Finite element analysis of new lower extremity exoskeleton ankle joint

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Abstract

In order to improve the safety and comfort of human-computer interaction and the adaptability to complex and unstructured environments, a structure based on the combination of active flexible driving and passive compliant structures was designed by analyzing the structure and movement patterns of the human ankle. The degree of freedom of the new wearable ankle joint exoskeleton, and the structure of the three-degrees of freedom of the exoskeleton ankle joint movement reference axis intersect at a point. The passive flexure was achieved by adding a linear spring group to the abductor adduction and external rotation joints, and a series flexible actuator was introduced to the flexion-extension joint to achieve an active flexible drive. The kinematic model and dynamic model with the ankle joint as the center of gravity were established. The overall structure and key components were analyzed and optimized by the finite element analysis software. The flexible performance of the passive joint of the sacroiliac joint was analyzed by the dynamic analysis software. The study verified the rationality and effectiveness of the organization

Keywords

Exoskeleton sacroiliac joint; Flexibility; Statics; Shock resistance.

1. Introduction

The lower extremity exoskeleton robot technology is an emerging technology that has developed rapidly in recent years. It has played an important role in the military, medical, and civilian fields, and has become one of the research hotspots of current robotics. Since the beginning of the 21st century, various technological powers have increased their emphasis on the development of external bone robots, increased the investment in research and development of exoskeleton robots, and developed prototypes of exoskeleton robots that can achieve different functions and tasks and achieved numerous research results . Lower extremity exoskeleton robots can be roughly divided into three categories. The first category is lower extremity exoskeleton robots that enhance human functions. They are mainly used in military and earthquake relief fields, such as BLEEX and XOS. The second category is rehabilitation training for lower extremity exoskeleton robots. The purpose is to assist the doctor in the rehabilitation and restorative training of the limbs of the patient, such as Lokomat; the third type is the lower extremity exoskeleton robot that assists the human body to walk, mainly for assisting the disabled, the elderly and the lower extremity muscle weakness patients to achieve normal walking and improve Their self-care ability, such as HAL, ReWalk.

One of the research focuses of exoskeleton robot is the structural design of hip joint and knee joint and the optimization of joint driving mode. Members and others designed a Four-Degree-of-Freedom wearable hip exoskeleton robot to assist balance and motion, Ronnape and others designed a knee joint of an exoskeleton robot with a cross-four-bar mechanism to store and release energy]. In order to simplify the research, the ankle joint design of most prototypes of exoskeleton robots only considers the human body's single-degree-of-freedom motion on the sagittal plane. Although some prototypes also consider the other two directions of motion, the alignment of the human ankle joint rotation axis and the rotation axis of each direction of the exoskeleton movement is not considered. The problem. This is not conducive to the actual wear and application of exoskeleton robots, and it is a great challenge to the comfort of users.

At present, the ankle joint of exoskeleton robot is mostly located outside the foot. The ankle joint mechanical structure of BLEEX prototype is analyzed and developed by the University of California, Berkeley. In order to realize the drive of bending and stretching motion, the bending and stretching axis are separated from the abduction and adduction axis. There is also a form of Hooker's hinged ankle joint, which enables the abduction and adduction axis to intersect the flexion and extension axis, and is more flexible. You can see that the adduction axis and the rotation axis are outside the foot, and only the flexion / extension axis coincides with the ankle axis. The most prominent research on ankle joint in China is the Walking-Assisted exoskeleton ankle joint of Professor Xiangtan. Although series elastic actuator is added, it only realizes the flexible drive in sagittal plane and neglects the movement in other directions. This is not ideal for the real human-computer interaction effect, and it is not entirely consistent with it. The actual movement mechanism of human ankle joint.

2. Lower extremity exoskeleton ankle design

In the new type of exoskeleton flexible ankle joint device designed in this paper, the abduction-adduction motion and the bending-extension motion intersect the reference axis of the rotation-in-extension motion, and the deviation of the reference axis of the abduction-adduction motion and the bending-extension motion is very small, which can be neglected in the kinematics calculation, so it can be equivalent to the three-degree-of-freedom motion. The moving datum intersect in the ankle joint activity center of the human body.the structure diagram of series elastic driver is composed of DC servo motor, synchronous belt, synchronous pulley, harmonic reducer, flexible transmission module, etc. The DC servo motor is connected in parallel with the harmonic reducer through the synchronous belt to reduce the transverse dimension of the driver. The rigid wheel of the harmonic reducer is fixed by the bracket, and the input drive disc of the flexible wheel and the hybrid drive module is fixed. The input disc compresses six groups of linear springs, and the spring's restoring force is used to drive the output bracket to rotate, so as to realize the flexible output of force and torque. An explosive view of the related parts of the malleolus internal and external rotating structure is shown. The rotating motion is mainly composed of the upper end cover of the malleolus rotating part, thrust bearing, rotating slider, buffer spring and the lower end cover of the malleolus rotating part. The ring of the thrust bearing and the rotary slider is partially confined between the upper end cover of the rotating part of the ankle and the lower end cover of the rotating part of the ankle. The two semicircular bulges under the rotating slider are matched with the middle of the groove on the lower end cover of the rotating part of the ankle so that the rotating slider can rotate at a certain angle. At the same time, in order to improve the impact resistance of the device, two pairs of buffer springs are installed on both sides of the semicircular bulge of the rotating slider. They are located in the groove of the lower end cover of the rotating ankle. Without force, the rotating slider is balanced in the middle. It has a certain position and has a buffering effect on rotational motion.

