Design and analysis of a lower extremity exoskeleton with the humanoid knee joint

Tingting Li¹,², Jian Li¹,²,³, Zhonghua Han¹,², Jiechao Yang¹,² and Qiang Li¹,²

¹First Research Institute of the Ministry of Public Security of PRC, Beijing 100048, China
²Beijing Zhong-Tianfeng Security Protection Technologies Co., Ltd, Beijing 100048, China
³E-mail: 13811582306@163.com

Abstract. Exoskeletons should have certain capabilities and characteristics such as human performance enhancement, low impedance and comfortable. In this paper we present a lower extremity exoskeleton. In order to achieve the characteristics of exoskeletons mentioned above we choose the Series Elastic Actuator (SEA) as its driver. A novel humanoid knee joint is introduced into the exoskeleton to improve the coordination between exoskeleton and human body during work progress. A stable control method is proposed to achieve the exoskeleton joint following motion. Finally, the feasibility of control algorithm is verified by simulation.

1. Introduction

As a representative of human-machine interaction robot, exoskeletons as immediate areas of research focus developed rapidly in recent years. Hardiman [1] developed by Cornell University and General Electric Co. can be regarded as the first real attempt of exoskeleton robot. Limited by the technological conditions at that time, Hardiman had no practical application value. After a long period of development, many kinds of exoskeletons have been developed. For example, there are the Berkeley Lower Extremity Exoskeleton (BLEEX) [2] developed by University of California, Berkeley, the Human Universal Load Carrier (HULC) [3] developed by Lockheed Martin, the Mina and X1 [4] [5] developed by NASA, the Hybrid Assistive Limb (HAL) [6] developed by University of Tsukuba and Cyberdyne.

For exoskeleton robots that need to interact with human body, the safety and comfort are particularly important. Therefore, the compliant actuators are introduced into exoskeleton robots. For example, there are the lower extremity powered exoskeleton (LOPES) [7] developed by University of Twente, the Roboknee [8] developed by Yobotics, Inc., the Wilmington Robotic Exoskeleton (WREX) [9] developed by University of Delaware. Series Elastic Actuator (SEA), introduced into our design in this paper, proposed by Pratt [10] has characteristics of low impedance, high force-fidelity and good bandwidth of actuators enabled the exoskeleton control algorithm.

According to anatomical description of knee joint movement proposed by Freudenstein et al. in 1969 [11], the flexion and extension of knee joint is generated by relative movement between femur and tibia, the instantaneous rotation center of knee joint changes with the rotation of knee joint. But at present researches, most exoskeleton robots use the single-axis rotation knee joint with a fixed rotation center, which causes exoskeleton robots to be unable to adapt to the changes of human knee joint during work process. To solve this problem, a novel humanoid knee joint is introduced into this paper.
The rest of this paper is organized as follows. Section 2 introduces the design of the exoskeleton with humanoid knee joint. Section 3 introduces the control algorithm of exoskeleton system. Therefore, the feasibility of control algorithm is verified by simulation in Section 4.

2. Design of the exoskeleton

The exoskeleton is designed as shown in Figure 1, it consists of thigh components, calf components, SEA and humanoid knee joint. The abstract model of exoskeleton is shown in Figure 2.

![Figure 1. The exoskeleton mechanism](image1)

![Figure 2. The abstract model of exoskeleton.](image2)

According to the abstract model of exoskeleton cosine theorem, we can get the following equations:

\[
L = \sqrt{r^2 + l_1^2 - 2rl_1 \cos(\pi - \alpha_1)}
\]

\[
\alpha_j = \arccos\left(\frac{l_1^2 + L^2 - r^2}{2Ll_1}\right)
\]

The SEA driving force can be obtained by the following formula:

\[
F = \frac{\tau_{\text{ankle}}}{r \sin \alpha} = \frac{Ks(\alpha - \alpha_i)}{r \sin \alpha}
\]

2.1. Series elastic actuator

At present researches, the widely used driving modes of exoskeletons can be divided into: hydraulic actuator, pneumatic muscle actuator and motor driver. The hydraulic actuator has the advantages of large driving force and direct driving mode, but the complex and huge hydraulic components do not meet the requirements of the exoskeleton we designed. The pneumatic muscle actuator has the advantages of compliance driving and direct driving mode, but the pneumatic muscle actuator is difficult to control and the drive force of the pneumatic muscle is difficult to meet requirements of our design. Considering the requirements of actuator weight and actuator driving force, we choose the motor driver as the exoskeleton actuator. For the exoskeleton, cooperate with human body, safety and comfort between the exoskeleton and human interaction are the core requirements. Therefore, series elastic actuator (SEA) [10], proposed by Jerry Pratt et al., is selected in this paper, as shown in Figure 3. The schematic diagram of the series elastic actuator [12] is shown in Figure 4.
2.2. Humanoid knee joint

As the most complex and largest joint of the human body, the knee joint is composed of two joints: femoral tibiofemoral joint and patellofemoral joint, mainly including joint capsule (ligament), distal femur, patella, proximal tibia, meniscus, anterior cruciate ligament (ACL) and posterior cruciate ligament (PCL). Figure 5 shows the anatomy of knee joint. In 1969, Freudenstein, et al. proposed an anatomical description of knee joint movement. In the sagittal plane, knee joint has more than one degree of freedom. The instantaneous rotation center (ICR) of human knee joint is shown in Figure 6.

