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Structural Design and Analysis of Lower Limb Exoskeleton Robotics

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Abstract

With the acceleration of the global aging process and the increase of cardiovascular an cerebrovascular diseases, more and more patients are paralyzed due to accidents, so the exoskeleton robot began to appear in people's sight, and the lower limb exoskeleton robot withrehabilitation training is also favored by more and more people. In this paper, the structural designand analysis of the lower limb exoskeleton robot are carried out in view of the patients' expectation ofnormal walking. First, gait analysis and structural design of lower limb exoskeleton robot. Based onthe analysis of the walking gait of normal people, the freedom of the three key joints of the lower limbexoskeleton robot hip joint, knee joint and ankle joint is determined. at the same time, according tothe structural characteristics of each joint, the three key joints are modeled respectively, and theoverall model assembly of the lower limb exoskeleton robot is completed. Secondly, the kinematicsanalysis of the lower limb exoskeleton robot was carried out to obtain the relationship between thelinear displacement, linear speed and acceleration of each joint, so as to ensure the coordination ofthe model with the human lower limb movement. Thirdly, the static analysis of typical gait of hipjoint, knee joint and ankle joint is carried out to verify the safety of the design model under thepremise of ensuring the structural strength requirements. Finally, the parts of the model were 3Dprinted, and the rationality of the design was further verified in the process of assembling the model.

Keywords: *Exoskeleton Robots; Mechanical Structure Design; Finite Element Analysis; Motion Simulation*

1 Introduction

With the development of society, human demand for material and spiritual needs is increasing day by day. People may suffer injuries in some traffic accidents or sports, and some injuries are irreversible to the body. Spinal injuries can cause many people to be unable to carry out daily life or even walk. For example: paraplegia. Paraplegic patients generally experience paralysis of both lower limbs, sensory disorders below the corresponding plane of injury, autonomic nervous system dysfunction, and other problems. Many patients may become bedridden due to complications caused by not actively implementing scientific and effective treatment plans, and rely entirely on the help of others to complete daily life. With the development of science and technology, more and more rehabilitation training robots have entered rehabilitation centers, and the development of such robots has given hope to patients and their families. The main users of existing lower limb exoskeleton rehabilitation robots include postoperative patients, elderly people, chronic diseases, etc. Taking knee joint surgery patients as an example, if good rehabilitation training is not provided to the patients, surgical complications such as joint adhesion and stiffness may occur. With the increasing severity of China's aging problem, the elderly population will gradually face problems such as inability to take care of themselves, chronic diseases, cardiovascular diseases, etc. The rehabilitation needs of the elderly population are constantly increasing. In the near future, open training for the elderly will become one of the mainstream groups in the medical rehabilitation market.

The lower limb exoskeleton rehabilitation robot is a wearable device used for rehabilitation training, which can provide postoperative rehabilitation training for elderly and disabled patients. The lower limb exoskeleton robot not only retains the advantages of bipedal walking robots, but also utilizes the human body's main control ability and advanced sensing technology to solve traditional drawbacks such as poor walking stability and lack of walking planning ability. It not only has the effect of protecting and supporting the human body, but also can provide appropriate force compensation to the wearer through the driving device, thereby improving various indicators such as human strength.

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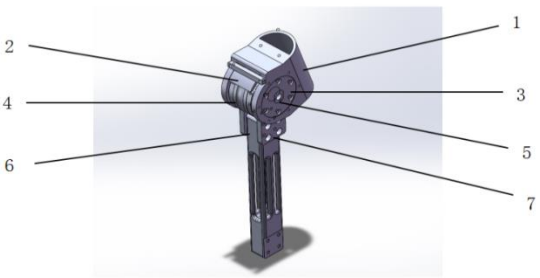
2 Model Establishment of Lower Limb Exoskeleton Robotics

As an auxiliary equipment for patient rehabilitation training, lower limb exoskeleton robots need to meet the requirements of analyzing the structure and movement status of healthy human bodies, while also being designed and calculated according to the principles of bionics. Based on the existing simplified model of human lower limb joints, the following conclusions can be analyzed:

The hip joint is a ball and socket joint that performs flexion, rotation, and lateral movements in the sagittal, coronal, and horizontal planes of the human body; Knee joint master's hinge joint, usually performing flexion and extension movements in the sagittal plane; The structure of the ankle joint is similar to that of the hip joint, which is also a ball and socket joint. It can flex, extend, and flip in the sagittal, coronal, and horizontal planes of the human body.

