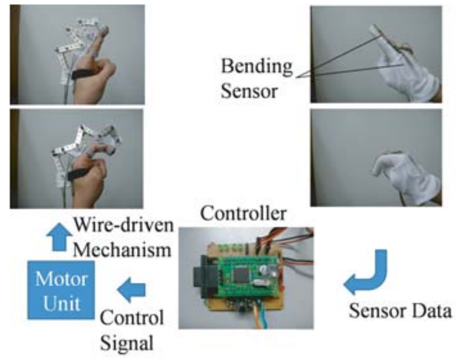


Fig. 10. Control System of the Rehabilitation for Hemiplegic Subjects.

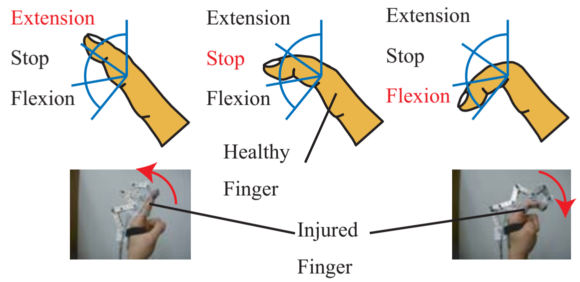


Fig. 11. Determination of the Range of Motion.

VIII. Future Works

In future, we intend to resolve the following issues in order to improve the practical application of our proposed system. (1)We must improve the movement range of the machine because the certificated hand rehabilitation machine is required to move human fingers at the following angles: 85[°] at the MP joint, 110[°] at the PIP joint, and 65[°] at the DIP joint [5]. (2)We must develop the rehabilitation machine for use with five fingers and investigate its performance by testing it on actual patients.

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