As we can see from Figure 6, the instantaneous rotation center changes with the rotation of knee joint. But at present researches, most exoskeleton robots use the single-axis rotation knee joint with a fixed rotation center, which causes exoskeleton robots to be unable to adapt to the changes of the human knee joint during work process. And prolonged use the exoskeleton robots will cause problems such as uncomfortable wearing and soft tissue contusion. In this paper, a novel bio-inspired humanoid knee joint, as shown in Figure 7, is designed to solve this problem.

The humanoid joint is mainly composed of two parts: calf connector and thigh connector. The curved guide rail is designed according to the knee joint movement trajectory, it can make the
exoskeleton robot knee joint rotation match the human knee joint. The humanoid knee joint axis moves in the sliding guide rail to adapt to the change of rotation radius and center of the knee joint during rotation. It is worth noting that the meniscus, which is a component of human knee joint, plays an important role in knee joint movement. In addition to absorbing shocks, increasing joint contact surface and lubricating joint, the meniscus also has functions of bearing load, dispersing load and maintaining joint stability. In the humanoid knee joint, the compression springs play a similar role to the meniscus of human knee joint.

**Figure 7.** The structure of humanoid knee joint.

**Figure 8.** Overall framework of the exoskeleton robot distributed control system.

3. Control architecture
In this section, according to the working characteristics of the exoskeleton robot, the overall framework of the exoskeleton robot distributed control system is established, as shown in Figure 8. The motion control module is the core function of the exoskeleton, it determines the accuracy and efficiency of exoskeletons and the safety and comfort of users. The control method, which uses the force control of SEA as inner-loop and the contact force control between human and exoskeleton as outer-loop, for the exoskeleton motion module is introduced in this section.
3.1. Control method of SEA

The control method of SEA adopts cascade control, the block diagram of control system as shown in Figure 9, velocity control of motor as inner-loop, force control of SEA as outer-loop.

***Figure 9. Block diagram of SEA control system.***

$C_r$ is controller of force-loop, $C_\omega$ is controller of controller of velocity-loop. The output of the control system of SEA is shown in follows:

$$T_i(t) = \frac{k_s C_r V T_d(t) - k_s c_t(t)}{s + k_s C_r V}$$  

(4)

Where $T_i$ is load torque, $T_d$ is desired torque, $k_s$ is stiffness of SEA, $\theta_i$ is the output angular, $V$ is the transfer function instead of velocity-loop.

3.2. Joint tracking control method of the exoskeleton

For the exoskeleton, following movement to the human body is the core function. The joint tracking control method of the exoskeleton is designed in this section. The physical model of the exoskeleton is shown in Figure 10. $k_s$ is stiffness of SEA, $k_h$ is the contact stiffness between human body and exoskeleton, $\theta_i$ is the joint rotation angle of exoskeleton, $\theta_h$ is the joint rotation angle of human, $T_h$ is the contact torque.

***Figure 10. Physical model of exoskeleton.***

Cascade control method is also used for the joint the joint tracking control of exoskeleton robot, force control of SEA and contact force control between human and exoskeleton are adopted as inner-loop and outer-loop, respectively. An external pressure sensor is used to collect the contact force between exoskeleton and human body, which is used as the feedback signal of the contact force control system. According to the adaptive stable algorithm [13]:

$$\lim_{t \to \infty} \Delta \dot{x}(t) = \lim_{t \to \infty} \dot{x}(t) - \dot{x}_d(t) = 0$$  

(5)

Where $\dot{x}(t)$ is actual velocity, $\dot{x}_d(t)$ is desired velocity. As the force tracking error is controlled to be infinitely close to zero, the exoskeleton can follow the human body to realize the walking assistance. A PI controller is designed to control the contact stiffness as follow:
\[
\dot{x}_d(t) = \dot{\hat{\gamma}}(t) \hat{F}_d(t) - P \Delta \hat{F}_c(t) - T \Delta F_c(t)
\]

(6)

Where \(\hat{\gamma}(t)\) is the time varying estimate of compliance between exoskeleton and human body, \(\hat{F}_d(t)\) is the first time derivative of desired force trajectory, \(\Delta F_c(t)\) is the contact force error. The first time derivative of \(\hat{\gamma}(t)\) is used to recognize the contact compliance:

\[
\dot{\hat{\gamma}}(t) = -\lambda \hat{F}_d(t) \Delta F_c(t), \lambda > 0
\]

(7)

Figure 11 shows the block diagram of the joint tracking control system.

![Block diagram of control system.](image)

**Figure 11.** Block diagram of control system.

![Simulation results of position tracking.](image)

**Figure 12.** Simulation results of position tracking.

![Simulation results of contact force.](image)

**Figure 13.** Simulation results of contact force.
4. Simulations
A virtual block diagram of the exoskeleton control method is established to verify the feasibility of the control strategy by using MATLAB & Simulink. The simulation results are shown in Figure 12 and 13. Figure 12 shows the knee joint angle curve of human and the exoskeleton, respectively. It can be seen that the movement of exoskeleton knee joint is stable, and the exoskeleton can track human motion well. Figure 13 shows the contact force curve. It can be seen that the maximum force deviation is very small, that means real contact force is stable and the resistance force is very small. Therefore, the simulation results show that joint position tracking can be achieved by using the control method designed above.

5. Conclusions
In this paper we present a lower extremity exoskeleton with humanoid knee joint. The exoskeleton actuated by Series Elastic Actuator (SEA) have the capabilities of low impedance and comfortable. A novel humanoid knee joint is introduced into the exoskeleton. A control strategy based on the SEA force control is designed and simulated in this paper. Analysis of the simulation results shows that the joint tracking can be achieved by using the control method. In the future work we will design an experimental prototype and conduct experimental researches on it.

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