The Optimization on Structure of Weight-bearing Lower Extremity Exoskeleton based on Analysis of Multi Degree of Freedom

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Abstract

In order to offset load torque, many weight-bearing lower extremity exoskeleton install gas spring in the hips which make the human walk abnormally in single leg support phase due to the disappearance of the rotation junction. To solve this problem, aiming at the exoskeleton robot "ELEbot", this paper using the reciprocal screw theory calculate and determine the "ELEbot" degrees of freedom and constraints in the single leg support phase and then put forward an improved mechanism to meet demand for degrees of freedom in this posture and verify the rationality of the drive configuration.

Keywords

Weight-bearing Exoskeleton; Reciprocal Screw Theory; DOF.

1. Introduction

The idea behind the design of the negative heavy lower extremity exoskeleton is that the human provides the intelligent control system for the skeleton suit and the skeleton suit provides most of the force required for the human load. However, the gravity of the load attached to the body's back consistently deviates from the hip joint of the wearer and exoskeleton robot, causing huge torques to the joint. In order to balance, the human body often adopts adjustment measures such as leaning forward and increasing the lateral swing of the trunk during walking, so as to reduce the impact of the load moment on the body [1]. This seriously affects the normal standing posture and gait of the wearer. In order to solve this problem and offset the torque of the load gravity on the human hip, an air spring is set in the hip of the negative heavy exoskeleton robot. However, the increased counter torque structure will make the person unable to continue the backward swing due to the resistance of the air spring in the single-leg supported phase motion, resulting in the loss of rotational freedom in the sagittal plane of the hip. Moreover, experiments have found that in this state, the hip belt of the exoskeleton exerts an upward pull on the human body, preventing human gravity from affecting the soles of the exoskeleton feet. The exoskeleton performs gait recognition by the pressure of the soles of the feet, which leads to errors in gait recognition [2]. Because the sensors do not detect pressure, the hydraulic drive system does not provide support in the single-leg support phase, making it impossible to walk normally. This indicates that the distribution of degrees of freedom of the existing mechanical mechanism of lower limb exoskeleton can not meet the requirements of human normal walking under the single-leg supporting gait. Therefore, it is necessary to analyze the degree of freedom of exoskeleton garment machinery and optimize the existing mechanical structure. In this paper, ELEbot designed by East China University of Science and Technology is used for modeling analysis.

2. Freedom Analysis of "ELEbot"

Human lower limb motion joints are mainly composed of hip joint, knee joint and ankle joint, and the motion of each joint of lower limb is mainly divided into three types: flexion/extension, abduction/adduction and rotation [3]. The unilateral lower limb of human body has a total of 7 degrees of freedom, as shown in Figure 1. Considering that the lower limb exoskeleton should have coordinated movements with the human, "ELEbot" is designed to have the same degree of freedom and movement form as the human lower limb, namely the hip joint has three degrees of freedom, namely flexion/extension, abduction/adduction, and pronation/pronation around the three basic axes. One degree of freedom of the knee joint is flexion/extension motion around the frontal axis. The 3 degrees of freedom of the ankle joint are flexion/extension, abduction/adduction, and pronation/pronation around the three basic axes. As the hip joint of the lower extremity exoskeleton robot has a certain deviation distance from the human hip joint on the coronal plane, the high pair and low band are adopted to eliminate this deviation. Three rotational pairs are set in the hip of the robot to replace the ball pair, as shown in Figure 2.

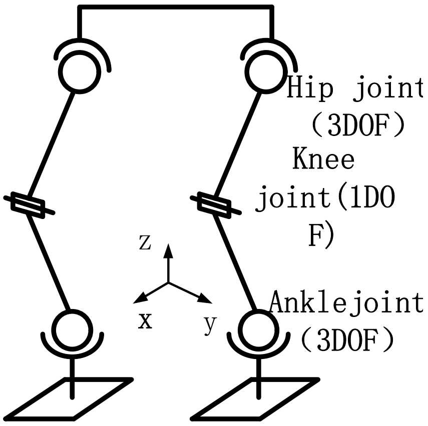

Figure 1. Distribution of ideal DOF of human lower limbs

In the process of human wearing exoskeleton, walking gait can be divided into swing phase and support phase. When swinging, the human exoskeleton system takes the foot as the executive organ, and its distribution of degrees of freedom is shown in Figure. 2. In the support phase, the self-locking of the rotational pair on the hip plane of the exoskeleton disappeared, and the rotational pair on the sagittal plane also disappeared due to the action of the air spring, and the distribution of their degrees of freedom was shown in Figure 3.