2.1 Hip joint design

As the main joint component connected to the lumbar support and lower limbs, the hip joint needs to ensure the same motion characteristics as the human body and the overall coordination of the lower limb exoskeleton robot. Therefore, in the design of the hip joint, two femoral connection plates are used to connect it to the main leg, and the joint movement is completed on the inner side of the hip joint through the cooperation of shafts and bearings. Finally, due to the limitation of wide joint flexion motion, a joint limit plate is added on its joint support frame, as shown in Figure 1.

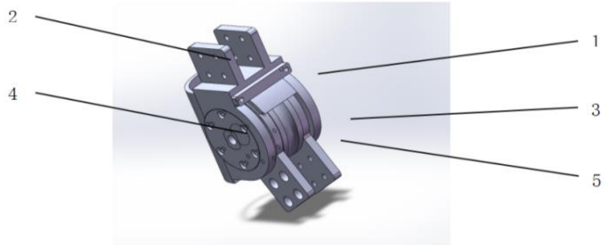


1-Hip joint support frame; 2-Hip joint limit; 3-Hip joint axis fixation plate; 4-Hip joint turbine; 5-Hip joint axis; 6-Thigh; 7-Femoral connecting plate

Figure 1 Hip joint model diagram

2.2 Knee joint design

The knee joint, as the middle part of the lower limb structure, plays a connecting role, and its movement direction is opposite to the direction of the hip joint's support frame. The fixed plate on the support frame is connected to the thigh, and the lower leg is connected to the tibia connecting plate. The lower leg can meet the rotation requirements through the cooperation of the shaft and bearing. During the movement of the knee joint, due to the angle limitation, a limit is added on the support frame of the knee joint to meet its movement requirements, as shown in Figure 2.

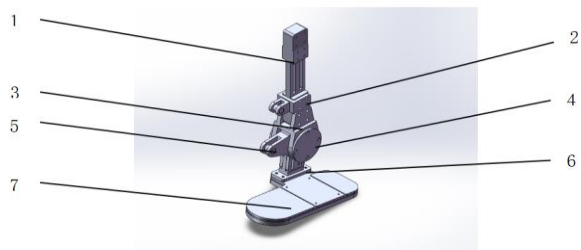


1-Knee joint limit; 2-Knee joint support frame; 3-Tibial connecting plate; 4-Knee joint axis; 5-Knee joint turbine

Figure 2 Knee joint model diagram

2.3 Ankle joint design

The ankle joint of the human body is the most complex component among the three key joints. There are many factors that need to be considered in the structural design of the ankle joint. For example, as the joint component with the smallest range of movement, the connection between the foot pedal and the ankle joint should not only rely on shafts and bearings for driving. At the same time, spring support frames need to be added at the ankle joint movement and lower leg parts. During the patient's use, springs with different elastic coefficients can be changed by restoring the situation, as shown in Figure 3.



1-shank; 2-Ankle joint spring support; 3-Ankle joint support frame; 4-Ankle joint bearing end cap; 5-Ankle joint rotation axis transition plate; 6-Foot connection plate; 7-Foot board

Figure 3 Ankle joint model diagram

2.4 Overall design of lower limb exoskeleton robot

After designing three key joints, assemble them as a whole and draw the adjustable lumbar spine of the lower limb exoskeleton robot, as shown in Figure 4.

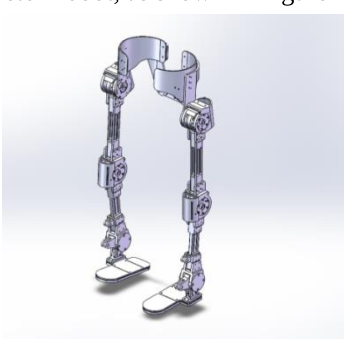


Figure 4 Overall assembly diagram

In the process of designing the joint range of motion for the entire lower limb exoskeleton robot, considering the safety of future use, limit plates are used to control the joints at each joint to ensure that they are within a reasonable range of motion and prevent secondary injuries to patients due to excessive movement amplitude, as shown in Table 1.