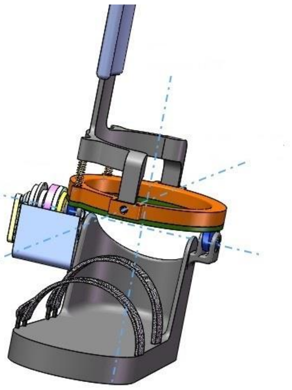

Figure 1 The overall structure of the exoskeleton foot and foot device

Figure 2 Explosion diagram of the external rotation of the internal rotation

3. Exoskeleton robot dynamics modeling

Exoskeleton dynamics primarily analyzes the forces and moments acting on the exoskeleton . The driver can only obtain the desired force and torque to get the desired motion. The Lagrange dynamics method establishes the exoskeleton dynamics equation to obtain the relationship between force, mass and acceleration, and also obtain the moment, moment of inertia and angular acceleration. The relationship between the two, and then get the desired force and torque, choose the right driver. In this paper, only the swing period of the ankle joint is studied, so the model is simplified, and the dynamics modeling of the two-bar linkage composed of the calf rod and the foot is performed. By substituting the ankle joint clinical gait analysis (CGA) trajectory curve into the kinetic model, the true forces and moments acting on the exoskeleton can be obtained.

Exoskeleton kinetic energy：

$$K_1 = \frac{1}{2}m_1(p_1\dot{\theta}_1)^2 + \frac{1}{2}I_{zz1}\dot{\theta}_1^2 \tag{1}$$

$$K_2 = \frac{1}{2}m_2(l_1\dot{\theta}_1)^2 + \frac{1}{2}m_2 p_2^2(\dot{\theta}_1 + \dot{\theta}_1)^2 + m_2 l_1 p_2\left(\dot{\theta}_1^2 + \dot{\theta}_1\dot{\theta}_2\right)c_2 + \frac{1}{2}I_{zz2}\dot{\theta}_2^2 \tag{2}$$

$$\mathrm{K}(q_i,\dot{q}_i) = \frac{1}{2}(m_1 p_1^2 + m_2 l_1^2)\dot{\theta}_1^2 + \frac{1}{2}m_2 p_2^2(\dot{\theta}_1 + \dot{\theta}_1)^2 + m_2 l_1 p_2\left(\dot{\theta}_1^2 + \dot{\theta}_1\dot{\theta}_2\right)c_2 + \frac{1}{2}I_{zz1}\dot{\theta}_1^2 + \frac{1}{2}I_{zz2}\dot{\theta}_2^2 \tag{3}$$

Exoskeleton potential energy：

$$U_1 = m_1 g p_1(1 - c_1) \tag{4}$$

$$U_2 = m_2 g l_1(1 - c_1) + m_2 g p_2(1 - c_{12}) \tag{5}$$

$$\mathrm{U}(q_i) = (m_1 p_1 + m_2 l_1)g(1 - c_1) + m_2 g p_2(1 - c_{12}) \tag{6}$$

Lagrange function:

$$\mathrm{L}(q_i,\dot{q}_i) = \mathrm{K}(q_i,\dot{q}_i) - \mathrm{U}(q_i) \tag{7}$$

Lagrange kinetic equation is：

$$\tau = \frac{d}{dt}\frac{\partial L}{\partial \dot{q}} - \frac{\partial L}{\partial q} \tag{8}$$

$$\tau = \frac{d}{dt}\frac{\partial K}{\partial \dot{q}} - \frac{\partial K}{\partial q} + \frac{\partial U}{\partial q} \tag{9}$$

$$\tau_1 = (I_{zz1} + m_1p_1^2 + m_2l_1^2 + m_2p_2^2 + 2m_2l_1p_2c_2)\ddot{\theta}_1 + (m_2l_1p_2c_2 + m_2p_2^2)\ddot{\theta}_2 - 2m_2l_1p_2s_2\dot{\theta}_1\dot{\theta}_2 - m_2l_1p_2s_2\dot{\theta}_2^2 + (m_1p_1 + m_2l_1)gs_1 + m_2gp_2s_{12} \tag{10}$$

$$\tau_2 = (m_2p_2^2 + m_2l_1p_2c_2)\ddot{\theta}_1 + (I_{zz2} + m_2p_2^2)\ddot{\theta}_2 + m_2l_1p_2s_2\dot{\theta}_1^2 + m_2gp_2s_{12} \tag{11}$$

