Design and Optimization of a New Index Finger Exoskeleton Robot with Underactuated Mechanism

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Abstract. Spinal cord injury and stroke are the main diseases that lead to loss or decline of hand function, and hand rehabilitation exoskeletons can be used to help restore hand function. Due to the problems of traditional hand exoskeletons such as heavier weight, higher cost and limited mobility, this project aims to improve an index finger exoskeleton robot with an underactuated mechanism, improve its bending and extension angles, and optimize the robot to a certain extent. flexibility. At the same time, the genetic algorithm is combined in the control system to make all the control indexes reach excellent. This project establishes a 3D model through Solidworks, and at the same time proves the feasibility of improvement by establishing a kinematic model. In terms of design, the mechanism is adjusted according to the range of activities of MCP(metacarpophalangian joint) and PIP(proximal interphalangeal joint) to optimize the flexibility of the design model. In the aspect of control system, the genetic algorithm is combined with system identification and PID(Proportion Integration Differentiation)control, in order to reach the objective of establishing a more precise training model and finding appropriate PID parameters. This project has a positive effect on the medical efficiency of the underactuated hand exoskeleton.

Keywords: Exoskeleton; Underactuated Mechanism; Motion Simulation; Hand Function Rehabilitation; SEA Control.

1. Introduction

Due to uncertain factors such as illness and accidents, some patients' hand health is affected, resulting in hand dysfunction. Hand dysfunction is the most serious disabling movement disorder reported [1]. Therefore, in the medical industry, Portable robotic devices have received a great deal of attention over the last decade, these devices are collectively called exoskeletons, which can be used as rehabilitative aids for patients suffering from temporary muscle dysfunction (neurological disorders) recovery from patients.Among the limbs/joints that may require rehabilitation, the index is the most important - due to its flexibility and independent muscular attachment.It allows not only a good grip, but also a very accurate handling of small objects in daily tasks.The human index includes three joints (MCP (metacarpophalangian joint), PIP (proximal interphalangeal joint), DIP (distal interphalangeal joint)) and three phalanges (proximal, median and distal joint) [2].Evidence indicates that portable robotic systems are a viable option for precisely performing this therapeutic intervention with a minimum of human intervention [3].

Natural science's bionic research on shell organisms [4, 7] has derived a wearable mechatronics "clothing", that is, a wearable exoskeleton. In order to ensure the performance of the wearable exoskeleton, the design of the driver is particularly important, which provides the power system and control system for the exoskeleton [5, 7]. Since the conventional driver lacks a flexible mechanism and lacks a certain buffer capacity, especially when the driver provides Larger torques may cause harm to the human body. In contrast, the series elastic actuator (SEA) connects elastic elements in series between the driving source and the output load end, providing a buffering effect and ensuring the safety of the human body. In terms of control algorithm, Pratt and his colleagues who proposed serial elastic actuators initially used PID combined with feedforward compensation for control decision-making to control SEA in walking robots and bouncing robots [6, 7]. After that, more and more scholars study the use of PID control in SEA, and PID control has become an effective method to control SEA. In fact, exoskeleton control system, the system is often time-varying, nonlinear, and requires high real-time performance. At the same time, it is usually hard to get a precise mathematical model of the object, and it is difficult to achieve the expected effect with traditional PID control. In order to improve the control effect, this study combines traditional PID control with genetic algorithm to control SEA, so as to achieve the purpose of controlling the hand exoskeleton. The genetic algorithm is an optimal parallel randomized search method proposed by Professor Holland in the US in 1962 to simulate the natural genetic mechanism and the theory of biological evolution [7]. The genetic algorithm is not only suitable for single-goal optimisation, but also for multi-objective optimisation. Depending on various control systems, for one or more objectives, the genetic algorithm can find suitable parameters within the specified range [8]. Given the high degree of freedom of the MCP and PIP joints of the index finger, flexion and extension are possible. We have optimised the amplitude of movement of the MCP and PIP seals in the new under-actuated mechanism, to improve the MCP and PIP joint index exoskeleton robot's flexibility. The dual loop connection of the mechanism to the PIP and MCP joints of the index improves the amplitude of movement of both joints to a certain extent, but they cannot add new strengths or couples to the fingers. The index finger has the special property of flexibility, and the double-ring connection allows the mechanism to adapt to the human hand joints for better flexion and extension. The new underactuated mechanism accommodates the degree of freedom of the hand to match the degree of freedom of the index finger joint. In order to enable the index finger to move laterally, we built a rotation point under the rotary joint at the CMC with the vertical direction as the y-axis and the index finger as the x-axis. The rotation point is located under the CMC joint and is attached to the hand. The distal material forms the fixation structure. This allows the index finger to rotate laterally to both sides while increasing the operability of the underactuated mechanism.