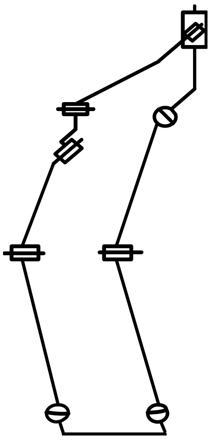

Figure 2. DOF distribution in swing phase

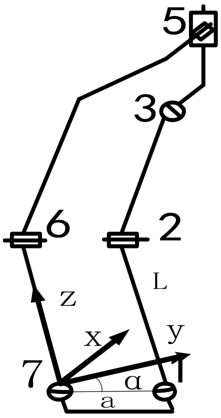

Figure 3. Dof distribution in single-leg support phase

The leg of the exoskeleton robot is z-axis, and the rectangular coordinate system is established as shown in the figure. L is the length of the leg, and Angle α is the Angle between the distance between the exoskeleton ankle joint and human ankle joint, axis A and axis Y. Coordinates of each point: Point 7 (0,0,0), point 1 (0, acosα,-asinα), point 2(0, acosα ,L--asinα), point 3 (X3, Y3, Z3), point 4 (X4, Y4, Z4), point 5 (X5, Y5, Z5), point 6 (X6, Y6, Z6); point 7 is the ball pair passing through the point (0,0,0), and the motion spiral is expressed as:

$$\$_7 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}^T$$

6 is the rotation pair passing through the point (X6, Y6, Z6) along the direction (0, cosα,-sinα), and the moving spiral is expressed as:

$$\$_6 = \begin{bmatrix} 0 & 0 & L & -L\cos\alpha & 0 & 0 \end{bmatrix}^T$$

5 is the ball pair passing through point 5 (X5, Y5, Z5), and the motion spiral is expressed as:

$$\$_5 = [1 \quad 0 \quad 0 \quad 0 \quad -z_5 \quad y_5]^T$$

Thus, the motion spiral matrix of motion chain 765 can be expressed as:

$$\$^T = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & L & -L\cos\alpha & 0 & 0 \\ 1 & 0 & 0 & 0 & -z_5 & y_5 \end{bmatrix}$$

It can be known from the screw theory that, according to the reciprocal screw theory, the reciprocal product of the constrained screw of the motion chain and its free motion screw is zero. By $\Re = \$^T E$:

$$\Re = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ -L\cos\alpha & 0 & 0 & 0 & 0 & L \\ 0 & -z_5 & y_5 & 1 & 0 & 0 \end{bmatrix}$$

Then the terminal constraint of the moving chain$\Re$x=0, where; x=$\$^r$ represents the terminal constraint of the chain of motion:

$$\$^r = \begin{bmatrix} 0 & \frac{y_5}{z_5} & 1 & 0 & 0 & 0 \end{bmatrix}^T$$

1 is the ball pair passing through the point (0, acosα,-asinα), and the motion spiral is expressed as:

$$\$_1 = \begin{bmatrix} 1 & 0 & 0 & 0 & a\sin\alpha & a\cos\alpha \\ 0 & 1 & 0 & -a\sin\alpha & 0 & 0 \\ 0 & 0 & 1 & -a\cos\alpha & 0 & 0 \end{bmatrix}^T$$

2 is the rotation pair passing through the point (0, Acos α, L-Asin α) along the direction (0, cosα,-sinα), and the moving spiral is expressed as:

$$\$_2 = [0 \quad \cos\alpha \quad -\sin\alpha \quad L\cos\alpha \quad 0 \quad 0]^T$$

3 is the ball pair passing through the point (X4, Y4, Z4), and the motion spiral is expressed as:

$$\$_3 = \begin{bmatrix} 1 & 0 & 0 & 0 & -z_3 & y_3 \\ 0 & 1 & 0 & z_3 & 0 & -x_3 \\ 0 & 0 & 1 & -y_3 & x_3 & 0 \end{bmatrix}^T$$

Thus, the motion spiral matrix of chain 123 can be expressed as:

$$\$_{123} = \begin{bmatrix} 1 & 0 & 0 & 0 & a\sin\alpha & a\cos\alpha \\ 0 & 1 & 0 & -a\sin\alpha & 0 & 0 \\ 0 & 0 & 1 & -a\cos\alpha & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha & L\cos\alpha & 0 & 0 \\ 1 & 0 & 0 & 0 & -z_3 & y_3 \\ 0 & 1 & 0 & -z_3 & 0 & -x_3 \\ 0 & 0 & 1 & -y_3 & x_3 & 0 \end{bmatrix}^T$$

It can be seen that $Rank(\$_{ren}) = 6$,this means that kinematic chain 123 is a kinematic chain with zero constraint. Thus, the terminal constraint of the end-effector is:

$$\$^{r} = \begin{bmatrix} 0 & \frac{y_5}{z_5} & 1 & 0 & 0 & 0 \end{bmatrix}^{T}$$

Represents the presence of binding force along the Z-axis, which explains why the human body and the lower limb exoskeleton exert an upward pull on the human body at the belt connection during the backswing of the single-leg support phase. Therefore, it is necessary to optimize the mechanical structure of the lower limb exoskeleton and redistribute the degrees of freedom.