Collate:

$$\begin{aligned} M(q) &= \begin{bmatrix} I_{zz1} + m_1p_1^2 + m_2l_1^2 + m_2p_2^2 + 2m_2l_1p_2c_2 & m_2l_1p_2c_2 + m_2p_2^2 \\ m_2p_2^2 + m_2l_1p_2c_2 & I_{zz2} + m_2p_2^2 \end{bmatrix} \\ V(q,\dot{q}) &= \begin{bmatrix} -2m_2l_1p_2s_2\dot{\theta}_1\dot{\theta}_2 - m_2l_1p_2s_2\dot{\theta}_2^2 \\ m_2l_1p_2s_2\dot{\theta}_1^2 \end{bmatrix} \\ G(q) &= \begin{bmatrix} (m_1p_1 + m_2l_1)gs_1 + m_2gp_2s_{12} \\ m_2gp_2s_{12} \end{bmatrix} \end{aligned} \tag{12}$$

Considering that human beings have a certain force on the exoskeleton ankle joint and there is friction in the mechanism, the dynamic equation of the exoskeleton ankle joint is obtained.

4. Finite element analysis of exoskeleton ankle joint

In order to verify the bearing capacity of the ankle joint of the lower extremity exoskeleton robot, it is necessary to carry out the mechanical simulation analysis of the ankle joint. The ankle joint of the new lower extremity exoskeleton robot designed in this paper is not in the same line with the big leg and the shank rod because the rotation axis passes through the ankle joint activity center. In this paper, a three-dimensional model is established by SolidWorks, which is imported into the finite element analysis software to analyze the structure. The track curve of ankle clinical gait analysis (CGA) is replaced by the dynamic curve of the upper segment. In the mathematical model, the real force and torque acting on the exoskeleton can be obtained, and the maximum torque is taken as the applied load to determine the designed exoskeleton ankle-foot device to meet the strength requirements.

This section will analyze the overall model of the exoskeleton ankle joint. Figure 1 shows the overall structure of the exoskeleton ankle-foot device. To facilitate analysis, spring, roller bearing and actuator are simplified, and unnecessary chamfers, rounded corners, abduction addendums and material properties of the rotation module are set to alloy steel. In order to reduce the overall weight, the rest of the parts are made of aluminum alloy, the model is 214-T4, its modulus of elasticity is 72.4GPa, Poisson's ratio is 0.33, density is $2800 kg/m^3$, yield strength is 290 Mpa, aluminum alloy has the advantages of light weight, soft, high strength, easy processing, low cost and so on. The contact mode between each part is set to be bound contact, and the mesh is divided. The mesh size is 3.309mm. The total number of mesh elements is 63138 and the total number of nodes is 102935. Fixed the upper end of the legs of the exoskeleton and applied a surface load equivalent to the human body weight plus the lower extremity exoskeleton weight of 800N at the bottom of the shoe. The static stress analysis results are shown in Figure 3 (stress, displacement and strain diagrams from left to right, respectively).

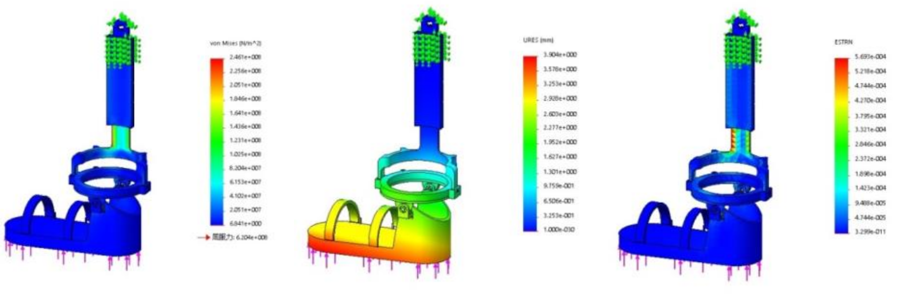

Fig. 3 analysis of exoskeleton ankle foot model

The simulation results show that the maximum stress of the abduction-in-addendum at the ankle is 246.1 MPa, which is much less than the yield strength of alloy steel 620.4 Mpa and aluminum alloy 290 Mpa. The phenomenon of stress concentration is also solved. The maximum displacement and deformation of the component appear at the sole of the shoe is 3.90 mm, which meets the strength requirements of the material. Range. In order to make the foot wear comfortable, the rear part of the foot can be made of aluminum alloy skeleton, the exterior is attached with hard plastic, the front and sole are rubber materials, playing a cushioning role.

5. Conclusion

(1) The kinematic principle and research status of the ankle joint of exoskeleton robot are analyzed, and a new type of three-degree-of-freedom exoskeleton ankle joint device is designed. The passive flexible joint is on the horizontal and coronal plane, and the active flexible joint is on the sagittal plane.

(2) The kinetics of lower extremity exoskeleton was analyzed with the ankle as the center of gravity, and the simplified model of ankle kinetics was established.

(3) Finite element analysis of the key components and the whole model of the new exoskeleton ankle joint was carried out, and the analysis results were improved and optimized.

In the follow-up study, the experimental prototype will be built on the basis of this paper, focusing on the joint flexibility performance, motion efficiency characteristics, fast tracking characteristics and boost effect compared with the simulation results. Further optimize the structure design and determine more accurate structural parameters.

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