Structural design and modal 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 replacement surgery, and based on ergonomics, the idea of personification design and the basic design idea of force transfer between human body and exoskeleton are discussed, objective to develop a rehabilitation exoskeleton robot for leg rehabilitation after knee joint replacement surgery. The robot can detect the movement trend of the human body, judge the motion intention in use, and promote the movement of the hind leg, so as to achieve the purpose of rehabilitation training of the knee joint. The modal analysis of the lower limb rehabilitation exoskeleton robot is carried out, and the first six order natural frequencies and vibration modes are obtained.

1. Introduction
The design and research of lower limb rehabilitation exoskeleton robot is designed to help the patients with lower limb dysfunction movement to complete the rehabilitation process or to help the patients complete the necessary actions in daily life [1]. Many medical institutions and scientific research institutions at home and abroad currently attach great importance to the research of exoskeleton robot for lower limb rehabilitation, The Federal Institute of technology in Zurich, Switzerland, has developed a rehabilitation training robot LOKOMAT, which can be put into markets [2]. The rehabilitation robot has four degrees of freedom, and uses a weight reduction device and a treadmill to drive the patient to perform gait movements in a reciprocating manner. Nanyang Technology University has developed a 14 degree of freedom gait rehabilitation training robot system, NaTUre-gaits, to assist the hemiplegic patients in walking on the floor. The system can perform rehabilitation training on the basis of the weight reduction mechanism. It can achieve pelvic control, balance control and gait control [3]. The University of Delaware research team has developed a four DOF active exoskeleton robot, ALEX, which proposed a force field controller in conjunction with visual feedback in the control approach, providing additional power to the patient's needs [4]. Zhejiang University has developed a four degree of freedom wearable lower limb exoskeleton system [5][6]. A four degree of freedom gait rehabilitation robot has been developed by Shanghai University. The patient can perform gait rehabilitation training on the treadmill [7][8][9]. However, these devices have many problems, such as bulky structure, difficult control, poor motion coordination, insufficient energy supply time and so on. Moreover, there are few studies on the exoskeleton rehabilitation robot for the rehabilitation of the lower limb after knee replacement surgery in China.

Objective to investigate the needs of rehabilitation training after knee replacement, this paper presents a lightweight new exoskeleton robot for rehabilitation of patients with knee replacement,
which provides the basis for the study of rehabilitation training after knee replacement.

2. Analysis on the Overall Design Requirements of Lower Limb Rehabilitation Exoskeleton Robot

Through the study of the design method of the external skeletal robot of the lower limbs, it is determined that the anthropogenic design idea based on ergonomics is used, and the method of "human-exoskeleton" is based on the binding method of the big leg, soles of the feet and the back Power transmission of the basic design ideas. The whole system is mainly composed of exoskeleton hardware main body, sensor, control system and other peripheral auxiliary equipment. The overall structure of the lower limb exoskeleton robot is shown in Figure 1.

According to the background of the application of the external bone: that is, for patients with knee replacement after bed rehabilitation and postoperative walking to determine the lower extremity exoskeleton robot related design indicators: knee opening degree of $0^\circ$ / $-110^\circ$, the first Stage design load of 20N.m, the maximum angular velocity of $2\text{rad}/\text{s}$ is more convenient to dismantle a certain modular; have a certain dust-proof capacity, the surface easier to clean.

![Figure 1 Rehabilitation of Exoskeleton Robot](image)

2.1. Design of Knee Joint Structure for Rehabilitation Skeletal

The knee is the only drive joint and the focus of the entire exoskeleton design. Figure 2 shows the overall structure of the knee joint using the crank slider mechanism drive unit, using a brushless DC motor drive. Compared with the electric drive mode used in the design, the hydraulic or pneumatic drive has the advantages of simple structure, convenient function and low noise. The working principle is: DC motor through the drive screw on the slider movement, and then in turn drive the connecting rod, elastic body, rocker, which pass the force to the nylon bandage attached to the legs and feet.

