The Design of Wearable Auxiliary Rehabilitation Equipment Gloves

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Abstract. In order to help hand dysfunction people to rehabilitate hand muscles and train hand muscles, we designed and developed a wearable rehabilitation equipment glove. First, we collected data from a sample hand and fitted its motion trajectory. Through analysis and comparison, we decided to use the linkage mechanism as the actuator and pneumatic drive as the driving method. In order to ensure flexibility, accuracy and stability, we designed and optimized the number and position of the connecting rods. Finally, we will get a set of rods that can simulate the movement of the fingers, and use springs to increase the flexibility of the mechanism. We studied the rigidity of the mechanism and determined the material of the device. After obtaining the model, we will perform a static analysis on the final state of the finger to ensure the safety of the device.

Keywords: wearable rehabilitation equipment, exoskeleton structure, pneumatic series elastic drive

1. Introduction
Stroke is one of the most devastating diseases, and 85% of stroke patients worldwide suffer from hemiplegia [1]. Researches have shown that the alteration of the functionality of the upper limbs (UL) is one of the highest complaints of individuals with stroke due to the limitations in performing important manual daily activities [2]. However, the hand dysfunction caused by stroke can be cured by physical therapy, but the general rehabilitation treatment consumes a lot of human and material resources, so the research on rehabilitation robot has become a hot spot. Because of the hands’ complicated movement, researches face a series of problems such as how to accurately simulate the human hand trajectory and how to achieve good human-computer interaction ability. In order to overcome these problems, this paper has designed a new wearable auxiliary rehabilitation equipment glove based on under actuated connecting rod and series elastic actuator (SEA). After calculating and optimizing the length of each link, a set of rods with the best hand motion trajectory can be obtained. And the under actuated design and the addition of the series elastic drive make this glove a good human-computer interaction. The wearable auxiliary rehabilitation equipment glove can drive the patient's hand movement by applying a certain force to each part of the patient's hand, and after a plurality of training, the purpose of rehabilitation can be achieved.
2. Conceptual Design

The design of mechanism is mainly divided into the configuration design and size synthesis. On the basis of the configuration, the size of its constituent units (namely all links) should be optimized in the step of size synthesis, so that the error between ideal condition and the actual condition will be as small as possible, thereby better achieving the function.\cite{3} By studying and comparing existing hand rehabilitation robots, we initially developed our configuration and, after theoretical calculations, determined the final configuration.

The final configuration consists of three sections, a sleeve section, a rod set and a pneumatic drive. In the sleeve section, a sleeve that mimics the shape of the human hand is designed to be easily used as the main part of the glove for the wearable auxiliary rehabilitation equipment glove. Each component is designed with a linkage set to connect the casing and transmit motion. The index finger, index finger, middle finger, ring finger and little finger are similar, so their rod groups share a similar structure. We used an 11-bar three-degree-of-freedom mechanism to simulate the trajectory. Due to the different lengths and trajectories of each finger, the length of each rod group needs to be optimized until it completely conforms to the predetermined trajectory. A 7-bar-1-free-free free mechanism was used to simulate the flexion and extension of the thumb.

The mechanism adds a spring between the cylinder and the output rod to form a series of elastic actuators (SEA) \cite{4}. SEA is a flexible drive that connects the elastic component in series between the motor and the load. Due to the introduction of the elastic component, the output of the robot is passively flexible, which can buffer the external force, thus ensuring that the robot can be friendly and safe with the environment and people \cite{5}. The specific movement is that with the cylinder’s inflating and deflating, the output rod makes a reciprocating linear motion, and one end of the output rod is connected with each finger lever group, so the movement of the output rod is transmitted to each rod group, thereby driving the fingers of the glove.

3. Motion trajectory analysis

This product is designed to help the patients with hand functional obstacle to recover their hand muscles and train the hand muscles, so its movement track is required to conform to the trajectory of the human hand. It has discussed the function of the motion parameters of the finger joints according to the analysis of human hand biological structure, which mainly includes the structure of the human finger joints and the finger size, and the performance requirements and schemes were proposed on the basis of the previous study. Table 1 and Table 2 collected all the data needed of the Chinese adults’ hand joints and the phalanx as a sample (Table 1 Table 2).

| Table 1. Sample hand data sheet. |
|----------------------------------|
| thumb | index finger | Middle finger | Ring finger | Little thumb |
| First knuckle length | 22 | 23 | 23 | 19 |
| Second knuckle length | 31 | 28 | 29 | 29 | 22 |
| Third knuckle length | 36 | 46 | 52 | 50 | 40 |
| First joint length | 15 | 15 | 14 | 13 |
| Second joint length | 19 | 17 | 19 | 17 | 16 |

| Table 2. Maximum rotation angle of finger joints. |
|----------------------------------|
| MP  | PIP  | DIP  |
| Maximum angle of rotation | 66° | 96° | 45° |

