Mechanism design and static analysis of exoskeleton robot for rehabilitation of lower limb

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Abstract: According to the actual needs of rehabilitation training after knee joint surgery, and based on human lower limb kinematics principle, modern design method and bionics design method, the mechanical mechanism of lower limb rehabilitation exoskeleton robot was designed after knee joint surgery, so as to study the rehabilitation of exoskeleton robot. Through the analysis of the functional requirements, configuration options and driving modes of exoskeleton robot for lower limb rehabilitation, a new rehabilitation exoskeleton robot for lower limb is designed and static analysis of the key components of the knee joint of the rehabilitation exoskeleton robot is carried out. Based on simulation analysis results, we optimized the design of the structure, and the rehabilitation robot lightweight, modular design method is put forward after knee surgery, and the wearable Lower Limbs Rehabilitation Exoskeleton Robot and human walking posture has good following.

1. Introduction

The lower limb rehabilitation exoskeleton robot is a typical exoskeleton booster device[1], which is worn outside the lower limb of the patient, providing the patient with functions such as assisting, protecting, passive training, body support, etc., to complete the body itself is difficult to complete the activities. At present, many institutions at home and abroad are actively studying the lower extremity exoskeleton robot. In the field of medicine, some foreign research institutions such as Berkeley Bleeding Technologies have developed eLegs to help paraplegic patients get rid of wheelchair exoskeleton systems. University of Tsukuba, Japan[2]has developed a HAK series of lower extremity exoskeleton robots for assisting patients with gait disorder. Japan's Kanagawa Institute of Technology [3] for the nurse developed a "power auxiliary service" PAS. The inventors of Israel have developed a “rewalk” walker to help the leg paralyzed to re-stand[4].

In recent years, more and more domestic institutions and scientific research institutions have carried out research on rehabilitation equipment, and made a series of research results. the functional electrical stimulation of pedal training and upper limb rehabilitation equipment were studied by Jiang Hongyuan[5,6], Harbin Institute of Technology. Cheng Fang [7], Tsinghua University and Fang Bin [8], Shanghai University and others had carried out a more in-depth study of the suspension rehabilitation robot for lower limbs. In this paper, a new type of lower limb rehabilitation exoskeleton robot is designed to help patients to carry out rehabilitation training and rehabilitation training in the posterior rehabilitation of knee joint. It has the characteristics of light weight and modularity. Through the motor drive pulley, screw movement, so that the leg movement to complete the knee rehabilitation training. The structure is optimized by mechanically analyzing the designed model. And we produce the prototype of lower extremity rehabilitation exoskeleton robot finally.

2. Structure Design of Lower Limb Rehabilitation Exoskeleton Robot

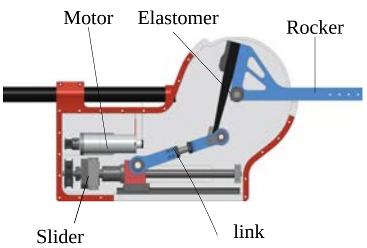
Based on ergonomics anthropomorphic design ideas and the basic design idea of force transfer between human skeleton and exoskeleton is put forward based on the binding and fixation of the legs, feet and feet. The whole system is mainly composed of exoskeleton hardware body, sensor (deceleration sensor, circular grating, etc.), electronic control system and other peripheral auxiliary equipment (leg, waist nylon strap), as shown in Fig. 1. Because in this paper, the design of lower limb exoskeleton robot is to help the patient walk on and rehabilitation training, so in order to simplify the mechanical structure, single leg four degrees of freedom is designed, respectively is: hip 2 degrees of freedom, knee 1 degrees of freedom, ankle 1 degrees of freedom, the small of the back because of no load requirements set the degrees of freedom.

Fig. 1 Rehabilitation Exoskeleton Robot and Walking Aid Stick

2.1 Knee Joint Structure Design

The knee is the only drive joint and is also the focus of the design of the entire exoskeleton robot. The overall structure of the knee joint shown in Fig. 2 is a crank slider mechanism drive unit, which is driven by a brushless DC motor. With the design of the electric drive mode, compared to hydraulic or pneumatic drive, with a relatively simple structure, easy function, less noise and so on.

In order to prevent the patient from falling when the mechanism is invalid, a self-locking slider crank mechanism is adopted in the structural design, which has the characteristics of simple structure. The slide block screw rod as the prime mover in turn drives the connecting rod, elastic body, rocker, will force fixed on the legs and feet of nylon straps. In the part of the screw, we choose the ball screw pair with noise and friction which is smaller than the ordinary screw rod, higher efficiency and higher accuracy, which is also beneficial to accurate movement output.



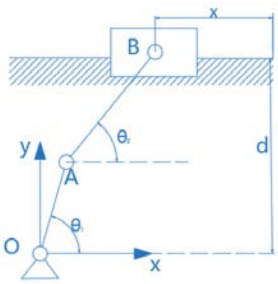


Fig. 2 Knee structure Fig. 3 Brief Analysis of Mechanical Structure of Knee Drives

2.1.1 Mechanism analysis

To the knee rotation axis as the origin, horizontal to the right along the thigh direction for the x-axis direction, the vertical x-axis positive axis for the y-axis, the establishment of Cartesian coordinates shown in Figure 3. Other symbols are defined as shown in Table 1 below.

