Kinematics and dynamics analysis of the weight-bearing lower limb exoskeleton

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Abstract

In this study, the forward kinematics, the inverse kinematics and the overall structure design of the hydraulically driven wearable exoskeleton were analyzed. The kinematics model of weight-bearing lower limb exoskeleton is established by Matlab, and the locus curve of lower extremities end are obtained. The correctness of the kinematics model is verified by Adams. Finally, the dynamic simulation of the weight-bearing lower limb exoskeleton is carried out by Adams and the torque of the joints of the lower limbs is obtained, which provides the basis for the selection of hydraulic cylinders.

Keywords

Exoskeleton, kinematics, dynamic, Matlab.

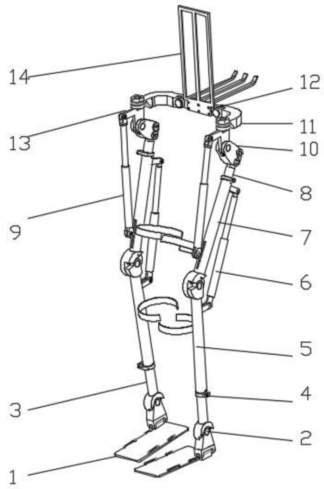
1. Introduction

The exoskeleton robot is a kind of human intelligence and robot machinery can be combined, through perception, decision-making and implementation level of organic man-machine coupling, enhance the system performance of the wearable equipment, can improve certain human physiology and has certain protective role on human body [1]. The broad development prospects of exoskeleton robots have attracted the attention of many countries and research institutions, and more and more scholars have invested in the study of the exoskeleton of the lower extremities [2]. The exoskeleton robot technology has been applied in many fields, such as military, medical, civil and so on [3-4].

According to different functions will be mainly divided into rehabilitation exoskeleton type and power type [5], the biggest difference lies in the rehabilitation exoskeleton robot is a robot driven by patient motion, robot active and passive people, need to consider the weight of the human body and the gait trajectory planning problem, and assist exoskeleton robot is composed of a wearer control path, and by collecting mechanical skeletal motion sensing system composed of signal sensor to the central processor, and then determine the wearer's walking intention, send the information to the control system, then control the exoskeleton drive movement, action signals collected at the same time, the mechanical exoskeleton joint of limbs (angular displacement, angular velocity, angular acceleration etc.) as a feedback signal to form a closed-loop control, realize the exoskeleton follow the wearer movement [6]. The weight-bearing exoskeleton studied in this paper is a power assisted exoskeleton. Its main role is to equip the exoskeleton with additional power system to provide additional power assistance for wearers, thereby enhancing the body's carrying capacity. The coordinate systems used in the modeling and simulation are all: the forward direction of the X axis is forward, the Y axis is vertical up, and the Z axis is determined by the right hand criterion.

2. The structural design of the exoskeleton of the lower extremities

The lower limb exoskeleton designed in this paper is made of 7075 aluminum alloy with high strength, which has 3 degrees of freedom of the hip joint, 1 degrees of freedom of the knee joint and 3 degrees of freedom of the ankle joint. The overall structural design of the exoskeleton in the lower extremities is shown in Fig.1, in which the width of the waist and the length of the thighs and calves can be adjusted. Due to the joint exoskeleton during walking angle in the coronal and horizontal plane changes very little, and the ankle joint force is small, in order to reduce the weight of exoskeleton, only in the hip and knee flexion and extension direction is arranged on the hydraulic drive unit, so this paper only studies the hip and knee joints in sagittal plane. On the surface of flexion and extension.



1-shoe body, 2-ankle joint component, 3- leg inner rod, 4-tight buckle, 5- leg outer rod, 6-hydraulic device of knee joint, 7-thigh outer rod, 8- thigh inner rod, 9- hydraulic device of hip joint, 10- cam connector, 11- waist connector, 12- waist expansion device, 13- hip joint block, 14- The back frame.

Fig.1 The overall structure of the exoskeleton of the lower extremities

3. The forward kinematics and the inverse kinematics analysis

In this paper, a male with a height of 175 centimeters and a body weight 60kg (the length of the thigh 496mm and the leg length 396mm) was analyzed as an example. Because the walking data of human walking are the same, there exist only half gait cycle lag. So this paper only studies the motion data of the right leg in a gait cycle.

