Design and Analysis of Foldable Structures based on the Finger Exoskeleton Joint

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Abstract. A Mechanical Finger exoskeleton is a device designed to enhance or restore the function of a finger. With the advancement of science and technology, especially the development of robotics and biomedical engineering, such devices show great potential in the fields of rehabilitation medicine, industrial applications and human-computer interaction. For example, enhancing or restoring human function through wearable mechanical devices, especially in assisting the disabled, improving rehabilitation efficiency and military applications, shows great potential. In this paper, we will use solid works to conduct 3D modeling and Matlab coding to briefly elaborate the folding structure design and analysis of the mechanical exoskeleton finger joint. This study reveals the relevant models and simulations of the mechanical finger exoskeleton, which can increase the bending and stretching of the finger within the natural motion range and improve the flexibility characteristics. It can be adjusted according to the specific situation of patients, reduce medical costs, in the field of robotics itself, improve its flexibility and adaptability, improve task execution efficiency, convenience, lightweight and so on for most fields are a big advantage

Keywords: Exoskeleton, simulation, joint kinematics, Kinematics.

1. Introduction

With the continuous development of rehabilitation medicine, human-computer interaction technology and wearable devices, finger exoskeleton aid has shown potential in restoring hand activity and enhancing hand strength and flexibility [1]. This paper designs a folding finger exoskeleton joint structure designed to meet the needs of portability, comfort and personalization. On the way to achieve the goal, we need to consider the design, manufacturing, driving, application and other aspects. Design integrates mechanical engineering, material science and biomechanical principles, striving to be efficient, safe and flexible.

The core of the ability to simulate and enhance the natural movement of the finger. This design uses a multi-degree-of-freedom joint structure, including flexion / extension, lateral swing and rotation of freedom, to simulate the complex movement pattern of fingers. Each finger is composed of the drive unit (such as the motor or pneumatic element) [2], the transmission mechanism (Bowdoin line, connecting rod, etc.) and the support structure to ensure the accuracy and stability of force transfer [1]. In particular, the joints are modular design to facilitate adjustment and adaptation according to the user's finger size. In order to improve the portability and storage space utilization of the exoskeleton, the design introduces a folding mechanism. Specifically, a hinge or a deformable material is used as a key component of the joint joint, which can be folded and unfolded through simple operations (e.g. pressing, rotating) [3]. The exoskeleton shell is made of lightweight, high-strength material [4], and the non-stressed area is designed with folding slots or joint locking mechanisms to ensure a compact and stable structure after folding [5]. After the structural design is completed, material selection and performance analysis are carried out to ensure durability, comfort and cost reduction. At the same time, performance analysis verifies the feasibility and effectiveness of the design scheme. Before manufacturing, Solid Works (Hereinafter referred to as SW) software was used to model and simulate external skeletal joints, evaluate performance, mechanical properties and folding feasibility, and MATLAB was used for data analysis, numerical calculation and simulation. According to the simulation and test results, the design is optimized in detail. Possible directions for improvement include:

- Further optimize joint structure to improve motion accuracy and efficiency.
- Introduce more advanced drive technologies, such as smart materials or micro-motors, to improve response speed and control accuracy.
- Improved folding mechanism to make it easier and faster.
- Strengthen the investigation of user comfort, and improve the wearable experience by adjusting material selection, structural design, etc.

Mechanical exoskeleton is quite involved in various fields of human beings and has been explored and cited to a certain extent. When fine work is needed in rehabilitation, medical treatment, industrial military and other aspects, mechanical finger exoskeleton is needed to play a role. This paper studies the mechanical finger exoskeleton in order to enhance its comfort and improve its adaptability as much as possible. Through this simple research, we encountered many problems, but finally realized the establishment of finger model and related simulation and evaluation.

2. Method

2.1. Software and Analysis

The software tools to be used in this research are Matlab and SW, which are respectively used for data analysis, numerical calculation, simulation, three-dimensional drawing and SW analysis.

Solid Works: SW is a 3D computer-aided design software widely used in the field of mechanical design and engineering. This software provides a variety of functions and tools to help designers to easily create, simulate and analyze 3D models.

Matlab: Using its powerful data visualization ability and based on matrix operation, computing, visualization and programming are integrated into a simple and easy-to-use interactive working environment. This study will use the robot toolkit in Matlab and use link and other functions for trajectory simulation.

