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Multiple Rehabilitation Motion Control for Hand with an Exoskeleton

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Abstract—**This paper investigates the control algorithm of an exoskeleton for hand rehabilitation, which can realize the active, passive, and assisted rehabilitation motion. The active mode is accomplished with the force control algorithm during which the resistance is compensated in free space and the virtual interactive force is rendered to the finger in constraint space. The passive mode is realized by the position controller given the desired motion trajectory. The assisted mode is implemented in the customized positions by switching between the active and passive modes according to the predefined action procedure. The experiments are conducted to verify the proposed method, and the results show that the different rehabilitation motion are successfully accomplished and the maximum joint position error is less than 1.2 degree, which satisfies the requirement in hand rehabilitation application. The results demonstrate the validity of the proposed method.**

I. INTRODUCTION

As we know, the normal motor capability of hand is crucial and important for human-being's daily life. However, accident and diseases, stoke for instance, are apt to lead to loss of sensation and motor functions of hand. In order to recover the motor capability, the hand rehabilitation is a fundamental therapeutic approach. But the traditional rehabilitation approach is a time-and-resource-consuming process.

Recent research showed that the method of using mechatronic devices and virtual reality in rehabilitation training is feasible and effective [1]-[2] and is attracting much research interests [3]-[7]. Focused on the different mechanical structure and rehabilitation modes, some control algorithms are investigated [8]-[13]. However, simultaneous realization of the multiple rehabilitation modes in one rehabilitation device has not yet been investigated adequately.

The active, passive, and assisted rehabilitation motions are some fundamental rehabilitation modes and are used when rehabilitation proceeds on different stages, which propose the different requirements to the control algorithm. In addition, the different device scheme may propose different requirements to the controller as well. For example, for some existing exoskeleton-type hand rehabilitation devices, the Bowden cable transmission is utilized to satisfy the need of remote and changeable distance transmission and to reduce the weight exerted on the patient hand. Although there reaches a consensus that the friction between the cable and sheath accounts for the great part of the mechanical resistance, the problem to compensate the friction is still open and unresolved.

Aimed at the hand rehabilitation, our research group developed a wearable exoskeleton for index finger rehabilitation. In this paper we propose a control method which can realize the aforementioned three types of rehabilitation motion. The active motion is accomplished with the force control algorithm during which the resistance is compensated in free space and the virtual interactive force is fed back to the finger in constraint space. The passive motion is realized by the position controller given the desired motion trajectory. The assisted rehabilitation motion is implemented in the customized positions by switching between the active and passive motions according to the predefined action procedure. With the proposed approach, the exoskeleton possesses favorable backdrivability, and the measured maximum joint position error is less than 1.2 degree.

The remainder of the paper is organized as follows. Section II introduces the system architecture. Section III presents control algorithm for the different rehabilitation modes. Section IV depicts experiment and the results. Section V gives conclusion and discusses the future work.

II. SYSTEM DESCRIPTION

The hand rehabilitation system is comprised of the hand exoskeleton integrated with angle and force sensors, the control (including controller and driver), and the virtual environment. The system architecture is shown as Fig.1.

The exoskeleton device for index finger rehabilitation has 4 degrees of freedom and consists of three parts: the actuation module, the Bowden cable transmission and the exoskeleton, as shown in Fig 2.

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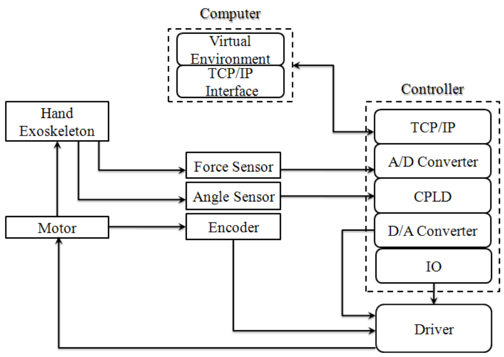

Fig.1. The system architecture

The exoskeleton is actuated by four actuators and is worn on the dorsal side of the hand. Based on the human hand anatomical structure, the exoskeleton is comprised of three parts which are attached to the phalanges – distal, middle and proximal phalanges, respectively. For each finger joint, two cables, each of which is housed in a sheath, are used to transmit force and motion from the actuator to the exoskeleton.