3.1 The forward kinematics

The D-H coordinate method is used to analyze the kinematics of the exoskeleton of the lower extremities. First, the D-H coordinate system is established. As shown in Fig.2, the Z_i axis coincides with the $i+1$ joint axis. The X_i axis is determined on the common normal line of the i joint axis and the $i+1$ joint axis, and the Y_i axis is determined by the right hand rule.

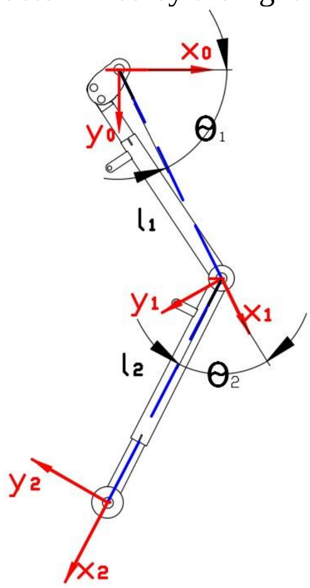


Fig.2 Diagram of D-H coordinate system

There is only a rotating joint in the exoskeleton of the lower extremities, so the $4*4$ D-H conversion matrix of the connecting rod is as follows:

$$T_1^0 = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & l_1\cos\theta_1 \\ \sin\theta_1 & \cos\theta_1 & 0 & l_1\sin\theta_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_2^1 = \begin{bmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & l_2\cos\theta_2 \\ \sin\theta_2 & \cos\theta_2 & 0 & l_2\sin\theta_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

$$T_2^0 = \begin{bmatrix} \cos(\theta_1+\theta_2) & -\sin(\theta_1+\theta_2) & 0 & l_2\cos(\theta_1+\theta_2)+l_1\cos\theta_1 \\ \sin(\theta_1+\theta_2) & \cos(\theta_1+\theta_2) & 0 & l_2\sin(\theta_1+\theta_2)+l_1\sin\theta_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Calculating the product of the homogeneous transformation matrix of each adjacent link, we get the relation between the motion locus of the lower extremity relative base coordinate system and the joint angular displacement.

$$\begin{aligned} x_1 &= l_1\cos\theta_1 \\ y_1 &= l_1\sin\theta_1 \\ x_2 &= l_2\cos(\theta_1+\theta_2)+l_1\cos\theta_1 \\ y_2 &= l_2\sin(\theta_1+\theta_2)+l_1\sin\theta_1 \end{aligned} \quad (2)$$

3.2 Inverse kinematics analysis

The inverse kinematics of the exoskeleton of the lower extremities is illustrated in Fig.3.

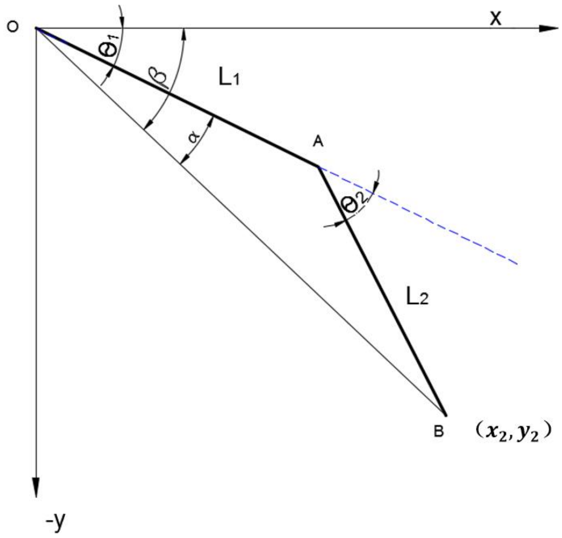


Fig.3 Inverse kinematics diagram

In the inverse kinematics by ankle joint coordinates（$x_2 \quad y_2$）can draw the thigh and leg swing angle θ_1 and θ_2. L_1 and L_2 represent the length of the thighs and the legs, respectively. In the ΔABC, the cosine theorem can be deduced.

$$x_2^{\ 2} + y_2^{\ 2} = l_1^{\ 2} + l_2^{\ 2} + 2l_1l_2\cos(\pi - \theta_2) \quad (3)$$