2.2. Material

For the choice of materials, in different fields, the use is very different, advantages and disadvantages are also influencing factors, so the choice of materials is the most important, such as can be divided into medical rehabilitation, industrial applications, robotics and so on, in the medical field recommended to use titanium alloy (high strength, light weight, corrosion resistance, good biocompatibility is the advantage, The main disadvantages are insufficient wear resistance and corrosion resistance), polymer materials such as PEEK, TPU, etc. (advantages are good flexibility and light weight, while the shortcomings are insufficient mechanical properties, durability, poor stability, complex processing and forming, etc.), shape memory alloys (can be recovered under certain conditions, but there is a certain risk in uncontrollable or unstable temperature conditions); In the industrial application stage, it is more recommended to use aluminum alloy (in love, good processing performance, low cost, but high cost, wear resistance and stability is insufficient), stainless steel (high height, corrosion resistance as the advantages of stainless steel, but there are also difficult to process and weld, increase labor costs and other deficiencies); In the research of high-performance robots, it is recommended to use carbon fiber composite materials (high strength, light weight, good flexibility, but there are technical difficulties, difficult production and other defects), polymer composite materials (high specific strength and high specific modulus, fatigue resistance, good shock absorption effect, etc., are advantages, but there are flammability, melting point is significantly reduced, and cost and technical difficulty) [4].

2.3. Design Process

First, the SW software is selected to build a model of a finger, and then cooperate with the exoskeleton machinery,as shown in Figure 1 below:

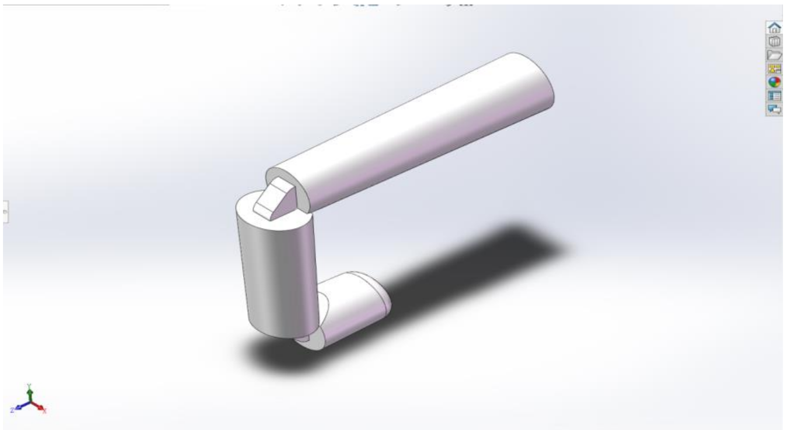

Fig. 1. Finger model (Photo credited: Original)

When the mechanical exoskeleton is combined with the fingers,as shown in Figure 2 below:

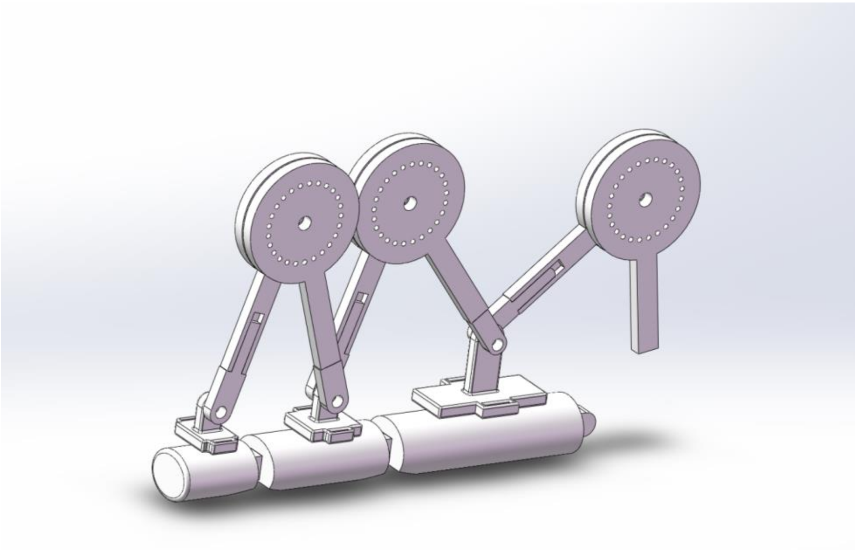

Fig. 2 Finger model combined with exoskeleton (Photo credited: Original)

Then use Matlab to do a trajectory planning, which involves Denavit-Hartenberg (Hereinafter referred to as DH)parameters and forward kinematics equations.