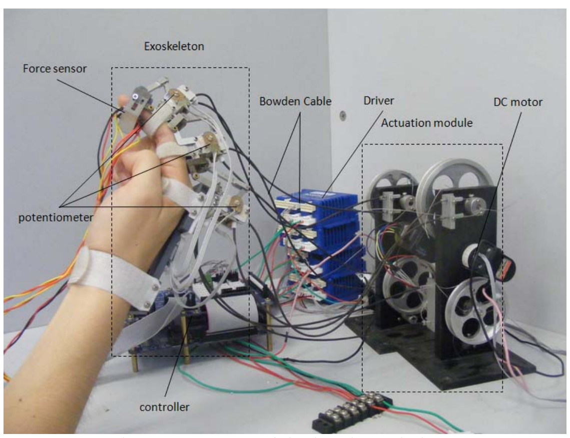

Fig. 2. Prototype of the hand exoskeleton

On each joint shaft of the exoskeleton, a potentiometer (SV01A103 MURATA manufacturiong Co., Ltd, Japan) is integrated to measure the rotational angle of the finger joint. Three force sensors (Honeywell_FSS, USA as shown in Fig 3) are installed on the bottom of the distal module of the exoskeleton to measure the fingertip force exerted by the human fingertips. The forces on three contact points are summed to obtain the resultant force which is exerted by the finger [14].

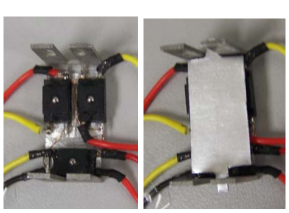
(a) (b)

Fig.3. (a) Layout of three force sensors (b) covered by a metal plate

The real-time controller (shown in Fig.2) is developed by our research group. It could sample the angle data and the force data in real time. The controller links to the host computer by the TCP/IP, and the sampling frequency is 1000Hz.

The motors are driven by the driver (Accelnet, Copley Inc, USA). The driver is connected to the controller through analog output channels. It could run under the torque mode, velocity mode or position mode.

The host computer runs the virtual environment. The GUI allows the therapist to choose the rehabilitation motion mode, and set the rehabilitation training parameters, such as range of motion, joint assistive angle, training time, training speed and so on.

III. CONTROL ALGORITHM

The active, passive, and assisted rehabilitation motions are some fundamental rehabilitation modes and are used when rehabilitation proceeds to different stages. And the control requiements is different. In general, a position control suitable for the passive mode to enable imposition of specific trajectories. A force control is needed in the active control mode to provide feedback force to the patient. The assisted mode integrates the active mode and the passive mode. The detailed control algorithm is described in the following subsections.

A. Active mode

During the active rehabilitation training, the virtual hand works in two different states: in constraint space and in free space. When it is in constraint space, the virtual contact force is fed back to the human finger. Otherwise the human finger is supposed to move without resistance of the device. Therefore, the mechanical resistance is demanded to be compensated in free space. For the continuous motion of abduction/adduction, the resistance of our device is not obvious. We only focus on the resistance compensation for the flexion and extension in the subsequent part.

In constraint space we use the impedance control algorithm [15] which has been widely applied, and the detail will not be described in this paper. The block diagram of control structure is shown in Fig. 4.