The purpose of this paper is to design and optimize a new underactuated index finger exoskeleton rehabilitation robot to achieve the effect of hand exoskeleton in medical rehabilitation. In the driver selection, SEA or traditional motors can be selected, and by using series elastic actuators (SEAs), flexible and comfortable interaction and human safety can be achieved.The introduction of passive conformity in the form of standard elastic actuators (SEAs) based on Bowden cables has been identified as a good source of power or torque with low inertia for exoskeletons with controlled impedance. [9], combining traditional PID control with genetic algorithms to Control SEA, so as to achieve the purpose of optimizing the new underactuated mechanism index finger exoskeleton rehabilitation robot. SEA can provide disengagement from actuator inertia, downshift capability, improved impact tolerance and high controller gain [10]. When optimizing the design, choosing to add a rotation point under the CMC rotary joint can allow the index finger to move laterally, improve the range of motion of the MCP and PIP, and improve the flexibility of the underactuated mechanism on these two joints to a certain extent. At present, most of the research on the index finger exoskeleton robot is in the aspect of forward motion, and we optimize the design in the lateral motion, which further improves the operability of the index finger exoskeleton robot with the underactuated mechanism at the MCP and PIP links. This has positive significance for promoting the development of index finger exoskeleton robots.

2. Method

2.1 Overall Mechanism Design and Control

2.1.1 Design Ideas and Methods

In the aspect of new underactuated mechanism, we optimize the range of motion of MCP and PIP joints, in order to improve the flexibility of forefinger exoskeleton robot at MCP and PIP joints. The double-ring bond between the PIP and MCP joints of the mechanism index can increase the amplitude of motion of both joints to some extent, but they can't add new force and torque to the fingers. The index finger has the special property of flexibility, and the double-ring connection can make the mechanism adapt to the human hand joint, so as to better flex and stretch. The new underactuated mechanism can adapt to the degree of freedom of the hand, so as to be consistent with the degree of freedom of the index finger joint.

SEA or traditional motor can be selected for driver selection. In the control system, the mathematical model of the object being checked must be determined. Because it is hard to determine the exact mathematical model in real life, the method of system identification combined with genetic algorithm is adopted to establish a model close to the actual model. In the control mechanism, PID and genetic algorithm are combined to find the appropriate PID parameters.

2.1.2 Overall Structural Design

The new under-actuated structure includes five sub-components, each of which is closely related to the index finger. The fixed parts are installed on the platform on the back of the hand. Part of the finger is an underactuated linkage mechanism composed of three links, which can rotate at a certain angle in the X and Y planes. The connecting rod transmits the force emitted by the actuator to the double rings of MCP and PIP index finger. Usability and ergonomics tests conducted with reference to [11]. It can be seen that because of the special flexibility of the exoskeleton of the forefinger hand, the movement angle of the forefinger in MCP and PIP joints is not as large as expected. The degree of flexibility has not fully met the expected requirements.

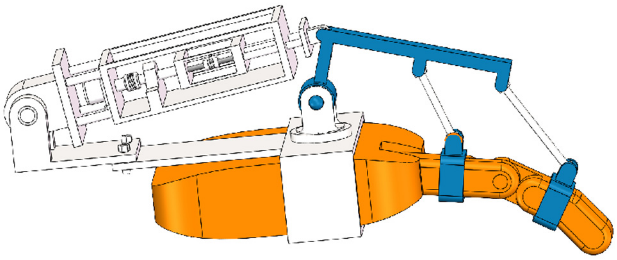
We think that the range of motion of the new underactuated mechanism is limited at MCP and PIP joints, and we optimize the mechanism at CMC, which effectively increases the range of motion of MCP and PIP joints and further improves the flexibility of the mechanism. In order to make the index finger move laterally, we built a rotation point with the vertical direction as the Y axis and the index finger direction as the X axis under the rotation joint at CMC. The rotation point is located below the CMC joint and forms a fixed structure with the distal material attached to the hand. This rotation point increases the range of motion of the exoskeleton of the index finger on the X-axis plane. Thus, the index finger can rotate laterally to both sides, and at the same time, the operability of the underactuated mechanism is increased.