2.3.1. Establish a kinematic model of the finger

For the three-joint finger, it can be reduced to three links connected by rotating joints, and the rotation angle of each joint determines the posture of the finger. This model can be described with the help of the DH parameter table.

2.3.2. Define the parameters of each aspect

θ(Theta): Joint Angle (maximum limit Angle of finger root is 60 degrees, maximum limit Angle of finger and fingertip is 90 degrees);

d (distance): linkage offset (both 0);

a (length): connecting rod length (finger tip: 18mm, finger middle: 32mm, finger root: 58mm);

α(alpha): connecting rod twist Angle (all 0);

2.3.3. Calculate the transformation matrix

$$T1=\begin{pmatrix} \cos 60 & -\sin 60 & 0 & 0 \\ \sin 60 & \cos 60 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} 1/2 & -\sqrt{3}/2 & 0 & 0 \\ \sqrt{3}/2 & 1/2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{1}$$

$$T2=\begin{pmatrix} \cos 90 & -\sin 90 & 0 & 58 \\ \sin 90 & \cos 90 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} 0 & -1 & 0 & 58 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{2}$$

$$T3=\begin{pmatrix} \cos 90 & -\sin 90 & 0 & 32 \\ \sin 90 & \cos 90 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} 0 & -1 & 0 & 32 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{3}$$

$$T=T1*T2*T3 \tag{4}$$

2.3.4. Realization with Matlab

The Link function in Matlab is used to introduce various parameters, including length, Angle, etc., to encode a completed whole. After running, the image can be displayed and the finger movement can be displayed in the Figure 3.

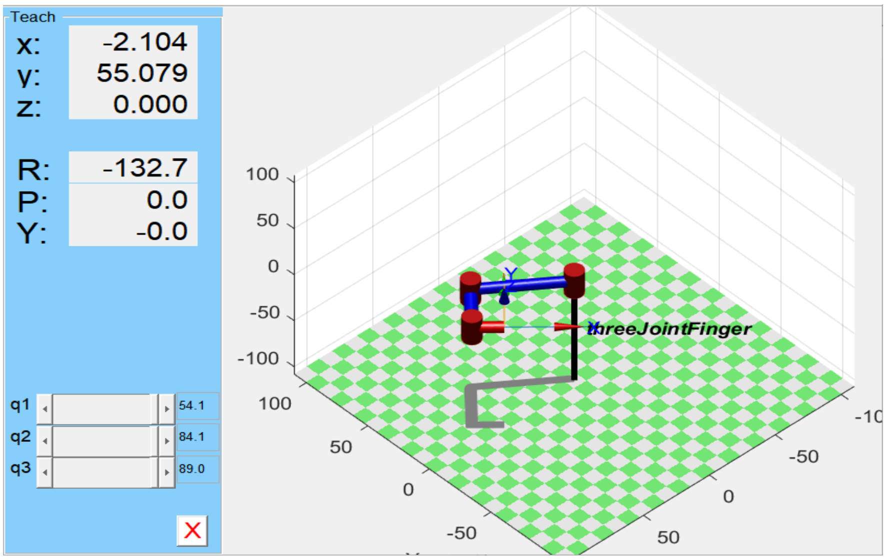

Fig. 3 Matlab Imic the finger model (Photo credited: Original)

2.3.5. Trajectory analysis

In order to generate trajectory data, we need to sample the range of joint angles. The linspace function is usually used to generate a uniform distribution of joint angles. The position of the end effector is then calculated by iterating through all possible combinations of joint angles. Then draw the trajectory diagram, using Matlab's plotting function (such as plot3), we can draw the 3D trajectory diagram of the end effector. By setting the axis label and title, you can more clearly show the characteristics of the trajectory. Finally, the trajectory characteristics are analyzed. After the trajectory diagram is generated, we can further analyze the trajectory characteristics. For example, the curvature, velocity, acceleration and other parameters of the trajectory can be calculated to evaluate the motion performance of the robot.

2.3.6. Conclusion summary

Construction of the transformation matrix: By defining the DH parameters for each joint (link length, link offset, joint angle, and link torsion angle), you can build a transformation matrix for each joint. These transformation matrices describe the frame transformation from one joint to the next.

Calculation of the total transformation matrix: multiply the transformation matrix of all joints to obtain the total transformation matrix from the base to the end effector. This total transformation matrix contains information about the position and attitude of the end-effector relative to the base.

