A novel End-effector Finger Rehabilitation Robot (EFRR) for stroke patients

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Abstract. This paper proposes a prototype of a novel end-traction finger rehabilitation robot with flexion/extension and adduction/abduction functions. The degree of freedom (DoF) and finger joint torque of a single-finger module has been analysed, and the calculation and selection of the motor driving force are completed. Finally, the design details of the mechanism and the hardware system of the robot are illustrated. This device minimized the mechanical size to some extent by using only one motor for a single finger, which also reduces the cost and increases the possibility of industrial application prospects.

1. Introduction

According to the studies, 55%-75% of stroke patients have finger movement dysfunction, and only 30% of them can recover from it [1]. In the early stage of the disease, it is difficult for the patients to exercise on their own, and if the deliberate exercise for the hand cannot be carried out timely, the muscles will permanently atrophy and may lose the ability to move flexibly [2]. Based on the theory of Continuous Passive Movement (CPM), the corresponding brain region can be continuously stimulated and the nervous system can be repaired through continuous passive rehabilitation training on the fingers [3-4], which can achieve the purpose of treatment.

Figure 1. End-traction Finger Rehabilitation Robot (EFRR).
The application of robots to the rehabilitation is able to reduce the labour intensity of physicians and conduct more scientific training for patients. There are three types of the finger rehabilitation robot: end-effector [5-6], exoskeleton [7-8] and soft robotics [9-10]. In this paper, a novel end-effector finger rehabilitation robot (EFRR) with flexion/extension and adduction/abduction functions is proposed (shown in Figure 1), and the rehabilitation movement of each finger is driven by one motor respectively, and the driving force has been calculated and analyzed.

2. Design of the flexion/extension exercise module for fingers

2.1. Degree of the freedom

The finger rehabilitation module of EFRR is composed of four units with similar structures but different sizes. The virtual prototype and structure diagram of the unit are shown in Figure 2. The degree of freedom (DoF) of each unit can be calculated by the formula:

\[ F = 3n - 2P_L - P_H = 1 \]  

(a) Virtual prototype of a single unit  
(b) Man-machine structure diagram  
Figure 2. Single unit and the man-machine structure diagram of the finger rehabilitation module

Where \( n \) represents the number of active components, \( P_L \) represents the number of low pairs and \( P_H \) represents the number of high pairs; The high pair between the finger motion trajectory restraint plate and the needle bearing is a virtual restraint, which ensures the fingers to move alone the plate; in addition, there is a coupling relationship between the finger joints, that is, the coupling relationship between the distal interphalangeal point (DIP) and proximal interphalangeal point (PIP) joints, and between DIP and metacarpophalangeal joint (MCP) joints, two constraints are added, so the DoF is 1, and the motion of each rod is determined.

2.2. Analysis and design of the motor driving force

The driving force is closely related to the torque of the finger joints. Due to the small size of the fingers, it is difficult to obtain joint torque directly through the sensors. Therefore, thin film pressure sensors are placed on the inside of the finger sleeve, on the upper and lower sides respectively, and the torque of the finger joint can be calculated indirectly through the contact force \( F \). The force analysis diagram is shown in Figure 3.

Figure 3. Finger joint force analysis diagram
The torque balance equation for the DIP joint is:

\[ T_{\text{DIP}} + m_3 g \cdot \frac{a_4}{2} \cos(\theta_2 + \theta_3 + \theta_4) = F \cdot a_4 \]  

(2)

The torque balance equation for the PIP joint can be:

\[ T_{\text{PIP}} + m_2 g \cdot \frac{a_3}{2} \cos(\theta_2 + \theta_3 + \theta_4) + m_3 g \left[ \frac{a_4}{2} \cos(\theta_2 + \theta_3 + \theta_4) + a_3 \cos(\theta_2 + \theta_1) \right] = \]

\[ F \cdot \cos(\theta_2 + \theta_3 + \theta_4) \left[ a_4 \cos(\theta_2 + \theta_3 + \theta_4) + a_3 \cos(\theta_2 + \theta_1) \right] + \]

\[ F \cdot \sin(\theta_2 + \theta_3 + \theta_4) \left[ a_4 \sin(\theta_2 + \theta_3 + \theta_4) + a_3 \sin(\theta_2 + \theta_1) \right] \]  

(3)

The torque balance equation for the PIP joint is:

\[ T_{\text{MCP}} + m_4 g \cdot \frac{a_2}{2} \cos(\theta_2 + \theta_3 + \theta_4) + m_3 g \left[ \frac{a_4}{2} \cos(\theta_2 + \theta_3 + \theta_4) + a_3 \cos(\theta_2 + \theta_1) \right] = \]

\[ F \cdot \cos(\theta_2 + \theta_3 + \theta_4) \left[ a_4 \cos(\theta_2 + \theta_3 + \theta_4) + a_3 \cos(\theta_2 + \theta_1) \right] + \]

\[ F \cdot \sin(\theta_2 + \theta_3 + \theta_4) \left[ a_4 \sin(\theta_2 + \theta_3 + \theta_4) + a_3 \sin(\theta_2 + \theta_1) \right] \]  

(4)

Where \( \theta_2, \theta_3 \) and \( \theta_4 \) are the rotation angles of the MCP, PIP, and DIP joints respectively. From formula (2) to formula (4), it can be seen that if the contact force \( F \) changes, the torque of the finger joints will change correspondingly, which affects the output of the motor driving force. Under normal circumstances, the maximum force exerted by a finger can reach about 25N and this value is selected to ensure the torque is sufficient. The relationship between \( T_{\text{DIP}}, T_{\text{PIP}}, T_{\text{MCP}} \) and movement time can be obtained by substituting the contact force \( F \) into formula (2-4), and it has been shown in Figure 4(a). The man-machine model is established based on the principle of virtual work. The displacement-time motion law of the slider is preset as: \( S = 30t - 30 \) and the change rule can be describe as Figure 4(b) shown.