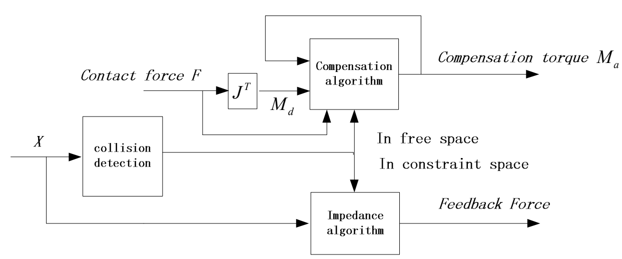

Fig.4. The block diagram of control structure

As aforementioned, in free space the exoskeleton is supposed to follow the motion of the finger and be compliant with the finger's motion. However, the friction between the cable and sheath, as well as the moment of inertia of the system, cause great resistance to the finger flexion/extension. Thus we propose a method to compensate the resistance. But the resistance due to the friction is difficult to be determined. To solve this problem, we propose to compensate total resistance caused by the friction as well as the moment of inertia altogether.

For the continuous motion of flexion and extension of the finger, the direction of resistant torque is opposite, and so is the compensation torque supposed to. Therefore the motion (flexion or extension) must be identified. Because the force sensors are assembled on the side of the finger pad, the contact force only exists during the flexion theoretically. So we can use the contact force information to identify the flexion from the extension. Considering that the tiny and involuntary shake of the finger may happen and the generated contact force may provide false information for identification of motion, we use a threshold force F_1 to avoid the misjudgment. If the measured contact force F is greater than F_1, the finger is considered in the motion of flexion. Otherwise, it is in the extension. F_1 is determined by experiment.

1) Compensation during the flexion

Taking one joint for example, the actuator module, the cable/sheath transmission and the exoskeleton module are simplified as follows (Fig 5).

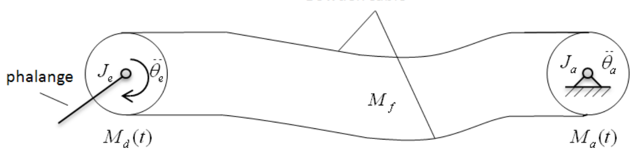

Fig.5. The simplified model for one finger joint

According to the equilibrium equation of the moment at a certain instant *t*, we have:

$$M_d(t) + M_a(t) = J_e \cdot \ddot{\theta}_e(t) + J_a \cdot \ddot{\theta}_a(t) + M_f(t) \qquad (1)$$

where $M_d(t)$ is the driving torque which is produced by the fingertip-exerted force;

$M_a(t)$ is the output torque of the actuator module which is used to compensate the system resistance;

$M_f(t)$ is the resistance torque due to the friction between the cables and the sheaths;

J_e and J_a are the moment of inertia of the exoskeleton module and of the actuator module, respectively;

$\ddot{\theta}_e(t)$ and $\ddot{\theta}_a(t)$ are the angular acceleration of the exoskeleton module and the actuator module, respectively.

If we want to compensate the mechanical transmission caused by the friction and the moment of inertia, the actuator module output $M_a(t)$ should be:

$$M_a(t) = J_e \cdot \ddot{\theta}_e(t) + J_a \cdot \ddot{\theta}_a(t) + M_f(t) \qquad (2)$$

Because $M_f(t)$ at instant t is unknown, we estimate $M_a(t)$ with the value at instant t-1. Considering that the time interval is small so the estimation is reasonable.

Basing on (1) we have：

$$J_e \cdot \ddot{\theta}_e(t-1) + J_a \cdot \ddot{\theta}_a(t-1) + M_f(t-1) = M_d(t-1) + M_a(t-1) \qquad (3)$$

Substituting (3) in (2), we have:

$$M_a(t) = M_d(t-1) + M_a(t-1) \qquad (4)$$

The active rehabilitative motion requires that it is the human hand that drives the exoskeleton. However, if the estimated $M_a(t)$ is greater than the actual resistance, the exoskeleton is then driven by the actuator, and the active rehabilitative motion is changed to passive rehabilitative motion which is not desired. On the other hand, the human fingertip will not contact with the sensors which means the contact force cannot be measured. To avoid the undesired problem we modify (4) as follows.

$$M_a(t) = \xi \cdot [M_d(t-1) + M_a(t-1)], (\xi \le 1.0) \qquad (5)$$

where the driving torque $M_d(t-1)$ could be calculated from the contact force measured by the force sensors. The coefficient ξ is determined by experiment.