![Figure 2 Knee structure](image)

In this paper, a self-locking slider crank mechanism was adopted to avoid the failure of the mechanism and cause the user to fall and improve the safety and reliability of the mechanism. In order to ensure accurate motion, the ball screw pair with small noise and higher efficiency and higher accuracy is adopted in this paper.

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 y-axis direction, as shown in Figure 3 to establish a Cartesian coordinate system. Other symbols are defined as shown in Table 1 below.
Table 1 Parameter Meaning

| Parameter | Meaning               |
|-----------|-----------------------|
| $\theta_1$ | XOA size              |
| $\theta_2$ | XOB size              |
| $x$       | Slider movement distance |
| $r$       | Rocker length         |
| $l$       | Link OB length        |
| $d$       | Crank slider structure offset |

Because the AB at the two points of the friction is small, so you can connect the rod AB a two-pole, its force and direction are along the bar direction. Because the O point is fixed as a rolling bearing, 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 4.

![Figure 3 Brief Analysis of Mechanical Structure of Knee Drives](image)

![Figure 4 Force Analysis of Mechanism](image)

$F_{A1}$ and $F_{A2}$ are obtained by pressing $F_1$ in the direction of the rod and the vertical bar OA, where $F_{A2}$ is equal to the force generated by the torque $M$ at the hinge A and the force $F_1$ on the slider B can be decomposed into $F_{yd}$ in the X and Y directions, $F_{yB}$. So the equations are obtained.

$$
\begin{align*}
F_1 &= -F_{A1} \cos \theta_1 - F_{A2} \cos(\theta_2 + \frac{\pi}{2}) \\
F_2 &= F_1 \\
F_{yA} &= -F_1 \cos \theta_1 \\
F_{yB} &= F_{A1} \sin(\theta_1) = F_{A2} \sin(\theta_2 + \frac{\pi}{2}) \\
F_{yA} &= M \times l_1
\end{align*}
$$

(1)

2.2. Ankle Joint and Hip Joint Design

Ankle joints and hip joints only take a simple support and provide the corresponding degree of freedom of the function, the design should be as much as possible to ensure its simple structure, lighter quality, and processing is relatively simple.

The ankle joint has only one degree of freedom, using a ball bearing to provide the required support and rotation. The schematic diagram of the ankle joint is shown in Figure 5.
Ankle and carbon fiber tube tightening and riveting, to prevent the soles of the feet and the thigh tube rotation. Deep groove ball bearings installed in the bearing seat, outer ring positioning, the other side with the bearing end cap for compression. The inner ring is attached to the shoulder of the connector and the other side is clamped with screws and washers. The foot plate can be made of ABS and other materials made of rubber, the actual support element of the foot is the support block, so it should be made of aluminum.

Exoskeleton hip has two degrees of freedom, they are outside the pendulum adduction and stretch bending, as shown in Figure 6. It is tightly fitted with the thigh part of the pipe, and the use of riveting way for axial positioning.

3. Modal Analysis of Robot as a Whole
In the design of wearable exoskeleton robot structure, it is necessary to analyze the dynamic characteristics of the exoskeleton robot by considering the static characteristics of the structure, which may lead to the irrational design of the external structure of the exoskeleton. When a patient is wearing an exoskeleton robot, it is possible to feel the impact of the road and all kinds of vibration may occur in the parts, which will cause fatigue damage to the exoskeleton robot structure. If the natural frequency of the exoskeleton robot is the same as the motor frequency, resonance may occur, causing the strength of the exoskeleton robot to be damaged and to produce large deformation. Through modal analysis of the exoskeleton robot, we can derive the natural frequency and natural form of the exoskeleton robot structure and determine whether it satisfies the requirements of the exoskeleton robot for its comfortable wear and safety. The life of exoskeleton robot is guaranteed, and the method of safety monitoring, damage identification and maintenance of exoskeleton robot is explored according to the result. Therefore, the modal analysis of lower limb rehabilitation exoskeleton robot is an important step in the product development process [10][11].