Thus, the oscillating angle θ_2 can be deduced.

$$\theta_2 = \pi - \arccos\frac{x_2^{\ 2} + y_2^{\ 2} - l_1^{\ 2} - l_2^{\ 2}}{2l_1l_2} \quad (4)$$

The angle β between the line OB and the X axis and the angle α between the line OB and OA. In order to find the value of θ_1, we need to solve the α and β first, which can be deduced from Fig.3.

$$\beta = \text{-arctan}\frac{y_2}{x_2} \tag{5}$$

In the ΔABC, the cosine theorem can be deduced.

$$l_2^{\,2} = x_2^{\,2} + y_2^{\,2} + l_1^{\,2} - 2l_1\sqrt{x_2^{\,2} + y_2^{\,2}}\cos\alpha \tag{6}$$

And

$$\alpha = \arccos\frac{x_2^{\,2} + y_2^{\,2} + l_1^{\,2} - l_2^{\,2}}{2l_1\sqrt{x_2^{\,2} + y_2^{\,2}}} \tag{7}$$

$$\theta_1 = \beta - \alpha \tag{8}$$

Therefore, the inverse kinematics equation can be expressed as

$$\begin{aligned} \theta_1 &= \text{-arc}\tan\frac{y_2}{x_2} - \arccos\frac{x_2^{\,2} + y_2^{\,2} + l_1^{\,2} - l_2^{\,2}}{2l_1\sqrt{x_2^{\,2} + y_2^{\,2}}} \\ \theta_2 &= \pi - \arccos\frac{x_2^{\,2} + y_2^{\,2} - l_1^{\,2} - l_2^{\,2}}{2l_1 l_2} \end{aligned} \tag{9}$$

4. kinematics simulation

4.1 kinematics simulation based on MATLAB

MATLAB is the abbreviation of MATRIX LABORATORY, it is a large American Mathematical Math Works company in 1980s launched the calculation tools for advanced technology, algorithm development, data visualization, data analysis and numerical computing language and interactive environment, has become the world's scientific research and engineering design of mathematical tools commonly used [7].

The joint angle data of this article is the CGA data [8] of the gait cycle of the Clinical Gait Analysis (CGA) and the gait cycle of 1s, as shown in Fig.4. According to the forward kinematics analysis the joint angle data of the lower limb skeletal and abroad, using MATLAB software for lower extremity exoskeleton modeling and Simulation of kinematics, trajectory curve of the lower extremities obtained in the X direction and Y direction of a gait cycle, as shown in Fig.5, the initial position is right heel, foot tip coming off the moment. It can be seen that the end locus of the end is in line with the characteristics of the end trajectory of a gait cycle of the human body, which verifies the correctness of the kinematic formula.