Table 1 Range Table of Three Joint Movement States

Joint	Motion	Safe Range(°)
Hip Joint	Swing	-5~5
	Rotate	-5~5
	Buckling	-20~35
Knee Joint	Buckling	-5~90
Ankle Joint	Buckling	-15~10

3 Kinematic Analysis of Lower Limb Exoskeleton Robot

3.1 Analysis of Hip Joint Movement

The thigh is connected to the tibial connection plate and assembled together with the hip joint, so in Solidworks' motion calculation column, motion analysis is performed through plugins. Add motor plugins to the existing joints, select the outermost vertex of the femur and the realization of the femur tibia connection plate as simulation units to generate the required corresponding result graph, as shown in Figure 5.

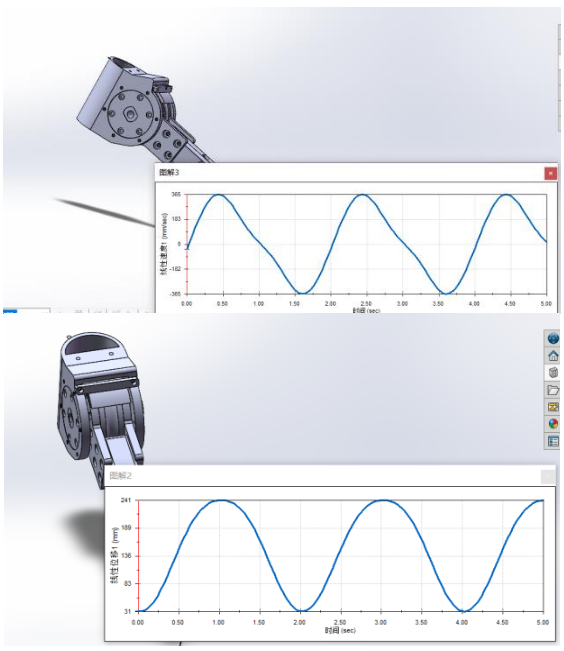


Figure 5 Linear displacement and linear velocity diagram

From the trajectory of the hip joint and calf, it can be concluded that the movement of the thigh forms a fan-shaped distribution centered on the hip joint axis. The distribution of linear displacement exhibits periodicity, with a period of 2 seconds, and the displacement reaches its highest point at 1 second. In the analysis of linear velocity graphs, the graphical pattern also exhibits periodic changes, reaching the first peak of 365 (mm/sec) at approximately 0.5 seconds and the lowest value of -365 (mm/sec) after 1 second.

3.2 Analysis of Knee Joint Movement

Due to the lack of connection with the thighs and calves, only the relevant data analysis of the tibial connection plate will be analyzed in this section. In the Motion analysis process of Solidworks, the lower end of the tibial connection plate and the upper end of the connection plate were selected as the corresponding point points to generate the required corresponding rendering, as shown in Figure 6.