2) Compensation during the extension

In this case there is no available contact force, so we use a constant torque to compensate the resistance.

$$M_a(t) = -M \qquad (6)$$

The constant torque M is determined by experiments which just overcomes the static resistance. The negative symbol means the direction is opposite to that during the flexion.

3) Compensation in the transition state

Besides flexion and extension, the case when the finger stops moving should be considered as well since compensation is not needed. Additionally, over-compensation may possibly happen with the aforementioned method which may cause the vibration of the motor. So only with the aforementioned compensation is inadequate. We define the third state (we call transition state) to improve the method. In the transition state, the compensation torque is set to be zero.

$$M_a(t) = 0 \qquad (7)$$

As shown in Fig.6, another threshold F_2, together with F_1, is used to define the range of transition state, which is also determined by the experiment.

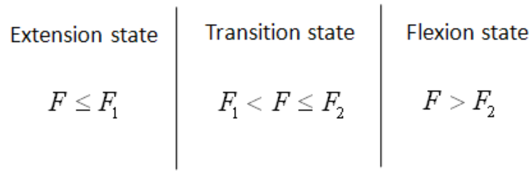

Fig.6. flexion, extension and the transition states

Summarily, the compensation control algorithm can be written as follows:

$$M_a(t) = \begin{cases} -M & (F \le F_1) \\ 0 & (F_1 < F \le F_2) \\ \xi \cdot [M_d(t-1) + M_a(t-1)] & (F > F_2) \end{cases} \quad (8)$$

B. Passive mode

In the passive motion mode, the human finger is driven by the hand exoskeleton. Thus, the task of control is to control the device to the desired positions. Considering the system security and stability, the PID controller is adopted independently for each controlled joint. To keep the precision in the position control, the potentiometer is used for measuring the angle of the finger joint at the exoskeleton as a position feedback in the closed loop. Thus, we have the relationship as following:

$$\Delta\theta = \theta_e - \theta_d \quad (9)$$

$$U = K_p \cdot \Delta\theta + K_I \cdot \int \Delta\theta \cdot dt + K_d \cdot \frac{d\Delta\theta}{dt} \quad (10)$$

where

θ_d is the desired angle of joint.

θ_e is the actual angle read from the potentiometer.

$\Delta\theta$ is the difference between θ_e and θ_d.

U is the input of the driver.

K_p is the proportional coefficient

K_I is the integral coefficient.

K_d is the differential coefficient

The driver is executed in the velocity mode which could control the speed of the motor directly. In the interior of the driver, the relationship between the input voltage and the speed of the motor could be pre-set as follow:

$$\dot{\theta}_{motor} = K \cdot U \quad (11)$$

where

$\dot{\theta}_{motor}$ is the speed of the motor.

K is the speed parameter set in the driver and it is a constant.

Then, if the transmission ratio of the actuator is n, we have the relationship about the speed of the actuator:

$$\dot{\theta}_e = \frac{\dot{\theta}_{motor}}{n} = \frac{K \cdot U}{n} \quad (12)$$

Substituting (10) into (12), we have:

$$\dot{\theta}_e = \frac{K}{n} \cdot (K_p \cdot \Delta\theta + K_I \cdot \int \Delta\theta \cdot dt + K_d \cdot \frac{d\Delta\theta}{dt}) \quad (13)$$

The block diagram of passive control mode is shown in Fig. 7.