2.2 Kinematic Model

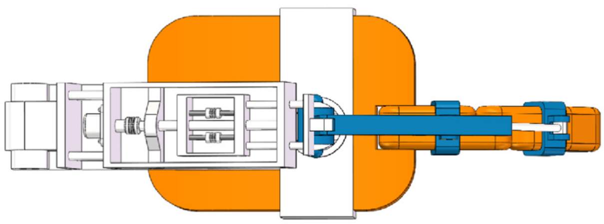
2.2.1 Kinematic Analysis

The human hand is highly articulated, leading to complex kinematics. The index finger contains three phalanges from the tip of the finger to the palm: the distal, medial (or middle) and proximal phalanges, which are meant to be joined by joints, including: the fingertip joint away from the palm (DIP), the relatively proximal fingertip joint (PIP) and the metacarpophalangeal joint (MCP) connecting the palm. The fingertip joint (1DOF) and the proximal interphalangeal joint (1DOF) function only in flexion/extension. Metacarpophalangeal joints (2DOFS) are joints with flexion/extension and abduction/adduction movements and therefore have relevant functions. The device makes contact with the proximal and medial phalanges, freeing the distal phalanges and providing assistance to the MCP (α Angle) and PIP (γ Angle) joints of the five fingers. In addition to this, the Angle between the middle phalanx and the horizontal plane is defined as β, which is necessary for the formalization of the kinematic model. Consider positive Angle for finger extension exercise and negative Angle for finger bending exercise.

The hand is a complicated functional member, composed of more than 30 muscles and more than 20 joints, which can perform various activities with high precision. Kinematics is very important for the function of hands. In order to ensure the safety of users, the kinematic compatibility of human exoskeleton must be ensured before the design stage and other development stages. If the device fails to achieve this compatibility, unwanted interaction forces may occur, which are mainly caused by misalignment between the exoskeleton and the human limb, and the effects of which cannot be compensated by the device actuator [12]. This design can swing up and down and swing sideways. Figure 1(a) and (b) showed main view of underactuated mechanism and top view of underactuated mechanism, respectively.



(a) Main view of underactuated mechanism



(b) Top view of underactuated mechanism

Fig 1. 3D model of index finger

The Grubler method [13] was used for determining the number of degrees of freedom. For single-finger planar connections, the Grubler equation shows that:

$$\text{Degree of Freedom}=3*(N-1)-2R1-R2 \tag{1}$$

N: the total amount of links in the plan link.

R1: the number of single-degree-of-freedom kinematic pairs (joints).

R2: The number of kinematic pairs (joints) with two degrees of freedom.

To verify the rationality of the model design, this project uses Adams software to simulate the kinematics of the model. And the moving range curves of fingertips in front and back (global coordinate system X axis) and up and down directions (global coordinate system Z axis) are obtained. Figure 2 showed curve of position coordinates of fingertips in front and back directions, and Figure 3 showed curve of position coordinates of fingertips in the up-down direction, Figure 4 represented fingertip movement track. Finally, Figure 5 showed curve diagram of fingertip movement trajectory.

