Research on Lower Extremity Exoskeleton System Based on Elastic Energy Storage Components

Kai Guo, Shasha Zhao, Bin Liu, Yongfeng Liu, Yingying Zhang and Hongbo Yang

Suzhou Institute of Biomedical Engineering and Technology, Chinese Academy of Sciences, Suzhou 215163, China
Email: guok@sibet.ac.cn

Abstract. In this paper, we study the field of rehabilitation walker technology. The passive energy storage gravity support exoskeleton is suitable for patients with lower limb dysfunction or limited function caused by lower limb joint, muscle tissue damage or bone disease. The equipment studied in this paper can assist patients to carry out normal ground walking and up and down stairs, realize patient self-care, slow down the patient’s physiological pain, and reduce the economic and energy burden of the patient’s family members. As the proportion of the elderly population continues to rise, the physiological decline during the aging process makes the elderly’s limbs less flexible, with limb motor dysfunction and lower limb motor dysfunction. Manual laborers have long been engaged in labor with repetitive and long working hours. It is easy to cause occupational chronic musculoskeletal injuries or other occupational diseases by maintaining the same or improper working posture for a long time.

1. Introduction
Patients with lower limb dysfunction will cause changes in muscle, tendon and connective tissue characteristics due to long-term inability to move the lower limbs, resulting in muscle stiffness and muscle atrophy. Occupational musculoskeletal injury has become an urgent problem for occupational economic compensation and occupational safety and health in Western countries [1, 2]. The occupational musculoskeletal injuries of manual laborers in China are also high, with a prevalence rate of 20% to 90%. In the electronics, construction, metallurgy, automotive and machinery manufacturing industries, the lower extremity exoskeleton robots play an irreplaceable role [3-6]. It can not only meet the needs of patients with lower limb dysfunction, but also provide the support and protection of physical laborers in heavy physical labor, thus reducing common labor injuries [7, 8].

This project plans to develop a passive energy storage gravity support lower extremity exoskeleton device, as shown in figure 1. The device not only has the function of supporting the lower limbs, but also has the function of assisting walking with passive energy storage. The device can assist patients with limited lower extremity function caused by lower extremity joints, muscle tissue damage or bone diseases to carry out energy-saving walking, and reduce lower limb labor injuries of workers who have repetitive movements, long working hours or forced positions.
Gravity assisted support
Infinitely variable stiffness energy storage component
Plantar pressure monitoring system
Ankle joint
Knee joint
Hip joint

Figure 1. The passive energy storage gravity support lower extremity exoskeleton device.

2. Research Content of Lower Extremity Exoskeleton
The lower extremity exoskeleton system studied in this paper involves more techniques. It mainly includes: human lower limb anatomy technology, human body lower limb motion biomechanical modeling and simulation technology, lower extremity exoskeleton and human lower limb coupling simulation analysis technology, lightweight design technology, weight assisted support and detection technology, and spring stepless variable stiffness technology.

2.1. Study on the Physiological Structure of Human Lower Limbs and the Degree of Freedom of Exoskeleton Joints
Study the bone structure of the lower limbs hip, knee and ankle, the structure of the muscle ligament, and the range of motion of each joint. The wearer’s walking is used as the research object to study the human gait cycle, and the movement characteristics of each joint during walking. According to the gait cycle and the motion characteristics of each joint, the degrees of freedom of the three joints of the lower extremity exoskeleton system are reasonably configured.

The degrees of freedom and corresponding objects of the three joints of the lower extremity exoskeleton system are shown in figure 2.

Figure 2. Degrees of freedom and corresponding objects of the three joints of the lower extremity exoskeleton system.

2.2. Biomechanical and Exoskeleton Kinematics Dynamics Modeling and Simulation Analysis of Human Lower Extremity
Establish a biomechanical model of human lower extremity motion, as shown in figure 3, and perform simulation analysis of kinematics and dynamics models. Study the motion characteristics of the human body under different motion states, and provide a theoretical basis for the structural design and positional arrangement of the energy storage components.
Figure 3. Biomechanical model of human lower extremity motion.

The kinematics and dynamics model of the lower extremity exoskeleton was established, and the simulation analysis was carried out to study the movement characteristics of the lower extremity exoskeleton. The coupling simulation analysis of the lower extremity exoskeleton and the lower extremity of the human body was carried out to study the assisting and perturbation effect of the lower extremity exoskeleton on the lower limbs of the human body under different movement states.

2.3. Gravity Assisted Support and Plantar Pressure Detection

The exoskeleton gravity assisting support device is designed to assist the wearer’s weight to reduce the load on the affected limb. The gravity assisted support condition is monitored in real time by the pressure sensor of the sole and wirelessly transmitted. The pressure collection device for the sole is shown in figure 4.

Figure 4. The pressure collection device for the sole.

2.4. Lower Extremity Exoskeleton Performance Test and Patient Metabolic Consumption Test

Reasonably arrange the position and number of energy storage components in the moving parts of each joint. Through the energy storage component, the energy of the joints of the lower limbs is cyclically stored and released in one gait cycle, thereby achieving the effect of assisting walking. The amount of stored energy of the energy storage component can be adjusted for different wearers to meet the individual adaptability and comfort requirements of the wearer.

The performance test of the prototype of the lower extremity exoskeleton joints, stepless variable stiffness energy storage components. Complete the metabolic consumption test of the patient wearing the lower extremity exoskeleton for flat walking, up and down stairs, and the gravity assisted support test.

3. Structural Design and Arrangement of Stepless Variable Stiffness Energy Storage Components

According to the AnyBody software simulation, the movement characteristics of the human body under different motion states are analyzed, and the motion characteristics when walking on the ground are shown in figure 5.
Figure 5. The motion characteristics when walking on the ground.

According to the simulated motion characteristics, one energy storage component is arranged in the joint parts of the hip, knee and ankle. The moving part of the hip joint stores energy when it is extended, and the moving part of the knee stores energy during flexion. The moving part stores energy during dorsiflexion, as shown in figure 6.

Figure 6. The moving part stores energy during dorsiflexion.

A cylindrical spiral compression spring is used as the energy storage component of the stepless variable stiffness energy storage component. The outline drawing and internal structure of the energy storage component are shown in figure 7.

According to the principle of the screw transmission, the hand wheel is rotated, the spiral rotation occurs between the rotating shaft and the spring, and the effective working number n of the spring changes, thereby realizing the stepless change of the spring stiffness K.

Figure 7. The internal structure of the energy storage component.
4. Conclusion
The existing lower extremity exoskeletons are basically driven, and each joint is equipped with a driving device. Each exoskeleton is equipped with an energy pack, and often these drives and energy packs (batteries, hydraulic pumps, air pumps) occupy most of the exoskeleton weight. Not only increases the size, weight, power consumption of the exoskeleton and the performance requirements of the drive device, but also causes the system to run out of control and the wearer to fall when the exoskeleton fails, which jeopardizes the safety of the wearer.

Studies have shown that the elastic energy storage elements used in this paper are also crucial for the walking of the biped robot. The lower extremity exoskeleton of the spring energy storage device can greatly reduce the energy consumption of the wearer during walking.

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