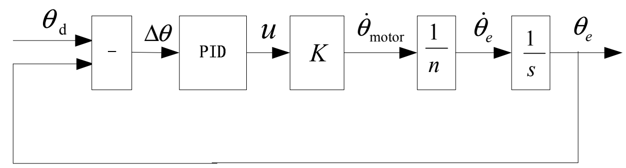

Fig.7. The block diagram of passive control mode

C. Assisted mode

The assisted mode is used when finger has some residual motion capability but has not yet reached the normal level. In clinical therapy there may be various approaches to carry on the assisted rehabilitation motion, so here we propose the following assisted motion procedure just for interpretation of our control method. With the assisted mode, the assisted parameters, here assisted angle and assisted time, are set. At the beginning the finger moves actively during which the controller runs on the active mode. Whenever the assisted motion is wanted, the controller is switched by an interactive trigger button to the passive mode, and the finger is then driven by the exoskeleton and move between the beginning position and the desired position. The assisted procedure ends when the interactive switch is triggered again or the assisted time is reached. The finger moves actively again and the previously described process repeats. The assist procedure can be customized and conducted at any position. Apparently the implementation of the assisted motion is essentially the control switching between the active mode and the passive mode.

The block diagram is shown in Fig8.

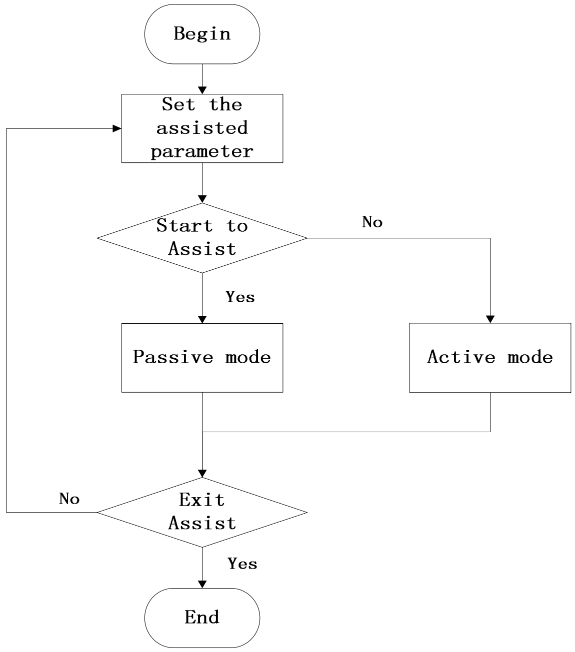

Fig.8. The assisted control algorithm

IV. Control Algorithm Experiment and Results

A. Experiment on active control mode

In the experiment, the human hand wore the exoskeleton and index finger made the motion of flexion and extension continuously for three times with and without resistance compensation, respectively. In two conditions, the relative position of the exoskeleton module and the actuator module was approximately kept unchanged to let the experiments carried out on the same conditions. The contact forces exerted by human finger during the flexion in the two conditions were measured, respectively, as shown in Fig.9. The coefficients for three finger joints were $\xi_{MCP} = 1.0$, $\xi_{PIP} = 0.9$, $\xi_{DIP} = 0.75$, and $F_1 = 400$mN, $F_2 = 500$mN. The constant compensation torques for the three finger joints were M_{MCP} =42mNm, M_{PIP} =24mNm, M_{DIP} =21mNm.

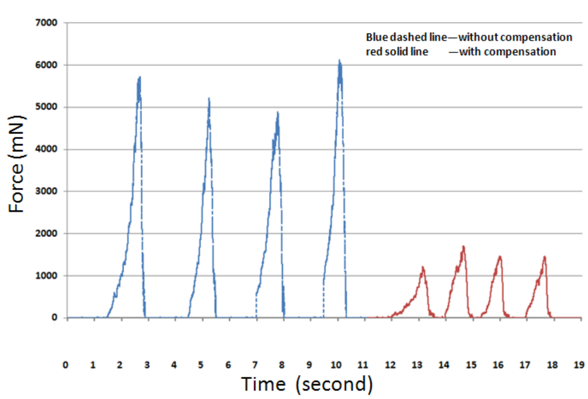

Fig.9. The measured forces exerted by the human fingertip

With the compensation control algorithm, the maximum output force of the human fingertip was less than two fifths of the maximum force without compensation during the motion of flexion. During the motion of extension, the fingertip force could not be measured, but the subject felt that it is much easier to rotate the finger with the compensation control.