Position and attitude extraction: The position vector of the end effector (usually the first three rows of the fourth column of the matrix) and the attitude information (the rotation part) can be extracted from the total transformation matrix.

Angle limitation considerations: In practical applications, the limitation of joint Angle (-60 degrees to +60 degrees, -90 degrees to +90 degrees, -90 degrees to +90 degrees) needs to be taken into account, and boundary checks are added to the calculation to ensure that the movement of the mechanical finger is within a safe range.

Kinematic analysis: By transforming the matrix, positive kinematic analysis can be performed, that is, calculate the position and attitude of the end effector given the joint angle. Furthermore, inverse kinematic analysis can be performed, calculating the desired joint angle given the target position and pose of the end-effector.

Simulation and verification: In MATLAB or other simulation environments, these transformation matrices can be used to simulate the motion of mechanical fingers to verify the correctness and performance of the design.

Practical applications: In practical applications, these transformation matrices are the basis for the design and control of mechanical finger exoskeletons. They can be used to develop control algorithms, achieve precise motion control, and perform performance evaluation and optimization.

2.4. Analysis Method (Improved DH analysis)

Connecting rod transformation matrix -DH method

Transform along and around Zi-1, then along and around X,i which was shown in the Figure 4.

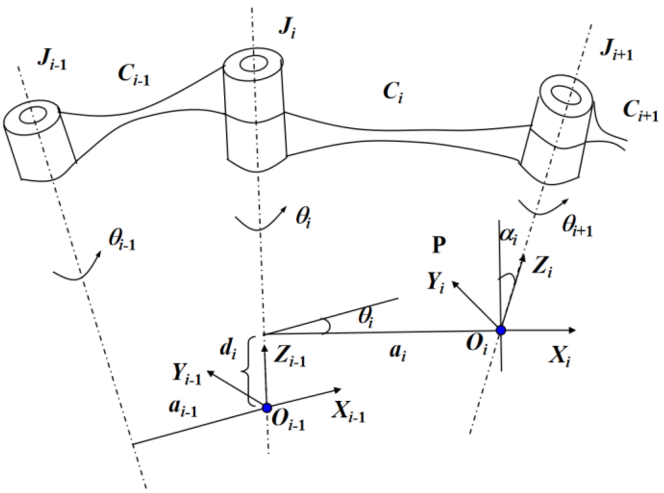

Fig. 4 Connecting rod model (Photo credited: Original)

Connecting rod transformation matrix: the C_{i-1}coordinate system can be transformed into the C_i coordinate system after two rotations and two translations.

The first time: take the Z_{i-1} axis as the rotation axis, rotate the Angle i, so that the new X_{i-1} axis is in the same direction as the X_i axis.

Second time: Shift di along the Z_{i-1} axis so that the new O_{i-1} moves to the joint axis J_i with the common perpendicular of J_{i+1} at the intersection with J_i

Third: Shift a_i along the new X_{I-1} axis (X_i axis) so that the new O_{I-1} moves to O_i.

The fourth time: Take the X_i axis as the rotation axis, rotate the Angle i, so that the new Z_{I-1} axis is in the same direction as the Z_i axis.

At this point, the coordinate system $O_{i-1}X_{i-1}Y_{i-1}Z_{i-1}$ and the coordinate system $O_iX_iY_iZ_i$ have been completely coincident. This relationship can be described by four homogeneous transformations from link C_{i-1} to link C_i. The total transformation matrix (D-H matrix) is:

$$A_i = \mathrm{Rot}(z,\theta_i)\mathrm{Trans}(0,0,d_i)\mathrm{Trans}(a_i,0,0)\mathrm{Rot}(x,\alpha_i)$$

$$= \begin{bmatrix} c\theta_i & -s\theta_i & 0 & 0 \\ s\theta_i & c\theta_i & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & a_i \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & c\alpha_i & -s\alpha_i & 0 \\ 0 & s\alpha_i & c\alpha_i & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c\theta_i & -s\theta_i c\alpha_i & s\theta_i s\alpha_i & a_i c\theta_i \\ s\theta_i & c\theta_i c\alpha_i & -c\theta_i s\alpha_i & a_i s\theta_i \\ 0 & s\alpha_i & c\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5}$$

The total transformation matrix is calculated after this [6]:

$$T=T1*T2*T3 \tag{6}$$

3. Results

3.1. Contrastive Analysis

The DH parameter for this time including Link Offset, Joint Angle, Link Length, Link Twist, were shown in the Table 1.