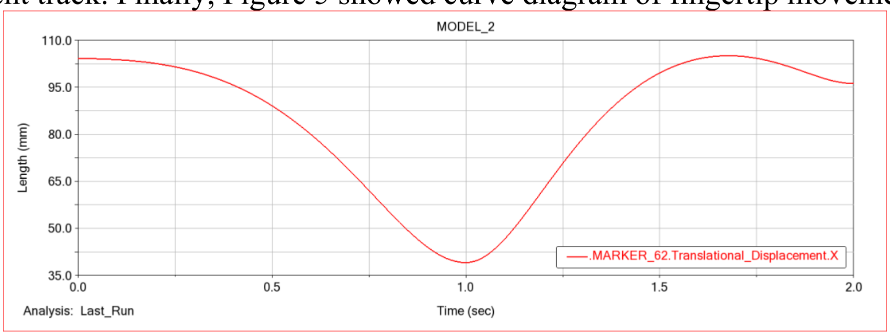


Fig 2. Curve of position coordinates of fingertips in front and back directions

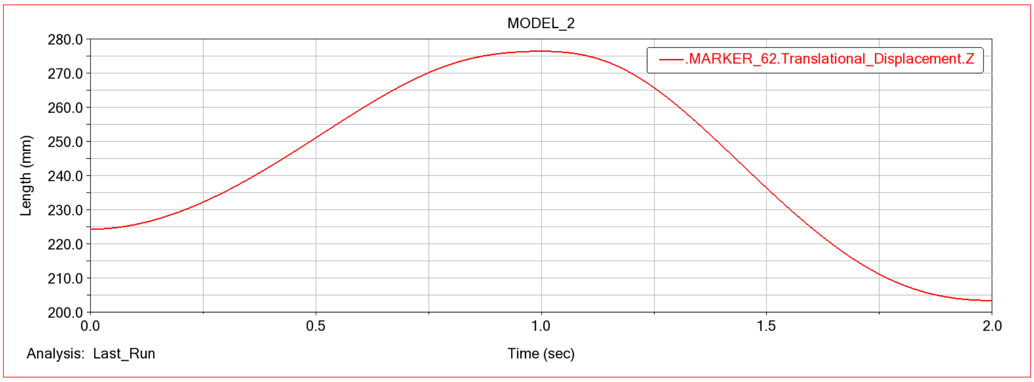


Fig 3. Curve of position coordinates of fingertips in the up-down direction

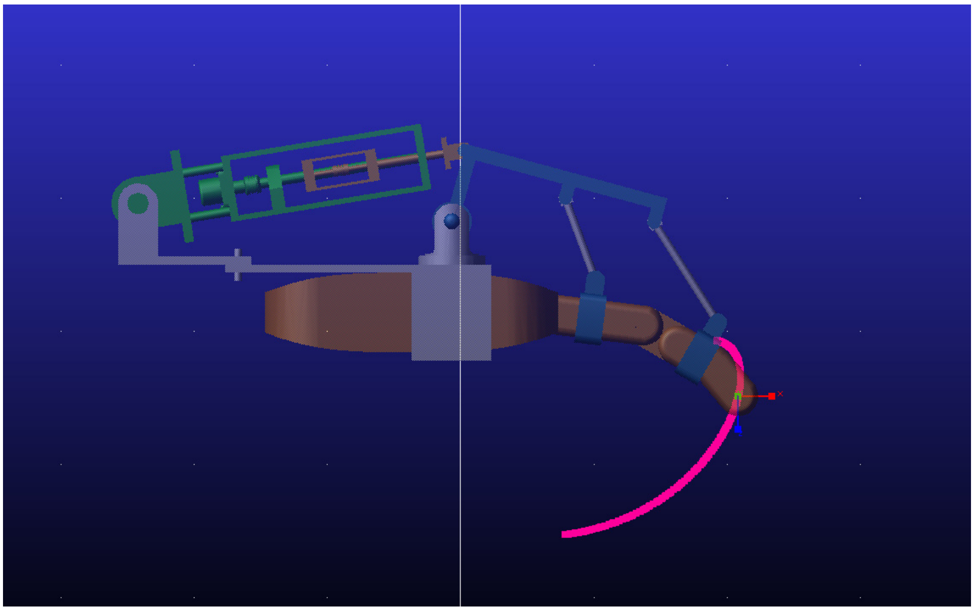


Fig 4. Fingertip movement track

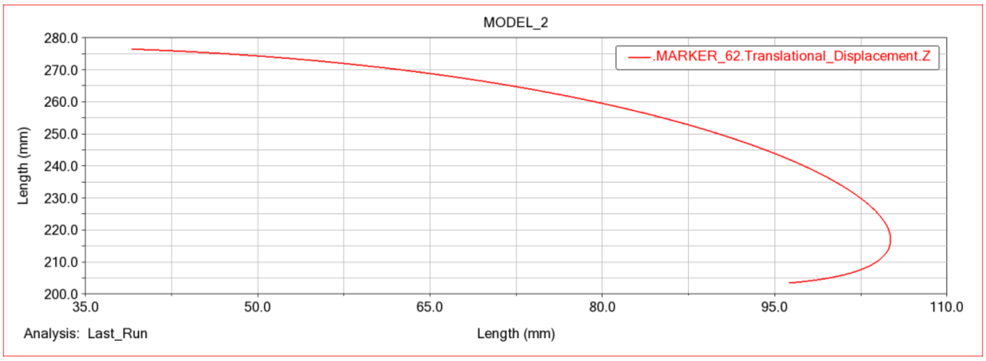


Fig 5. Curve diagram of fingertip movement trajectory

2.3 Control System Design

2.3.1 Establishment of Control Object Model

Due to the advantages of SEA in terms of safety and flexibility, it is very suitable for hand rehabilitation exoskeletons. In this project, a linear actuator combined with a spring, namely SEA, is used to drive the hand exoskeleton, and its structure, model establishment and simulation refer to [14]. The drive system consists of a motor reducer, a lead screw, a lead screw nut, a spring, a position sensor, and an output shaft. The structure can be seen in Figure 6.