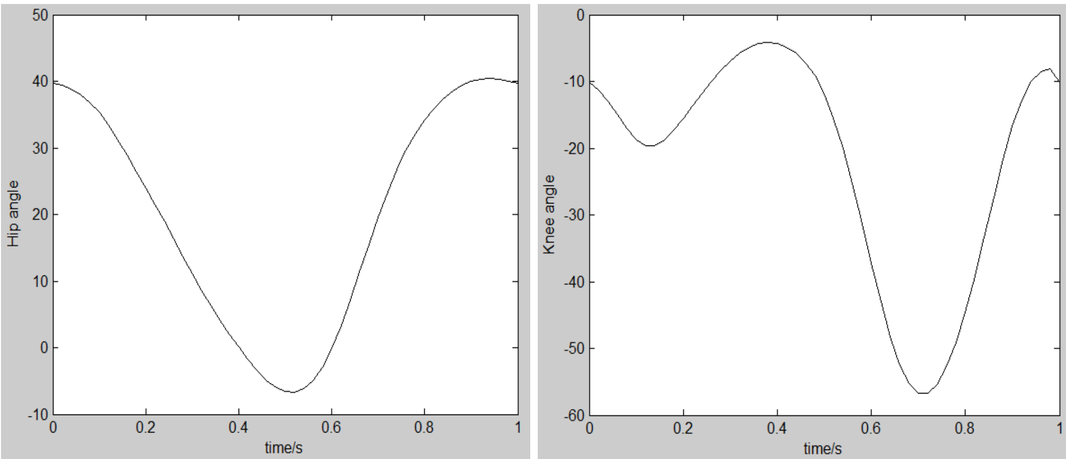


Fig.4 Joint angle data curve

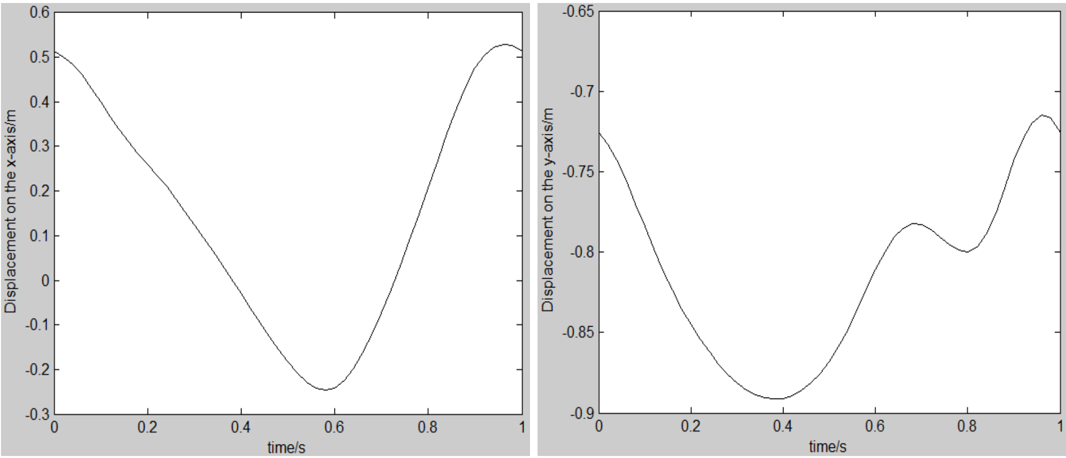


Fig.5 The end trajectories in MATLAB

4.2 kinematics simulation based on Adams

Adams is based on the calculation of dynamics of multibody system based on virtual prototype development system, including software modules and a number of professional fields, the kinematics and dynamics model which can be used to establish a complex mechanical system, the model can be rigid body, flexible or rigid flexible mixed model for various performance tests on products [9].

Kinematics analysis was carried out by using Adams software's skeleton model: firstly, Solidworks created the exoskeleton model into Adams software, and test the interference between various components; then set Mark in the center of each joint, because only on sagittal gait motion in the sagittal plane, so it will be added to the rotation pair the Mark point is positive in the counterclockwise direction, and the rest parts are fixedly connected; after each revolute add drive, using the AKISPL function as the driving function, the spline curve data for the above mentioned CGA data; the setting time of 1s simulation, simulation frame 100, kinematics simulation Adams simulation of the initial position, as shown in Figure 6, for the right foot, left foot tip off the moment.