Table 1 Parameter Meaning

Parameter	**Meaning**
θ_1	XOA size
θ_2	XOB size
x	Slider movement distance
r	Rocker length
l	Link OB length
d	Crank slider structure offset

Then the relationship between x and $\theta_1 \backslash \theta_2$ can be obtained from the geometric relationship in Fig. 3:

$$\begin{cases} d = r\sin(\theta_1) + l\sin(\theta_2) \\ x = r\cos(\theta_1) + l\cos(\theta_2) \end{cases} \tag{1}$$

Solution equation:

$$x = \begin{cases} l\cos[\arcsin(\dfrac{d - r\sin(\theta_1)}{l}) - 2k\pi] + r\cos(\theta_1) \\ -l\cos[\arcsin(\dfrac{d - r\sin(\theta_1)}{l}) + 2k\pi] + r\cos(\theta_1) \end{cases}, k \in N^* \tag{2}$$

Where θ_1 is in the range of 68 ° -158 °, we can draw the joint angle θ_1 on the slider position x curve, as shown in Fig. 4:

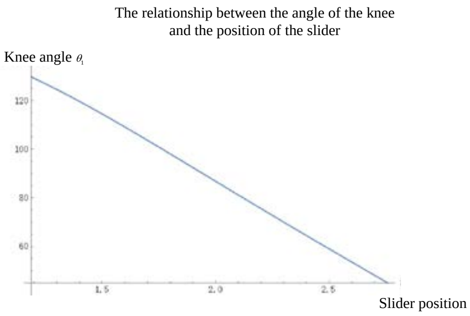


Fig. 4 the Relationship between the Angle of the Knee and the Position of the Slider

It can be seen from Fig. 4 that the relationship between knee angle θ_1 and x is almost linear, so the fitting method is used to deal with the problem of inverse kinematics. Using the Taylor expansion method, the function shown in equation (2) is expressed in the form of an error term $R_n(x)$ with an $O(x^2)$ in the form of a linear combination of the value $f(x_0)$ and the deviation $(x - x_0)$ at a point $x = x_0$:

$$f(x) = \frac{f(x_0)}{0!} + \frac{f'(x_0)}{1!}(x - x_0) + R_n(x) \tag{3}$$

The shift term will be transformed into the form of error term $R_n(x)$ about the function:

$$R(x, x_0) = f(x) - f(x_0) - f'(x_0)(x - x_0) \tag{4}$$

We can use the first-order Taylor expansion of this to replace the complex transcendental function of the original formula (2) by using the computational software Mathematical to find a minimum in the defined interval. In this way, it is possible to transform a problem of solving a nonlinear equation with a certain iterative method into a problem solving a linear equation, which greatly simplifies the calculation and provides a great convenience for the subsequent control system programming.

2.1.2 Force Analysis of Knee Joint Structure

The knee joint force analysis, as shown in Fig. 5:

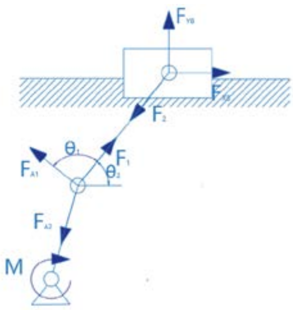


Fig. 5 Force Analysis of Knee Joint Mechanism

Because the friction between the two points of A and B is small, the connecting rod AB can be regarded as a two force rod whose direction of force is along the direction of the rod. A rolling bearing is installed at the O point, and the force acting on the lower leg can only retain the force of the vertical rod and simplify it to a torque M at the O point. The force analysis of the mechanism is shown in figure 5.

The F_1 is decomposed according to the direction along the rod and the vertical rod OA to obtain F_{A1} and F_{A2}, where F_{A2} and torque M produce equal forces at the hinge A, i.e., $F_{A1} = M \times r$. The force F_2 on the slider B can be decomposed into x and y in the direction of F_{AY} and F_{XB}. Thus the equations can be obtained:

$$\begin{cases} F_1 = -F_{A1}\cos\theta_1 - F_{A2}\cos(\theta_2 + \frac{\pi}{2}) \\ F_2 = F_1 \\ F_{XB} = -F_2\cos(\theta_2) \\ F_{A1}\sin(\theta_1) = F_{A2}\sin(\theta_1 + \frac{\pi}{2}) \\ F_{A1} = M \times l_1 \end{cases} \tag{4}$$

2.2 Ankle Joint and hip Joint Structure Design

The ankle and knee only assume the function of simple support and providing relative freedom, and the design should be as simple as possible to ensure that the structure is simple, the quality is light, and the processing is simple.

There is only one degree of freedom in the ankle, and ball bearings are used to provide the support and rotation required. As shown in Fig. 6.