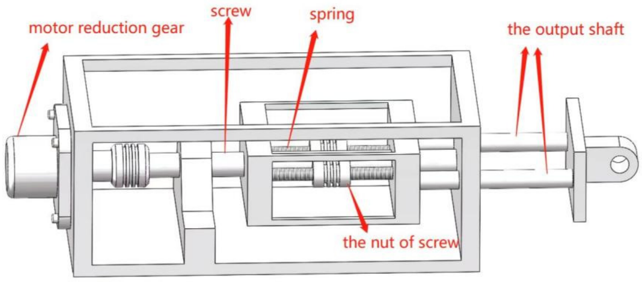


Fig 6. SEA structure diagram

According to the control purpose, the SEA model can be divided into three forms: position source, velocity source, and force source [15]. The objective of this project is to control the exit force from the SEA. In order to obtain the dynamic model of the series elastic actuator, the series elastic actuator is simplified into the dynamic model shown in Figure 7, where m_m is the equivalent mass of the motor, m_1 is the equivalent mass of the load, b_m is the damping coefficient of the motor, and k_s is the spring. Elastic constant, b_1 is the spring damping coefficient, x_m is the displacement variable of the screw nut, x_1 is the load displacement variable, F_m is the motor driving force, and F_1 is the output force.

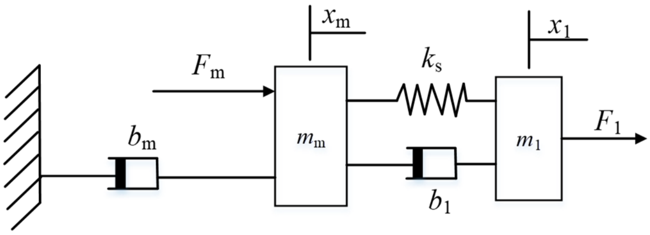


Fig 7. SEA kinetic model

According to the SEA kinetic model, the following equations are obtained:

$$F_m - F_1 = m_m\ddot{x}_m - b_m\dot{x}_m \tag{2}$$

$$F_1 = k_s(x_m - x_1) + b_1(\dot{x}_m - \dot{x}_1) \tag{3}$$

In the formula:$\dot{x}_m, \ddot{x}_m$ are the displacement speed and displacement acceleration of the screw nut in turn; $\dot{x}_1$ is the load displacement speed.

After Laplace transformation, the open-loop transfer function of the system when the driver end is fixed $(x_1 = 0)$ is:

$$G_1(s) = \frac{k_s + b_1 s}{m_m s^2 - (b_m - b_1)s + k_s} \tag{4}$$

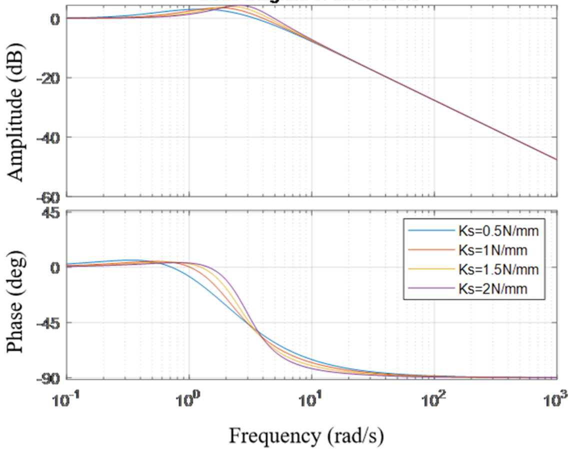


Fig 8. Bode plots of open-loop systems at different spring constants

where s is the Laplace transform factor, $b_1 = 1Ns/mm$,$b_m = 0.25Ns/mm$,$m_m = O.24kg$

The Figure 8 shows the Bode plot of the open-loop system at different spring constants. The figure shows that the right side of the phase angle curve is in the vicinity of -90º, and the system has good amplitude and phase angle margins. From the trend, the larger the predicted elastic coefficient, the smaller the phase angle margin of the system.

2.4 PID Control

PID (Proportion, Integral, Differential) control is a simple but effective control algorithm based on estimating "past", "current" and "future" information. The control strategy is widely used in [16, 17] in the industrial control process. The PID control can be used for the output force control of the SEA. The schematic diagram of the PID control is shown in Figure 9. PID is a kind of linear controller. The controller may form the deflection e(t) depending on the given value of r(t) and the real value of c(t). The proportion, integral and differential of the deviation value constitute the quantity of control by linear combination, in order to attain the goal of object control [17].