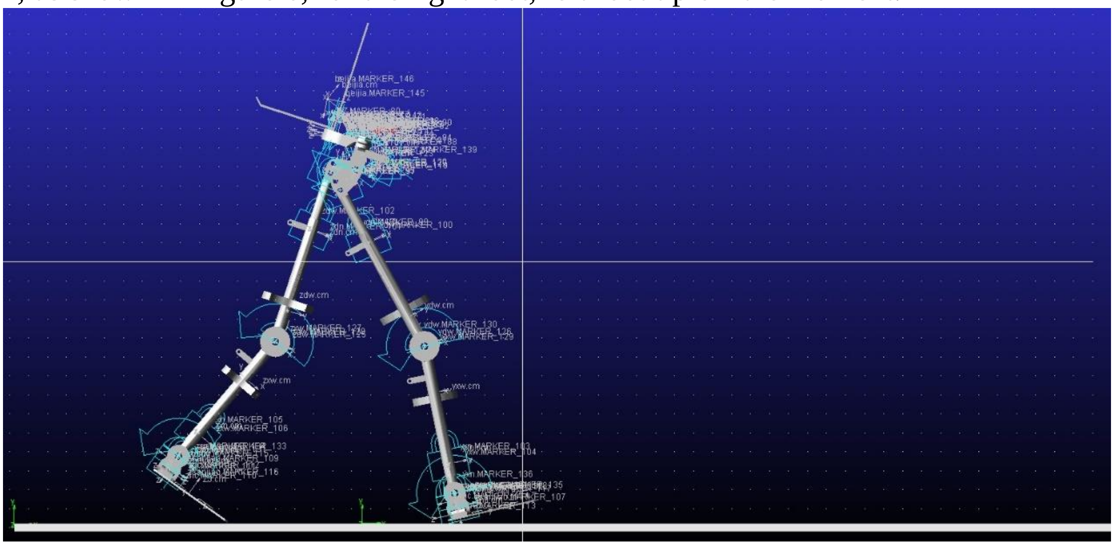


Fig.6 Adams simulation initial position

The obtained simulation data are processed in Adams/Post Processor, and the kinematic data of the exoskeleton model (as shown in Fig.7) are obtained. Fig.7 (a) and Fig.7 (b) are the trajectories of the lower extremities in the X direction and the Y direction in a gait cycle, respectively. Compared with Fig.5, the correctness of the mathematical model is verified. Fig.7 (c) and Fig.7 (d) curve of the angular velocity of the hip and knee joint, and Fig.7 (e) and Fig.7 (f) the curve of the angular acceleration of the hip joint and the knee, respectively.