Table 1. Experimental data parameter

connecting rod	d(mm)	θ (rad)	a (mm)	α (rad)
1	0	1.04719755	58	0
2	0	1.57079633	32	0
3	0	1.57079633	18	0

According to the improved DH method equation template, with the help of matlab programming code, bring in the provided parameters, get the final end position.

3.2. Concrete Calculation

Multiply T1 (above 1),T2 (above 2), and T3 (above 3) to get Ttotal, the final forward kinematics equation is obtained by substituting the parameters into the template formula, and the position and attitude of the end are obtained. and finally extract the X, Y, and Z coordinates of the end position,T1 is the transformation matrix from the base to the first joint,T2 is the transformation matrix from the first joint to the second joint, and T3 is the transformation matrix from the second joint to the third joint [7].

3.3. Code Interpretation

Start by defining the length and maximum limiting Angle of each joint. The range of joint angles is generated using the linspace function. Calculate the end effector position: by looping through all possible joint Angle combinations, calculate the end effector position and finally plot the end effector trajectory: Plot the 3D trajectory of the end effector using the plot3 function.

3.4. Evaluation Indicators

Evaluation of the performance of the mechanical finger exoskeleton includes many indicators, including range of motion, comfort, reliability, adaptability, etc., which help to understand the integrity, comfort and functionality of the exoskeleton. The more indicators considered, the more easily the mechanical finger exoskeleton can be studied in the field, enter the market faster, and expand the application field. The evaluation method of motion range can be used to measure the maximum motion Angle of each joint in different directions by Angle measurement, three-position motion capture, image analysis, etc. The comfort level can be evaluated by questionnaire adjustment, parameter detection, kinematics and dynamics analysis, etc. Reliability needs to be evaluated by long-term experiments, life testing, failure mode impact analysis (FMEA). The adaptability of users can be evaluated by subjective questionnaire survey, user experience feedback, data collection and other methods. Security, portability, risk assessment matrix, security testing, user feedback and modular design evaluation, compatibility testing, respectively. The most basic cost-benefit evaluation method can use cost analysis software, benefit evaluation table combined with return on investment (ROI) and life cycle cost (LCC) analysis to get evaluation results.

4. Conclusion

It is summarized from three aspects: design, material application and future market. In terms of design, the novelty of the structure is introduced. The traditional finger exoskeleton mostly uses fixed joints, while the folding structure design introduces the concept of dynamic self-adaptation, so that the joints can be flexibly adjusted according to the natural curvature of the fingers. In the structural design, in order to accurately describe the motion trajectory of the finger exoskeleton during folding and unfolding, a kinematic model was established to ensure the reliability of the exoskeleton under various operating conditions. In the use of materials, it is recommended to use new lightweight high-strength materials, which can greatly reduce weight and improve wearing comfort and portability while ensuring structural strength. In the future application field market, the field of rehabilitation medicine can target patients with hand dysfunction. Industrial production can improve efficiency, significantly improve the accuracy and efficiency of workers, improve production safety; To provide assistance to the elderly, the disabled and other groups in their daily lives.

References

[1] Dai Y, Chen J, Liu C, Yang D P & Zhao J D. Research progress and prospect of wearable flexible upper limb exoskeleton. Journal of Harbin Institute of Technology, 2024, 08,1-16.

[2] Zhao J T, Li S N, Cai C J, Wu L Y, Wang L Y, Chen J W &Wang J E. (2023). Research progress of hand function rehabilitation robot after stroke -- from the perspective of transmission mechanism. Chinese Journal of Rehabilitation Medicine, 2023, 11,1616-1622.

[3] Wu J. Design and Research of Upper limb Assisted exoskeleton (Master's Thesis, Liaoning Technical University). 2022.

[4] Chen L K. Configuration Design and Optimization of passive robotic exoskeleton (Master's Thesis, Shanghai University of Engineering Science). Master. 2021.

[5] Hussain fahad, Goecke roland, Mohammadian masoud. Exoskeleton robots for lower limb assistance: A review of materials, actuation, and manufacturing methods [J]. 2021, 235 (12):1375-1385.

[6] Mu X H, Chen J H, Du F P & Zhao X D. Research on joint drive and optimization of lower limb exoskeleton robot. Mechanical design and manufacturing, 2017, 7, 263-265.

[7] Meng Q L, Shen Z J, Chen Z Z & Nie Z Y. Design and research of bionic exoskeleton manipulator based on flexure hinge. Chinese Journal of Biomedical Engineering, 2020, 05,557-565.