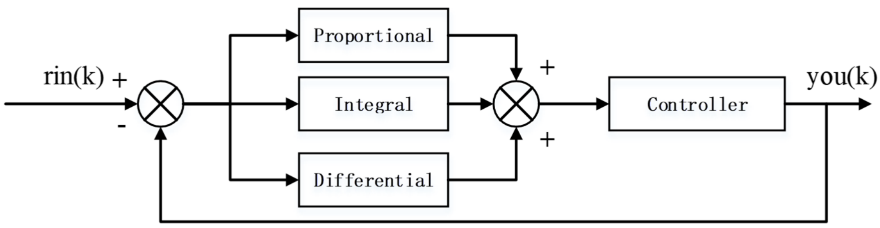


Fig 9. Schematic diagram of the PID control system

Its control rule is follows:

$$u(t) = K_P\left[e(t) + \frac{1}{T_I}\int_0^t e(t)dt + \frac{T_D de(t)}{dt}\right] \tag{5}$$

Kp is the proportional coefficient, TI is the integral temporal constant, and TP is the incremental temporal constant.

The control function of each link is as follows:

Proportion: This link can be proportional to the error amplification, can make the controller quickly control action, so as to achieve the purpose of reducing the control error.

Integration: In this link, as long as there is error, it will always have the effect of eliminating error, until the error disappears. The strength of the integral action is determined by the integration time constant, the larger the time constant, the smaller the integral action, and vice versa.

Differentiation: The differential action can predict the trend of change and introduce an early correction signal before the deviation signal becomes too large, so as to speed up the response speed of the system and reduce the adjustment time [17,18].

2.5 Genetic Algorithm

2.5.1 Basic principles of Genetic Algorithms

Genetic algorithm (GA) is a kind of effective problem-solving method inspired by Darwin's biological evolution theory. The basic idea is evolution, natural selection, survival of the fittest, and search method of genetic thought, according to the selected fitness function and through reproduction, crossover and mutation in the genetic screening, for each individual to cause retention of the fitness of individuals form a new group, the new generation of information on the group inherits and is better than that of the previous generation. Repeated like this, the fitness of individual members of the group can continue to improve. The algorithm is straightforward and can be handled at the same time. It can obtain the overall optimum solution effectively and accurately without initialization. Moreover, the structure of the modified algorithm is open and convenient to be combined with the problem, so it is feasible to be used for PID parameter optimization [19]. The process flow chart is shown in Figure 10.

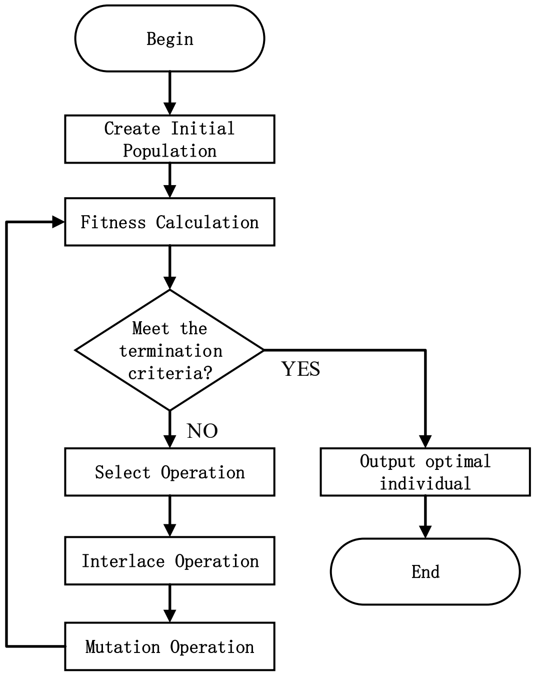


Fig 10. Flow chart of the genetic algorithm

2.5.2 Genetic Algorithm Combined with PID

The three Kp, Ki and Kd parameters in traditional PID control must be achieved through a lot of debugging and experience, and sometimes the control effect is not good. Combining genetic algorithm with PID control, and optimizing its parameters with genetic algorithm, good control effect can be obtained [20]. The control block diagram is shown in the following figure (see Figure 11).