3.1. Establishment of Finite Element Model of Lower Limb Rehabilitation Exoskeleton Robot
The whole model is simplified, and the non-structural parts such as motors, motors, supports and sensors are removed. It is not economical to keep these parts unavoidable, and removing these components can reduce the final calculation and calculation time. With the Groups View function, all components are grouped by contact, and parts that are not in contact with each other have different colors, so some of the components are added during the simplification process so that all parts are fixedly attached together.

We set the part spacing to 0.1mm to automatically generate contacts through software. This reduces the error of modeling and the problem of no contact between parts that should be touched by floating point rounding errors between parts with complex surfaces. This reduces the risk of modeling and the problem of parts that have a complex surface that are not in contact with the parts that should be touched due to the floating point rounding error. All parts are bound by contact to limit the slip and separation in all directions.

When there is no external force in modal analysis, all the degrees of freedom of all components need to be fully constrained. When the contact generation is completed, the above requirements can be achieved only by fully fixing the foot plate of the exoskeleton robot, as shown in figure 7.
We set the material properties of each component and divide the grid. Finally, the finite element model of the lower limb rehabilitation exoskeleton robot is set up as shown in Figure 8, and the total number of nodes is 386395, the number of units is 216587, and all the unit shapes are four sides body.

3.2. Modal Analysis Results

The first six order modal shapes of the exoskeleton robot under the condition of no external force are obtained, and the vibration modes of the exoskeleton robot are shown in figure 9.

![First order modal](image1)
![Second order modal](image2)
![Third order modal](image3)

![Fourth order modal](image4)
![Fifth order modal](image5)
![Sixth order modal](image6)

Figure 9 the First Six order modal shapes of Lower Limb Rehabilitation Exoskeleton Robot

The natural frequency of the first six orders of the lower limb rehabilitation exoskeleton robot is shown in Table 2.

| Modal order | Vibration frequency |
|-------------|---------------------|
| First order | 19.7Hz              |
| Second order| 22.4Hz              |
| Third order | 34.4Hz              |
| Fourth order| 49.4Hz              |
| Fifth order | 51.22Hz             |
| Sixth order | 73.41Hz             |

The results of modal analysis show that the first mode vibration is the left and right oscillation, and the maximum strain occurred in the hip joint. The second order mode vibration is the front and rear swing. The third-order modal vibration mode is the distortion of the value axis, and the strain occurs at the knee joint. The fourth order mode vibration is the extension of the front and rear bending. The fifth
order modal vibration mode is symmetrical outreach on both sides of the sagittal plane. The sixth order modal vibration mode is in the sagittal plane, and both sides extend in the same direction.

It can be seen from the vibration pattern that the vibration modes of the lower limb rehabilitation exoskeleton robot are smooth and without mutation. The results show that the bending stiffness of the exoskeleton robot is reasonable and satisfies the requirement of use. The modal analysis results can be used to the damage identification method of the natural frequency and vibration of the applied structure, which pave the way for lower limb rehabilitation exoskeleton robot defect detection. The damage identification method with natural frequency and mode change is high, and the error is small, and the measurement is convenient, and the measurement of natural frequency and model is independent of the structure and force.

4. Conclusion
In this paper, through the analysis of the need for rehabilitation training after knee replacement, a lower limb rehabilitation exoskeleton robot can be designed to assist patients with rehabilitation training. The device has four degrees of freedom, instead of the traditional single degree of freedom turning mechanism. Through the rational design of the main components of the parameters, so that it has a stable performance. The finite element analysis of the external skeletal robotic device designed in this paper is carried out to obtain the first and second natural frequencies and modes of the device in order to avoid the resonance of the exoskeleton robot and the natural frequency of the device, and improve the stiffness of the structure, so as to ensure that the exoskeleton robot in walking with the movement of the body to maintain coordination.

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