Since the device is mounted on the hand, the size and weight of the device must be minimized. Therefore, the mechanism employs an underactuated design that drives the movement of all three joints to move all the joints of the finger according to a predetermined trajectory and achieve a single finger flexion \cite{6}. Taking the index finger as an example, we used a camera to make a simple stroboscopic lens to record the trajectory of the sample finger flexion motion (Figure 1). The trajectory of the sample finger is obtained by fitting the position of the object using the spline curve and
analyzing the angular displacement of the movement of each joint of the index finger.

Analyze the movement process of the index finger to complete the flexion movement, and substitute the length data of the sample knuckles: 22 mm, 28 mm, and 46 mm, regardless of the left and right extension of the finger, the maximum bending angle of the three joints: 66°, 96°, 45°, with the finger parallel to the palm of the hand as the initial state. Using the programming software-MATLAB to make the two-dimensional simulation of the motion trajectory equation of the index finger, to obtain the motion trajectory of each joint point (Figure 2).

![Figure 1. Sample hand motion trajectory acquisition image.](image1)

![Figure 2. Sample hand motion trajectory.](image2)

This part mainly calculates the optimal rod length by the geometric relationship between the finger joint and the rod and the angular displacement of each joint during the movement. Due to the limited space, we take the analysis of the index finger as an example.

4. Kinematic calculation

This part mainly calculates the optimal rod length by the geometric relationship between the finger joint and the rod and the angular displacement of each joint during the movement. Due to the limited space, we take the analysis of the index finger as an example.

4.1. Establishment of the kinematic model of fingers and members

According to the human skeleton structure, the finger can be simplified to a 3 degree of freedom member structure, refer to figure 3[7]. AB is a finger sleeve designed with reference to the distal phalanx of the index finger, BC is the middle phalanx finger cot, and CD is the proximal phalanx finger cot. The intersections B, C and DE are the forefinger joints DIP, PIP, and MP. The remaining AF, FJ, FG, GK, GH, HE, and HI are exoskeleton rods that drive finger movement. The E point is fixed on the palm sleeve, and the HI rod is driven to rotate the rod HE within a certain angle range, thereby moving the remaining exoskeleton members.

![Figure 3. Finger and rod kinematics model diagram.](image3)

4.2. Determination of the length of the rod

Analytical methods are used to establish position equations for the mechanism. Here, the complex vector method is used to treat the mechanisms ABJF, FJCKG and GKDEH as a closed vector polygon[8], and the closed vector equation of the mechanism is represented in the plural form:

\[ \begin{align*}
L_{AF} + L_{HI} &= L_{BJ} + L_{AB} \\
L_{IC} + L_{GC} + L_{IK} &= L_{FJ} + L_{FG} \\
L_{KD} + L_{DE} + L_{HE} &= L_{GK} + L_{GH}
\end{align*} \]
Then the vector equations are respectively projected on the established Cartesian coordinate system, and the mapping relationship between the fingertip Cartesian space and the finger joint space is established, and the geometric relationship between the rod members and the joint angles can be obtained [9]. The projection equations for the three closed polygons are:

\[
\begin{align*}
(l_{FB} \sin \phi_{FB} - l_{FJ} \sin \phi_{FJ}) &= l_{AB} \sin \phi_{AB} + l_{BJ} \sin \phi_{BJ} \\
(l_{FB} \cos \phi_{FB} - l_{FJ} \cos \phi_{FJ}) &= l_{AB} \cos \phi_{AB} + l_{BJ} \cos \phi_{BJ} \\
(l_{FG} \sin \phi_{FG} + l_{FJ} \sin \phi_{FJ}) &= l_{JC} \sin \phi_{JC} + l_{CK} \sin \phi_{CK} + l_{GK} \sin \phi_{GK} \\
(l_{FG} \cos \phi_{FG} + l_{FJ} \cos \phi_{FJ}) &= l_{JC} \cos \phi_{JC} + l_{CK} \cos \phi_{CK} + l_{GK} \cos \phi_{GK} \\
(l_{GH} \sin \phi_{GH} + l_{GK} \sin \phi_{GK}) &= l_{KD} \sin \phi_{KD} + l_{DE} \sin \phi_{DE} + l_{HE} \sin \phi_{HE} \\
(l_{GH} \cos \phi_{GH} + l_{GK} \cos \phi_{GK}) &= l_{KD} \cos \phi_{KD} + l_{DE} \cos \phi_{DE} + l_{HE} \cos \phi_{HE}
\end{align*}
\]