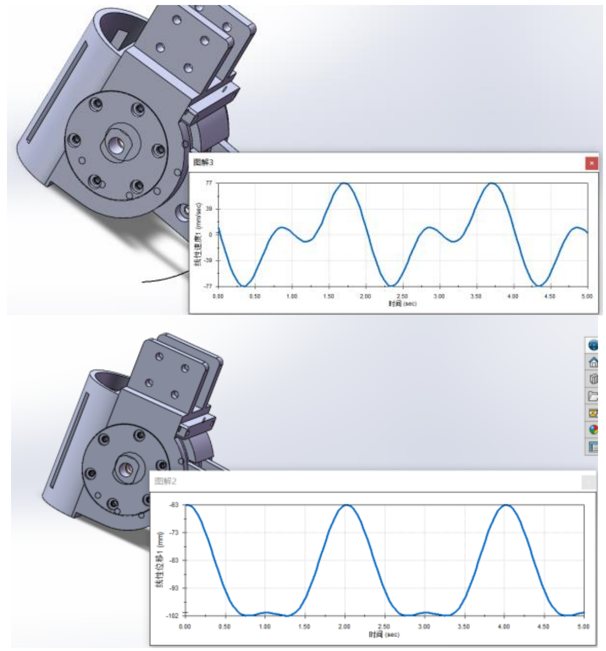


Figure 6 Linear displacement and linear velocity diagram

From the trajectory analysis diagram of the knee joint, it can be seen that the fan-shaped motion trajectory is formed at the lower end of the tibial connecting plate with the knee joint axis as the center. The diagram of linear displacement shows that during the movement of the knee joint, a cycle is formed every 2 seconds, and a peak value of -63mm is formed at the 2nd second; A continuous trough of -102mm occurs between 0.75 and 1.25 seconds, with a small peak forming at approximately -100mm at 1 second. In the analysis results of linear velocity, a period of 2 seconds is also formed. However, unlike linear displacement, linear velocity forms a slightly irregular graphical display, with a highest peak at 1.75s, approximately 77 (mm/sec), and a lowest peak at 0.3s, -77 (mm/sec).

3.3 Analysis of Ankle Joint Movement

In the analysis diagram of the ankle joint, the main research object is the movement of the foot. Therefore, in the Motion analysis process of Solidworks, the position where the front end of the foot and the foot plate are connected to the fixed plate are used as the point points in this study to generate the main analysis diagram, as shown in Figure 7.

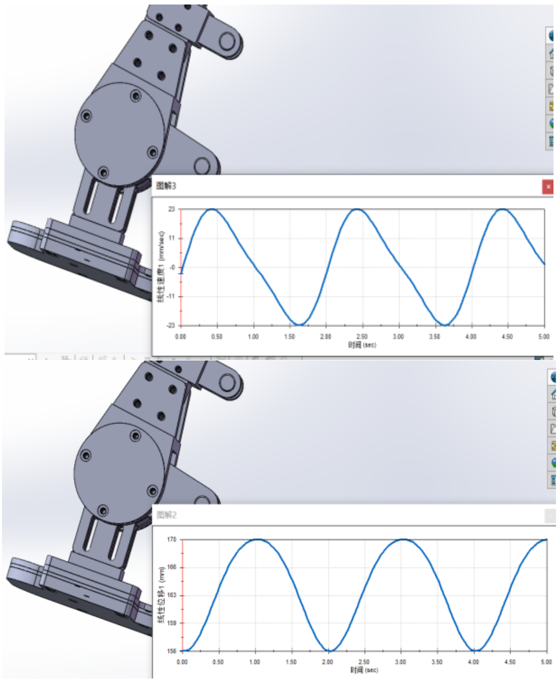


Figure 7 Linear displacement and linear velocity diagram

From the perspective of ankle joint movement trajectory, foot motion analysis is based on the selected front end of the foot as the analysis point and the ankle joint axis as the radius to generate the motion trajectory. According to the linear displacement analysis of the ankle joint, there is a periodic and regular change within 2 seconds, with only one peak and one minimum value in each cycle. The linear displacement of the highest point is 170mm, and the linear displacement of the lowest point is 156mm. The linear velocity of the ankle joint and foot varies regularly with a period of two seconds, with a maximum value of 23 (mm/sec) at around 0.4 seconds and a minimum value of -23 (mm/sec) at 1.6 seconds.

Table 2 Table of Linear Displacement and Linear Velocity Results for Three Key Joints

Joint	linear displacement (mm)			linear speed (mm/sec)		
	cycle	highest point	lowest point	cycle	highest point	lowest point
Hip Joint	2	241	31	2	365	-165
Knee Joint	2	-63	-102	2	77	-77
Ankle Joint	2	170	165	2	23	-23

4 Static Analysis of Leg Structure of Lower Limb Exoskeleton Robot

Based on the experimental subject (an adult male with a height of 175 and a weight of 60 kilograms) as a reference, this reference is used as the basic data for static analysis. Using the knee joint as the starting point of force and the hip joint as the fixed part in the static analysis of the thigh; In the static analysis of the calf, the ankle joint is used as the fixed part.The knee joint is used as the main force-applying part, and forces are applied in both horizontal and rotational directions to mimic the movement of the knee joint during human movement.At the same time, the hip and ankle joints are used to fix the thigh and calf, and the connection between the upper and lower legs of the lower-limb exoskeleton robot and the joints is used as a fixed point to ensure the restoration of the human form during movement.