3. "ELEbot" Mechanical Structure Optimization

In order to eliminate the binding force of the "ELEbot" mechanism on the z-axis between the single leg support and the human body, the "ELEbot" hip is equipped with a sliding pair along the Z-axis. The screw theory is used to prove the feasibility of this scheme. The scheme freedom setting is shown in the figure below:

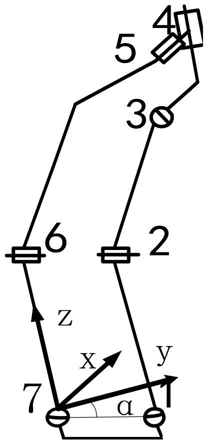

Figure 4. DOF distribution of the new mechanism

4 represents the newly added moving pair along the z-axis, whose motion spiral is:

$$\$_4 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}^{T}$$

It can be seen that, after adding a sliding pair, the motion spiral matrix of kinematic chain 765 can be expressed as:

$$\$_{765} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & L & -L\cos\alpha & 0 & 0 \\ 1 & 0 & 0 & 0 & -z_5 & y_5 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}^{T}$$

By the $Rank(\$_{gai}) = 6$; This means that kinematic chain 765 is a kinematic chain with zero constraint:

$$\$^{r} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^{T}$$

This means that by adding a z-axis sliding pair to the ELEbot hip, the lower extremity exoskeleton eliminates the z-axis binding on the human body, which is a good solution to this problem.

4. Degree of Freedom Simulation Verification and Mechanism Design Driver Scheme

After the degree of freedom redistribution of "ELEbot" is completed, it is necessary to verify whether the drive scheme can fully drive the motion of the optimized mechanical structure of the lower limb exoskeleton. It can be seen from the above that the optimized human exoskeleton system mechanism has 6 degrees of freedom on its end actuator, so that human movement will not be hindered. After wearing the upper and lower limb exoskeleton, human body can not only carry the load, but also realize a series of synchronous walking, running, jumping, squatting and other actions. "ELEbot" designed by East China University of Science and Technology has a driving scheme in which the lower limb exoskeleton provides the driving force to support a large load, while the human body only needs to provide a small force to drive the hip joint to rotate along the X, Y and Z axes and the ankle joint to rotate along the X, Y and Z axes [5]. It is proved that the driving scheme can give complete control to the end-effector motion. After these drives are imposed on the organization, the optimization organization becomes a "new organization." For kinematic chain 765, the matrix of its kinematic helix is:

$$\$_{765}^{T} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & -z_5 & y_5 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Its terminal constraint matrix is:

$$\$_{765}^{r} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^{T}$$

Similarly, for kinematic chain 123, the matrix of its kinematic helix is:

$$\$_{123} = \begin{bmatrix} 0 & \cos\alpha & -\sin\alpha & L\cos\alpha & 0 & 0 \end{bmatrix}^{T}$$

Its terminal constraint matrix:

$$\$_{123}^{r}=\begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & \cot\alpha \\ \tan\alpha/L & 0 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}^{T}$$

Then the constraints of the end-effector are expressed in the form of spiral matrix:

$$\$^{r}=\begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & \cot\alpha \\ \tan\alpha/L & 0 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^{T}$$

By the $\left|\$^{r}\right| \neq 0$ indicates, under the driving scheme, the exoskeleton suit actuator freedom of movement is zero, illustrates the driving scheme is feasible [4].

5. Discussion and Conclusions

Through the analysis of the degree of freedom of "ELEbot" mechanical structure in the phase space of single leg support, it is verified that the lower limb exoskeleton has constraints on human body along the Z-axis in this position, and the reason for the wrong gait recognition caused by the traction of the lower limb exoskeleton on human body in the single leg support phase is explained in principle. After the optimization of the mechanical structure, the rationality of the degree of freedom distribution is proved theoretically, and the traction force of the lower limb exoskeleton in the single-leg support phase is eliminated, and the driving scheme can also determine the mechanical structure of "ELEbot" after the drive optimization. The fourth generation prototype will be produced in the future to verify the feasibility of the new mechanism from an experimental point of view.

References

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