B. Experiment on passive control mode

The target is to control the exoskeleton joint to rotate along a predefined trajectory, here a sinusoidal path with the amplitude of 80 degrees, and the period of 12 seconds. The actual joint angles are measured by the potentiometer. All the joints were controlled with the same method, so we only take the DIP joint for example. The control parameters are K_P =0.5V/degree, K_I = 0.0625 V/degree, K_D = 0.007 V/degree/s, K =275rpm/V, The desired and actual trajectories and the error are shown in Fig. 10 and Fig. 11, respectively. The average error is about ± 0.225 degree and the maximum error is within 1.2 degree.

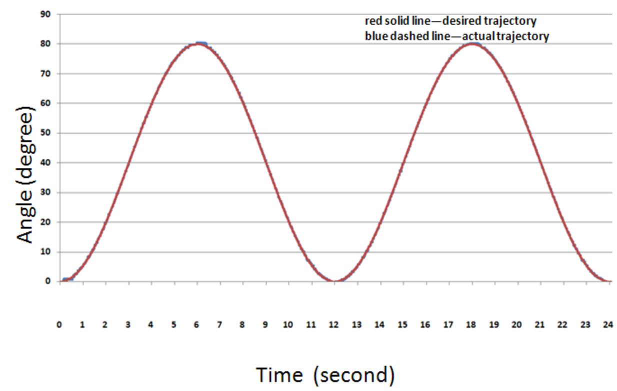

Fig.10. The desired and actual trajectories of DIP finger joint

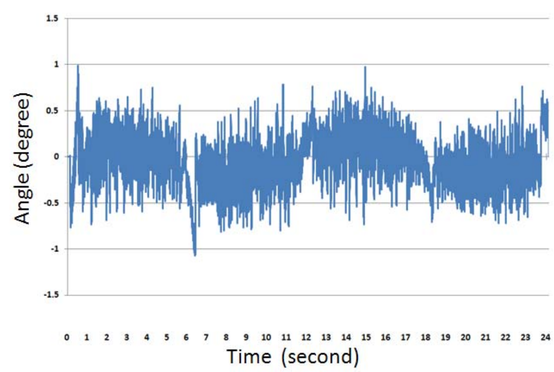

Fig.11. Position error between the expected and actual trajectory

C. Experiment on assisted control mode

Five healthy volunteers (1 female and 4 male) participated in the experiment. They are taught about the assisted motion process described in part C, section III first and then carry on the assisted motion for DIP joints. The maximal joints of volunteers are measured to ensure the after-assisted joint angle not to exceed the joint limits. The assisted angle is set to be 12 degrees. The angles before and after the assisted motion are measured by the potentiometer and the average angles are listed in Table I. The control parameters used in this experiment are K_P =0.5V/degree, K_I = 0.0625 V/degree, K_D = 0.007 V/degree/s, K =275rpm/V, $\xi_{DIP} = 0.75$.

TABLE I
THE MAXIMUM ANGLES OF DIP JOINT BEFORE AND AFTER THE ASSISTED MODE

DIP joint	Before assisted mode	After assisted mode	Actual assisted angle
male I	53.4°	65.4°	12.0°
male II	37.8°	50.4°	12.6°
male III	47.7°	60.2°	12.5°
male IV	50.8°	63.3°	12.5°
FeMale I	60.2°	72.6°	12.4°

Table I shows that after triggering the assisted button, the finger was then driven by the exoskeleton moves between the beginning position and the desired position. The actual assisted angles are basically corresponds with the expected assisted angle (12 degrees), and the maximum error is 0.6 degree. The experiment demonstrates that the proposed assisted control mode could be successfully accomplished.

V. CONCLUSION

Focused on the multiple requirements of the rehabilitation motion for hand motor capability, a control method which can switch between the force control and position control is proposed. With the proposed control algorithm, the exoskeleton could accomplish the active, passive, and assisted rehabilitation motions which is fundamental in hand rehabilitation application.

For future work, we are going to further test the performance of the exoskeleton, such as the position error due to the friction between the cable and sheath. We will also expand the method to the other rehabilitation mode.

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