In the polygon ABJF, to simplify the calculation, suppose \( l_{BI} \) is on a horizontal plane. And let \( m = \frac{l_{AF}}{l_{AB}}, n = \frac{l_{FJ}}{l_{AB}}, p = \frac{l_{BJ}}{l_{AB}} \), the projection equation is squared and then added to simplify:

\[
m^2 = (p + n \cos \phi_{FJ} + \cos \phi_{AB})^2 + (n \sin \phi_{FJ} + \sin \phi_{AB})^2
\]

\[
m^2 = [p + n \cos(\phi_{DFJ} + \phi_{FJ}) + \cos(\phi_{DFJ} + \phi_{FJ})]^2 + [n \sin(\phi_{DFJ} + \phi_{FJ}) + \sin(\phi_{DFJ} + \phi_{FJ})]^2
\]

where \( \phi_{DFJ} \) is the angular displacement of the \( x \)-bar motion, the maximum angular displacement of the joint DIP, that is, the angle ABJ, is 45°. As can be seen from the data acquisition results, the finger sleeve portions AB and BJ are known amounts. According to the trajectory simulation of the finger, the angular displacement of the rod FJ should be greater than or equal to 0, and the final angle should be less than 180°. The constrained equation of the polygon ABJF is

\[
\begin{align*}
(l_{AF} + l_{FJ} - l_{AB}) &= l_{BJ} \\
(l_{AF} - l_{FJ} - l_{AB}) &= -l_{BJ} \\
\phi_{DFJ} &
\geq 0 \\
\phi_{FJ} + \phi_{DFJ} &
\leq \pi
\end{align*}
\]

Its objective function is:

\[
\min(m, n) f(m, n, \phi_{FJ}, \phi_{DFJ}) = m + n
\]

That is, the shortest length of the rod is optimized.

In the polygon FICKG, let \( m = \frac{l_{FG}}{l_{JC}}, n = \frac{l_{GK}}{l_{CK}}, p = \frac{l_{FJ}}{l_{JC}}, q = \frac{l_{FJ}}{l_{JC}} \), simplify the formula (5) as above. Then list the constraint equations in combination with the actual motion situation:

\[
\begin{align*}
l_{FG} + l_{GK} &= l_{JC} + l_{CK} + l_{FJ} \\
\phi_{GK} + \phi_{DGK} &
\leq \frac{\pi}{180} \times \pi
\end{align*}
\]

Also, with the shortest length as the optimization condition, its objective function is:

\[
\min(m, n) f(m, n, \phi_{GK}, \phi_{DGK}) = m + n
\]

In the polygon GKDEH, the two-section link to the DE has little effect on the overall motion, so it can be simplified as a link. Let \( m = \frac{l_{GK}}{l_{KD}}, n = \frac{l_{HE}}{l_{KD}}, p = \frac{l_{DE}}{l_{KD}}, q = \frac{l_{HE}}{l_{KD}} \), simplify the formula (6) as above. Then list the constraint equations in combination with the actual motion situation:

\[
\begin{align*}
l_{DE} + l_{GK} &= l_{DE} + l_{KD} + l_{GK} \\
l_{HE} - l_{GK} &= l_{DE} + l_{KD} - l_{GK} \\
\phi_{HE} + \phi_{DHE} &
\leq \frac{\pi}{180} \times \pi
\end{align*}
\]

Also, with the shortest length as the optimization condition, its objective function is:

\[
\min(m, n) f(m, n, \phi_{HE}, \phi_{DHE}) = m + n
\]

After being brought into the operation of the MATLAB program, an optimal set of rod lengths can be obtained as shown in the Table 3, and the initial and final angles for the rods FJ, GK, and HE are as shown in the Table 4[10-12]. The rod group diagram is shown in Figure 4.
### Table 3. Rod initial and final angle table.

| Rod | AF     | FJ     | FG     | GK     | EH     | GH     |
|-----|--------|--------|--------|--------|--------|--------|
| Rod length | 14.8413 | 8.8413 | 29.5722 | 10     | 40.8692 | 22.8585 |

### Table 4. Rod length result table.

| Rod | FJ | GK | EH |
|-----|----|----|----|
| Angle initial value | 151.5 | 129.8 | 105.6 |
| Angular displacement | 17.2 | -49.8 | -99.1 |

**Figure 4.** Rod group diagram 1.

Changing the constraints on the program can optimize the set of bars based on production use. Figure 9 shows the results after limiting the minimum value of the GK rod. Figure 10 shows the result after avoiding the interference. It limited the minimum value of the FJ rod and the GK rod, and the angle between the FJ rod and the BJ rod, the angle between the GK rod and the CK rod, and the angle between the HE rod and the DE rod.