![Graph showing joint torque changes with time](image)

(a) Joint torque changes with time

![Graph showing driving force changing with time](image)

(b) Motor driving force changing with time

Figure 4. Finger joint torque and motor driving force.

It can be seen from the figure above that the driving force of the motor is related to the running time, as the time changes, the position of the slider is different correspondingly. Besides, it is also related to the contact force \( F \), when the \( F \) increases, the torques on MCP, DIP, and PIP joints increases, so as to
the required driving force. The power of the motor can be determined as:

\[ P_{\text{Motor}} = \frac{F_{\text{Drive}} \cdot \dot{S}}{\eta_{\text{all}}} = 2.75W \]  

(5)

Where \( F_{\text{Drive}} \) represents the maximum force of the motor, which occurs when \( t=4.13s \) and \( F=25N \); \( \dot{S} \) represents the speed of the slider; \( \eta_{\text{all}} = 0.6 \) represents the overall efficiency of the drive system. Considering the factors such as power, size, working voltage and so on, the proMOTION servo motor is selected. The parameters are listed in Table 1.

Table 1. Motor parameters of the EFRR.

| Motor Symbol | Voltage | Speed | Torque | Reducer | Ratio | Efficiency |
|--------------|---------|-------|--------|---------|-------|------------|
| proMOTION   | 28SYK   | 24    | 7300   | 0.02    | 114   | 0.73       |

The series is 28SYK43.24.90, the rated power is 14.8W, the rated speed is \( n_1=7300r/min \), and the rated torque is \( T_1=0.02N\cdot m \). The series of the reducer is P28HA and the reduction ratio is \( i = 64 \), the output speed of the reducer is \( n_2 = 114r/min \), the diameter of the pulley is \( d = 13mm \), the efficiency of the motor is \( \eta_m = 0.7 \), and the efficiency of the reducer is \( \eta_r = 0.73 \).

According to the final motor parameter table, it can be derived that the rated speed \( V_m \) that the motor drives the slider and the driving force \( F_m \) that the motor drives the slider are:

\[
\begin{align*}
V_m &= \frac{n_2 \times \pi d}{60} = 77mm/s \\
F_m &= \left( \frac{T_1 \cdot i \cdot \eta_r}{2} \right) \frac{d}{2} = 98N
\end{align*}
\]  

(6)

The results above indicate that the driving force and speed could meet the design requirements.

2.3. Detailed mechanical design of the flexion/extension exercise module

To a certain extent, the details of the mechanism design determines whether the functions can be successfully implemented as required. The design details include the installation method of the belt, the limit mechanism, the tension mechanism and so on. As for the belt installation, the synchronous belt needs to pass through a slider with square hole. The installation steps are as follows: first, the belt should be cut off; then, the two ends are passed around the pulley and inserted on different side of the square hole respectively; finally, the set screw and the connecting block are used to fix it. The belt may be slack after the installation steps above, so the tensioning mechanism play a role at this time. A tensioning block is fixed on the bottom plate, and there are two light hole with a diameter of 4mm are processed, which can fit the M3 threaded hole on the pulley holder. The pulley fixing frame can be pulled close to the tension block to achieve belt tension by tightening the M3 screws. The bottom of the pulley holder is connected to the bottom plate with waist-shaped holes, tighten the waist-shaped hole of the bottom plate and the four screws at the bottom of the pulley fixing frame after adjusting the belt tension, and the whole tensioning process is completed (shown in Figure 5(b)).

It is very important for the device to work in a safety condition. Therefore, certain measures should be taken from both software and mechanism design. The electrical limit of the flexion/extension exercise module is realized by the bearing frame, 3D printing switch touch frame and micro switches (shown in Figure 5(c-d)). The switch touch frame is fixed on the movable bearing frame by bolts and can move along with the slider, and there is an inclined surface between the frame and the micro switch. The
response time of the switch can be offset by adjusting the length and the inclination of the switch touch frame, so the machine can stop in time, which improves the security.

![Diagram of finger flexion/extension exercise module](image)

Figure 5. Schematic diagram of the key mechanism of the finger flexion/extension exercise module.

3. Hardware system of the EFRR

The hardware system of the EFRR mainly includes a central control unit, a human-computer interaction unit, a digital/analog signal acquisition unit and motor controller units.

The overall hardware system is arranged inside the mechanical frame to ensure the structure compact. The main electrical components include 24V power supply, power switches, limit switches, emergency stop buttons, voltage conversion module, Controller Area Network(CAN) module, motor drivers, pressure sensors, data acquisition control module and so on. Besides, it also includes some interfaces such as Recommend Standard 232(RS232) interface, 220V power supply interface and Universal Serial Bus(USB) interface and the specific layout is shown in Figure 6. The central control unit is a personal computer, and the RS232 communication interface and USB square port line are used to communicate with the personal computer. The computer can send the control command to the motor driver through the CAN bus to control the motors. The status information of the limit switches can be collected by the data acquisition control module and the pressure of sensors are transmitted back to the computer through the RS232 interface.

![Hardware system layout drawing](image)

Figure 6. Hardware system layout drawing.
4. Conclusion
This paper proposes a novel end-traction finger rehabilitation robot with flexion/extension and adduction/abduction functions. The analysis of the finger joint force provides a theoretical basis for the selected of the driving motor, the detailed mechanical design of the device such as tensioning module, limited module could ensure the mechanical reliability, and the hardware system of the device is the guarantee of the rehabilitation training. In the future, structural optimization and the design of the rehabilitation training programs will be carried out.

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