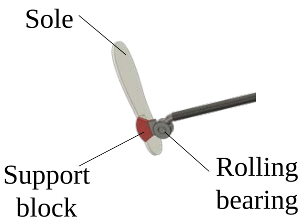


Fig. 6 Ankle Joint Design

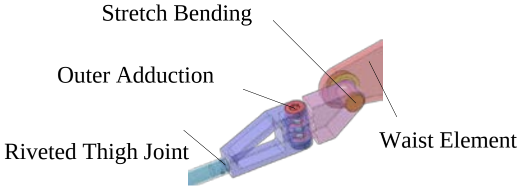


Fig. 7 Sketch of Hip Joint Structure

In this paper, we have designed a lower limb rehabilitation exoskeleton robot with two degrees of freedom, which are outer adduction and extended bending, as shown in Fig. 7.

3. Key Part Finite Element Analysis

Only by using the precise theoretical analysis method, it is often impossible to obtain the exact solution of the complex parts or the force of the mechanism. Therefore, the finite element analysis method can deal with the more complicated structure. In this paper, the finite element analysis software is used to solve the model.

In this paper, the main bearing parts of the knee are selected for analysis. The rocker is mainly used to transmit the driving torque of the knee joint. The model is simplified, leaving only the rocker, spindle and fixed block, which are directly related to the result. The design retains the fixed block in order to make the loading of the joystick more convenient and closer to the real situation.

The simplified model Fig. 8 shows:

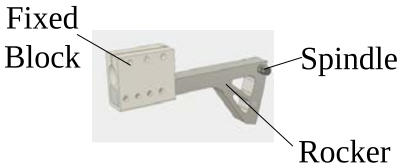
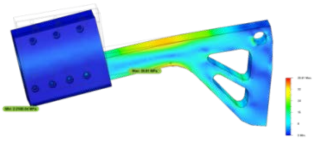


Fig. 8 Simplified model of rocker

The material of the fixed block is ABS plastic, the spindle is 45 steel, the rocker adopts 6061 aluminum, the density is 2.7e-6, the Young's modulus is 6.89e4MPa, the Poisson's ratio is 0.33, the tensile strength limit is 275MPa.The Material is commonly used in the manufacture of robot structural parts, with high strength, high rigidity. The constraints, loads and meshing grids are applied to the model, and the solution is set up and submitted to the calculation. The simulation results of the finite element model are obtained, as shown in Fig. 9 and Fig. 10.



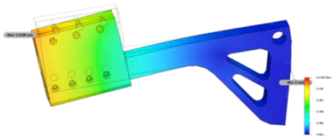


Fig. 9 Robot Knee Joint Rocker Stress Cloud Figure

Fig. 10 Robot Knee Joint Rocker Strain Cloud

The maximum stress occurs at the juncture of the beam and the auxiliary support. The value is 39.81MPa, far less than the tensile strength of 375MPa, and the overall average safety factor is 6.91, which can meet the requirements better. The maximum strain on the beam is 0.336mm, which occurs at the end of the beam.

4. Structure Optimization

From the above analysis results, it can be found that the structural safety factor is higher, which shows that the structure has reduced space. Thus, the blade is optimized using the automatic structure optimization function of the cloud provided by the Autodesk Fusion 360 software. The bar is filled with hollow part, as shown in Fig. 11, so the position of hollow parts can be calculated by the corresponding algorithm, so as to reduce weight.

In the process of optimizing the structure, this paper sets the optimization target of 50%, and then the iterator stops after the quality has changed to half. After that, the methods for generating contacts and grids are the same as before. No more details. Because of the large amount of calculation of the structure optimization, it is difficult to carry on the computation locally, so it is uploaded to the Autodesk cloud settlement machine for calculation. The calculation results are shown in Fig. 12.

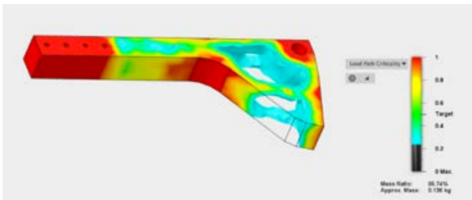


Fig. 11 Sketch of hollow part

Fig. 12 Rocker structural optimization results

As can be seen from Fig. 12, the rocker needs only one attached beam to achieve the required bearing effect, and the weight loss effect is obvious. The quality of the final structure is about 0.136kg and the mass ratio is 65.74%, which can be taken as an important reference for future structural improvement.

5. Conclusion

In this paper, we analyze the modeling of the external skeletal robot from different angles, and design a lower limb rehabilitation exoskeleton robot device. The device has four degrees of freedom, instead of the traditional single degree of freedom turning mechanism. By designing the main components parameters rationally, It has stable performance. In this paper, the finite element analysis of the external skeletal robotic device for lower limb rehabilitation is carried out, and the structural design parameters are optimized. The method of weight reduction and modularization of rehabilitation robot after knee joint surgery is put forward. Robot device and the human body walking attitude has a good follow.

6. Acknowledgements

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