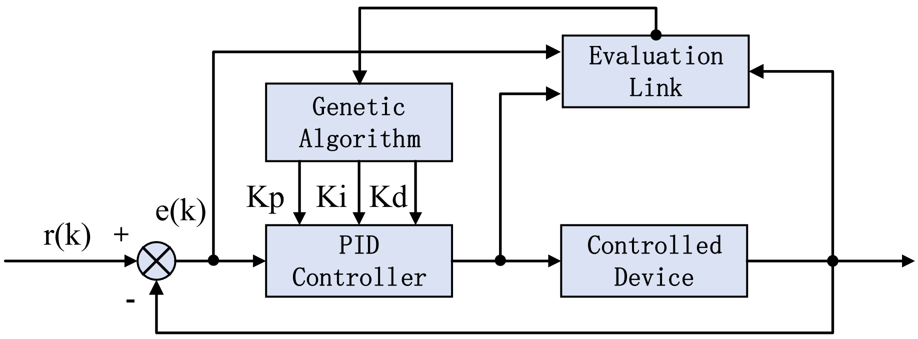


Fig 11. Block diagram of the GA-optimized PID control system

The basic process of PID controller is as follows [20-25]:

1. Three parameters of PID are represented in an unsigned binary number of certain digits, constitute chromosomes, the population consists of M chromosomes, and randomly produce an initial population.
2. Using the corresponding decoding method, the encoded individual is calculated through the fitness function.
3. By comparing the size of individual adaptive values, some individuals with higher adaptive values were selected from among the population to form the mating basin.
4. Individuals in the breeding pond are manipulated by two genetic operators to form a next-generation population.
5. Steps of 2-4 are performed repeatedly until the set genetic algebra is reached.

The system flow chart is as follows (see Figure 12):

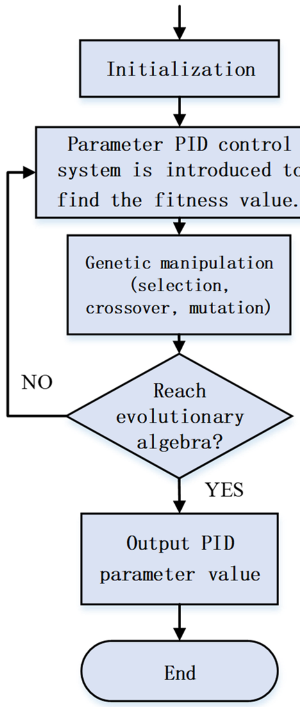


Fig 12. Flow chart of GA-optimized PID controller parameters

3. Results and Discussion

In this paper, the genetic algebra is set at 100, the original population is 30 individuals, the chance of crossing Pc is 0.9 and the chance of mutation Pm is 0.1. After optimization of the algorithm, three parameters are obtained (spring elastic coefficient Ks is 1N/mm): Kp = 62.08, Ki = 38.80, Kd = 0. The individual optimal fitness value of each generation is shown in the figure 13:

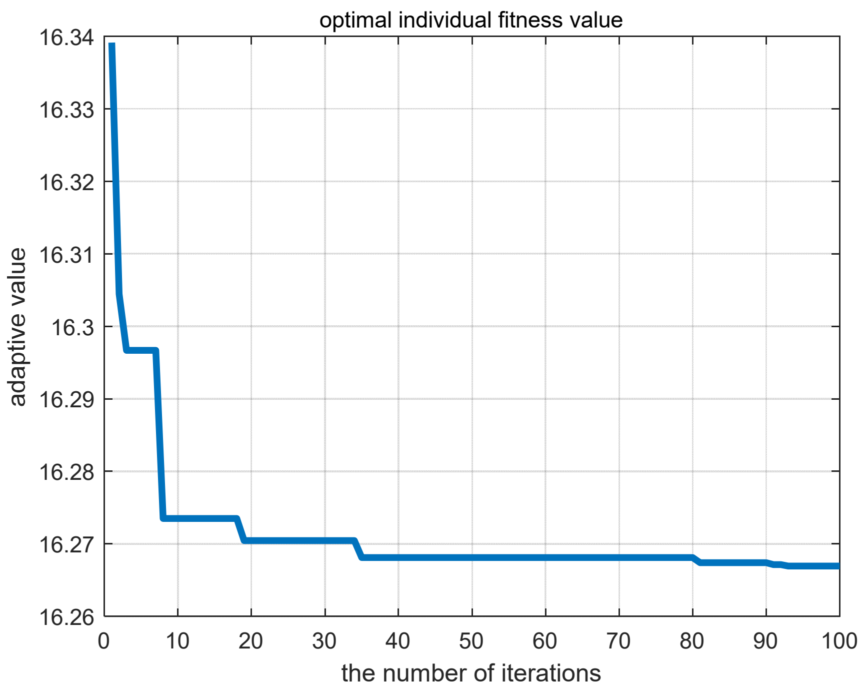


Fig 13. Optimal adaptation values for each generation

Step response curve and step response error curve of the control system (after optimization) are shown in Figure 14 and Figure 15:

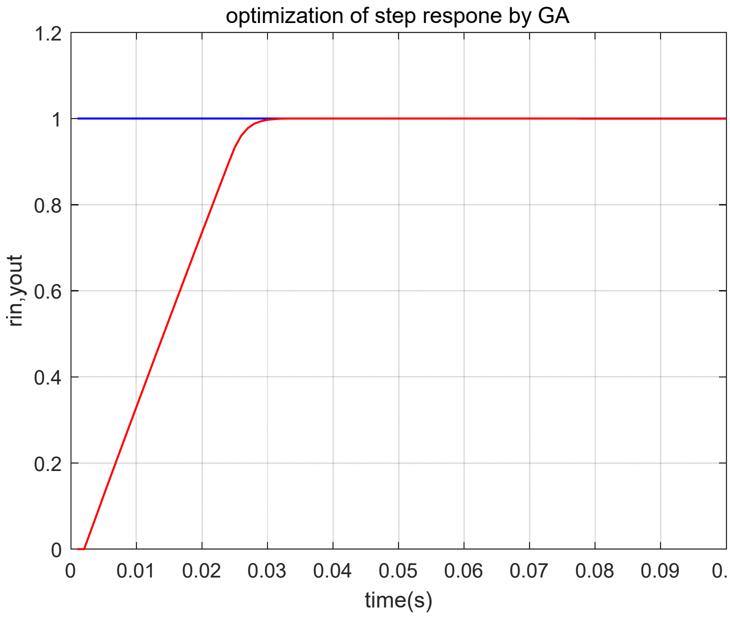


Fig 14. Step response curve of the GA-optimized PID control system

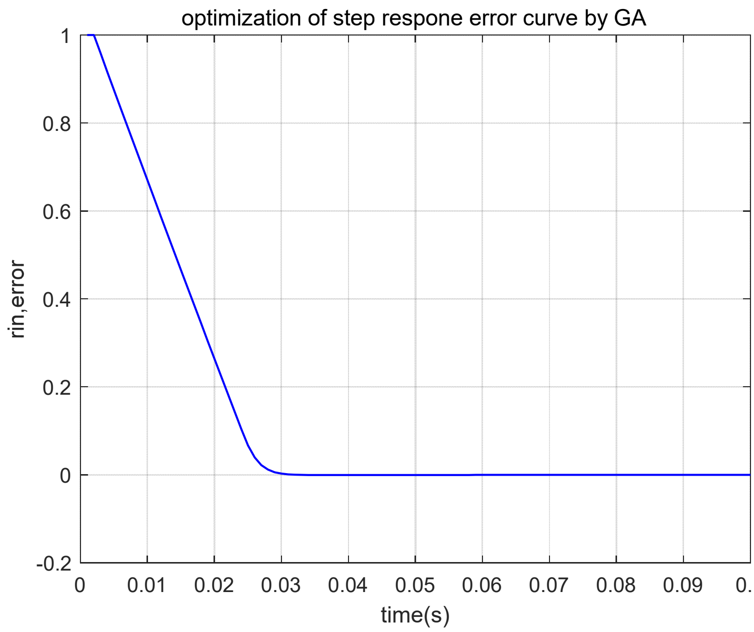


Fig 15. Step response error curve of the GA-optimized PID control system

According to the results, the system is stable in around 0.03 seconds, with no overregulation, and the control effect is good.

Through Solidworks modeling and simulation, we optimized the mechanism at CMC, which effectively increased the range of motion of MCP and PIP joints and further improved the flexibility of the mechanism. The kinematic simulation analyzes the range of movement of the index and fully demonstrates the efficiency of the improved design according to the data. Compared to traditional control methods, this schema improves the control schema and method of the new lower index exoskeleton robot, adopts SEA control, and combines PID with genetic algorithm in the control mechanism, so as to find the appropriate PID parameters. The flexibility of MCP and PIP joints is optimized.

4. Conclusion

Customizing exoskeleton for patients can improve the control method of index finger exoskeleton to a certain extent, which is more in line with the development of science and technology. So as to obtain a better treatment effect and accurate rehabilitation data of patients, thereby better improving the rehabilitation scheme. However, providing customized rehabilitation hand exoskeleton for each patient has a certain cost, which is not conducive to the widespread popularization of rehabilitation hand exoskeleton in medical treatment. The mechanical structure and control system in this paper has improved the mechanical structure and control system of the traditional hand index finger rehabilitation exoskeleton to a certain extent, can improve the flexibility of the exoskeleton to a certain extent, and can avoid the cost of individual customization to a certain extent, which has certain positive significance for the popularization of the index finger rehabilitation exoskeleton.

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