4.1 Static analysis of thigh

The two sides of the thigh are symmetrically shaped, so one section serves as the connection with the knee joint, while the other end serves as the connection with the hip joint.

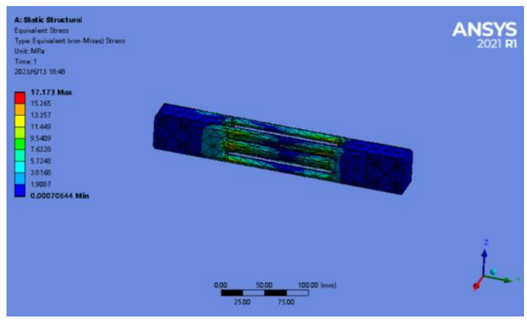


Figure 8 Distribution diagram of rotational stress

Due to the greater relative mobility of the knee joint in the human body, this analysis considers the knee joint as the main active area and adds fixed constraints to the hip joint contact area. Add a force of 90 rad/s rotating inward on the surface connecting the thigh and knee joint, and finally obtain the stress distribution diagram as shown in Figure 8. The stress distribution ranges from 0.0007 to 17.17 (MPa), with uniform stress distribution and high safety.

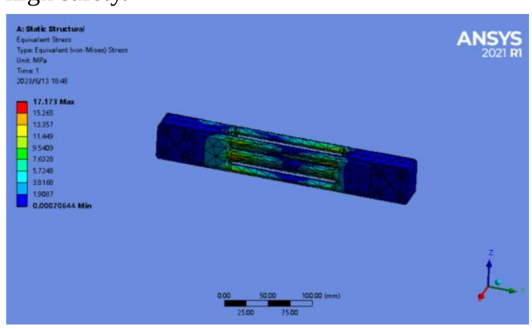


Figure 9 Horizontal stress distribution diagram

Under the condition of ensuring the hip joint connection remains unchanged, a horizontal force of 1.2 MPa is added to the knee joint force point according to the direction, and the stress distribution map is finally analyzed by software, as shown in Figure 9. The maximum stress distribution is 0.007～238.74 (MPa), with uniform stress distribution and high safety.

4.2 Static analysis of calf

The calf, like the thigh, has the knee joint as its main active joint. The connection between the lower leg and ankle joint serves as the fixed point for analysis, while the connection between the knee joint and lower leg serves as the loading point. A rotational force of 90 rad/s is applied at this point for final analysis, resulting in a stress distribution diagram as shown in Figure 10. The stress distribution is 0.001～20.00 (MPa), with uniform stress distribution and high safety.

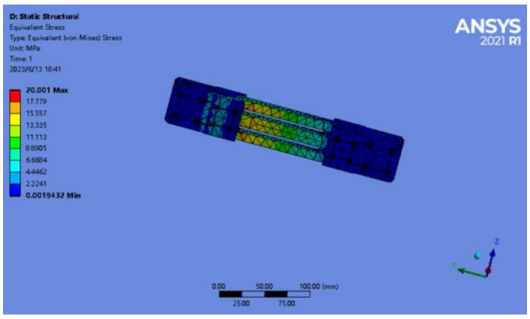


Figure 10 Distribution diagram of rotational stress

Under the condition of ensuring that the ankle joint serves as the force point without applying any loading force, a horizontal force of 12MPa is applied to the knee joint connection area, and the corresponding stress distribution diagram is finally analyzed, as shown in Figure 11. The stress distribution is 0.98-395.6 (MPa), with uniform stress distribution and high safety.

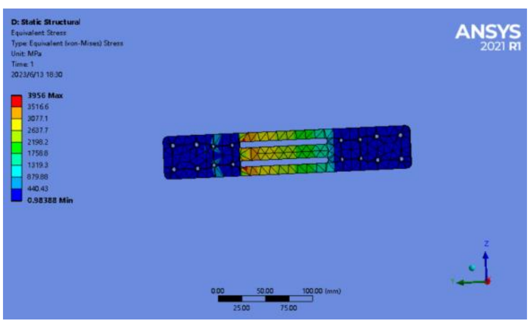


Figure 11 Horizontal stress distribution diagram

5 Additive Manufacturing of Lower Limb Exoskeleton Robots

5.1 Printing process

Save the modeled parts to STL format and use the slicing software CHITUBOX to perform slicing preprocessing, as shown in Figure 11. Set the exposure time of the bottom layer to a reasonable range value. If the exposure time is too high or too low, it will cause the printed part to be not firmly attached, resulting in printing failure.