**Figure 4.** Rod group diagram 2.  **Figure 5.** Rod group diagram 3.

### 4.3. Finite element analysis

The results of the comprehensive kinematic analysis are easy to know that when the finger lever is moved to the final state, the rods and the finger sleeve parts are subjected to the maximum force and torque. Therefore, we only perform static analysis on the final state of flexion of the index finger. The safe torques of DIP, PIP and MP2 are respectively taken into the force analysis of the rod for calculation. And the calculation results are shown in Table 5:

### Table 5. Rod force table.

|            | F AF | F FJ | F FG | F GH | F GK | F EH | F HI | M DIP | M PIP | M MP2 |
|------------|------|------|------|------|------|------|------|-------|-------|-------|
| the safety torque of the DIP | 4.37  | 17.08 | 19.47 | 47.23 | 46.62 | 236.31 | 234.91 | \     | 66.96  | 97.5  |
| the safety torque of the PIP | 1.04  | 4.08  | 4.65  | 11.29 | 11.14 | 56.46  | 56.13  | 1.67  | \     | 23.31  |
| the safety torque of the MP2  | 0.56  | 2.21  | 2.51  | 6.10  | 6.02  | 30.52  | 30.34  | 0.90  | 8.65  | \     |

It can be seen from the calculation results that when the safety torque of DIP is taken into the
calculation as a known amount, the torque received by the PIP joint has exceeded the safety torque and the average torque, which is less than the maximum torque. The torque of the MP2 joint has exceeded the maximum torque too. Therefore, this scheme is abandoned. When the safety torque of PIP is taken into the calculation as a known quantity, the moment of the DIP joint is less than the safety torque, and the moment of the MP2 joint has exceeded the safety torque and is less than the average torque. This option is also not adopted for security reasons. When the safety torque of MP2 is taken into the calculation as a known quantity, the torques of DIP and MP2 are less than their safety torque, so the option is preferred for the mechanism. (Figure 7 Figure 8 Figure 9 )

5. Physical model and control module

In order to achieve the wearability of the equipment, we designed the outer contour of the glove according to the shape of the human hand.

- **Small arm sleeve:** the lower part is fixed on the human arm, and the upper cylindrical cavity is used to fix 5 pneumatic series elastic actuators. (Figure 10)
- **Palm sleeve:** The palm of the hand passes through the inner cavity of the palm sleeve, and
the shape of the palm sleeve is designed according to the contour of the hand. The back of the palm sleeve is designed with five connectors for fixing the connecting rod. (Figure 11)

![Figure 9. Arm sleeve.](image_url)

![Figure 10. Palm sleeve.](image_url)

- **Finger sleeves:** The sleeve is in the form of an exoskeleton. Each finger has three corresponding finger sleeves. In order to avoid motion interference, the joint between the knuckles and the knuckles is placed on the side of the finger sleeve. (Figure 12)

![Figure 11. Finger sleeves.](image_url)

- **Overall model diagram:** As can be seen from the figure, the rehabilitation equipment gloves are mainly composed of five parts. The core motion device is a linkage mechanism. The pneumatic cylinder is mounted to the input of the drive rod. The output of the linkage is connected above each of the finger sleeves. In this way, the power starts from the pneumatic cylinder and reaches the finger sleeve through the linkage mechanism. (Figure 13)

![Figure 12. Overall model diagram.](image_url)

6. **Pneumatic control**
The pneumatic system includes: power source, control valve, actuator. The gas enters the actuator series elastic drive, changing the amount of contraction of the drive to control the movement of the finger.

![Pneumatic control diagram](image_url)

7. **Summary**
This product is mainly used to help hand dysfunction people to carry out rehabilitation training of hand muscles. This product can be worn like a glove, easy to use, and assist rehabilitation patients to complete rehabilitation training. In addition, this product adopts an exoskeleton design to support the
human hand from the outside, thereby improving its strength and endurance. The length of the rod set is accurately calculated. The analytical equations were used to establish the position equations to ensure the determination of the motion trajectory, which greatly reduced the number of drives. In order to ensure safety, static analysis of the final state of the finger grip is performed. At the same time, the drive structure has been optimized to replace the traditional drive with a pneumatic series of elastic drives, increasing structural flexibility and safe interaction. Finally, a 3D model of rehabilitation mechanical gloves was assembled using Inventor.

8. References
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