Figure 11 Slice parameters

During the process of placing the parts, move them into the 3D printer and raise the entire part by about 5mm to facilitate the fixation of the support body. Adjust the automatic support auxiliary material settings of the software and manually add them in areas with insufficient supportFinally, set the printing parameters for printing, as shown in Figure 13.

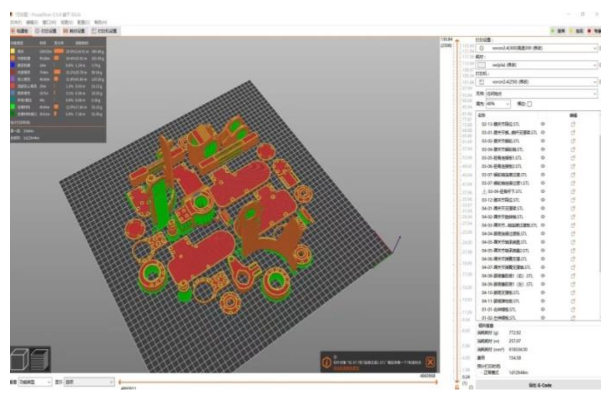


Figure 12 Model placement and printing parameters

After printing is completed, the support of the parts is removed and all parts are assembled into a complete lower limb exoskeleton robot, as shown in Figure 13.

Figure 13 Physical display

6 Conclusion

This article analyzes the design of lower limb exoskeleton robots. Through investigation and analysis of the existing social situation, it is found that there are many people in the world who need the help of exoskeletons to achieve their dreams of walking. At the same time, research on the development and production of lower limb exoskeleton robots at home and abroad has found that there are still many problems. Therefore, in this design, the lower limb exoskeleton robots will be redesigned and optimized. The following results are obtained from summarizing the entire text:

(1) Complete the analysis of normal human lower limb movement. Determine the motion status and degrees of freedom of the hip, knee, and ankle joints in a normal human body, and construct the required mechanical models based on the structural characteristics of each joint. Use Solidworks software to build and assemble the models.

(2) Conduct kinematic analysis on the three joints of the lower limb exoskeleton robot. Generate motion trajectories, linear displacements, and linear velocities of the hip, knee, and ankle joints through the motion calculation section in Solidworks software to ensure the overall motion coordination of the model.

(3) Using Ansys Workbench software, typical gait statics analysis was conducted on the hip, knee, and ankle joints, and the force analysis diagrams of the two legs were finally obtained. The safety of the model was also verified while ensuring that the strength requirements were met.

(4) Model printing of lower limb exoskeleton robots. The existing 3D printing technology was used to print the model at a 0.5x magnification and assemble it, further verifying the rationality of the model design.

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References

[1] Hybart Rachel, Ferris Daniel P. Embodiment for Robotic Lower-Limb Exoskeletons: a narrative Review. [J]. IEEE transactions on neural systems and rehabilitation engineering : a publication of the IEEE engineering in medicine and biology society, 2022,(11):22-25.

[2] Dao Quythinh, Dinh VanVuong, Trinh. Nonlinear Extended Observer-Based adrc for a lower-limb pam-based Exoskeleton [J]. actuators, 2022,11(12).111-115

[3] Sarajchi Mohammadhadi,alHares Mohamad Kenan,Sirlantzis Konstantinos. Wearable lower-limb exoskeleton for children with cerebral palsy. [J]. IEEE transactions on neural systems and rehabilitation engineering: a publication of the IEEE engineering in medicine and biology society, 2021(12):35-37.

[4] Boonekamp Francine J, Dashko Sofia,Duiker Donna,Gehrmann. Design and experimental evaluation of a minimal, Innocuous watermarking strategy to distinguish near-identical dna and rna Sequences. [J]. acssynthetic biology, 2020,9(6):35-38.

[5] Narina Ramesh, Iwaniec Marek, arawade Swapnil. Present and future of assistive robotic lower limb exoskeletons [J]. Matec web of conferences, 2022(357):46-49.