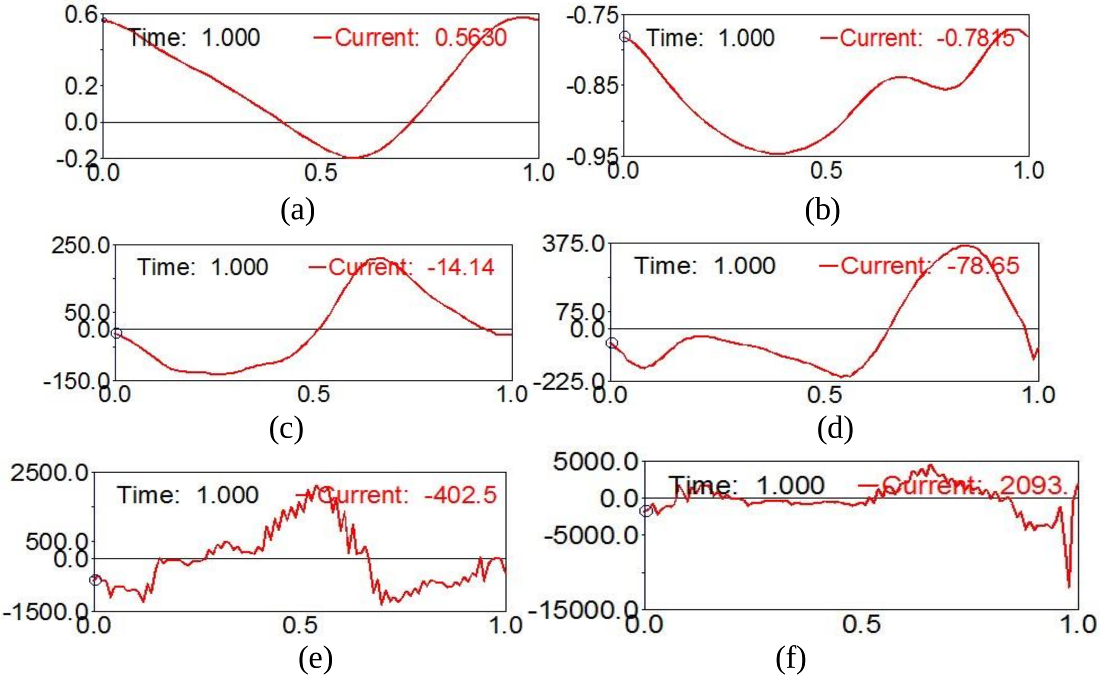


Fig.7 kinematic data diagram in Adams

5. Dynamic Simulation

Continue to carry out dynamic analysis using Adams software exoskeleton model based on kinematics model: create ground level at ground, and for each component adding mass and rotary inertia and the exoskeleton of feet and the ground contact were created, and add a force perpendicular to the upper limb in the waist center to replace the wearer the exoskeleton of Applied force. Set the simulation time of 1s, the simulation frame 100, dynamics simulation and the simulation data were obtained in Adams/Post Processor, get empty when the lower extremity exoskeleton leg joints joint torque change in a gait cycle in Fig.8. Fig. 8 (a) is the moment diagram of hip joint with no load. The maximum value is 60Nm. The maximum value is 60Nm, which occurs at the single foot supporting stage. The moment of the exoskeleton gravity center does not reach the upper part of the supporting leg, the minimum value is -130Nm. Fig.8 (b) is the knee joint torque change diagram, the maximum value of 25Nm, the minimum value of -20Nm, and the maximum value of the hip torque at the same time.

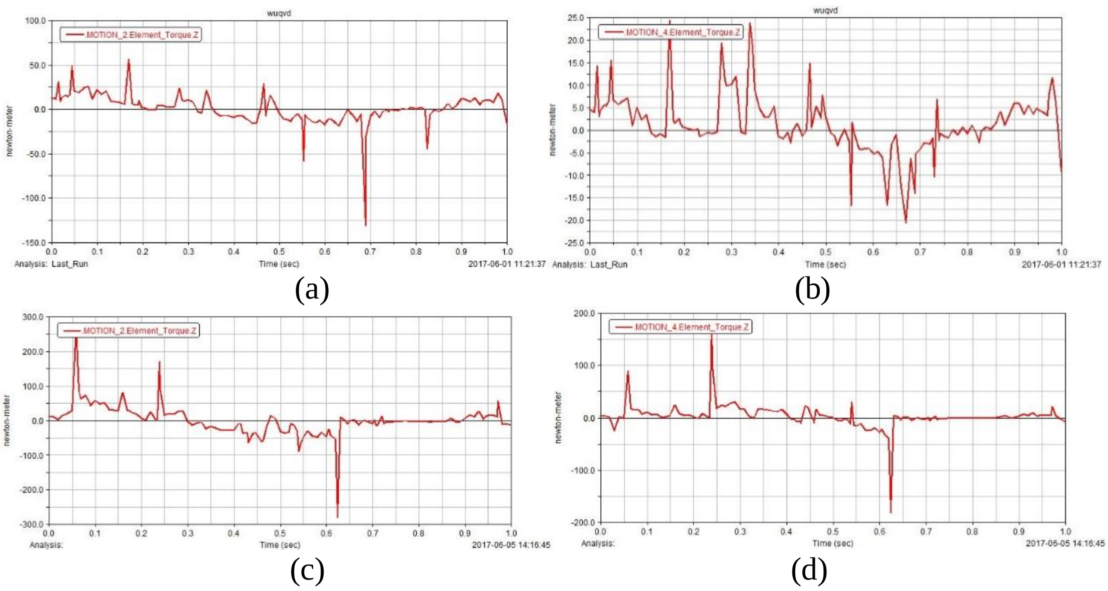


Fig.8 right hip joint torque change diagram

A 20kg load was added to the back frame, and then the dynamic simulation was carried out to get the joint torque variation of the lower extremity exoskeleton and right leg joints in a gait cycle at 20kg loading. Fig.8 (c) is a torque chart of hip joint with load 20kg. The maximum value is 280Nm. The maximum value is 280Nm at the single foot support stage. The moment of gravity center starts to move forward, the minimum value is -280Nm. It takes place on the left foot and the right foot, and moves the center of gravity forward. Fig.8 (d) is a torque chart of knee joint with load 20kg. The maximum value is 180Nm. The maximum value is 180Nm at the single foot support stage, and the minimum value of the exoskeleton moved forward to the top of the supporting leg is the same as the minimum moment of the hip joint. The above data provide the basis for the type selection of hydraulic cylinders.

6. Conclusion

This paper introduces the overall structure design of a hydraulically driven wearable exoskeleton, the kinematics forward and inverse solutions is analyzed by the D-H coordinate method. The MATLAB and Adams are used to simulate the kinematics of the lower extremities, and the curve of the end of the lower extremity and the curve of the angle, angular velocity and angular acceleration of each joint are obtained. Finally, on the basis of kinematics simulation, the dynamic simulation is analyzed by Adams, and the joint torque of the lower extremity joints when no load and load 20kg are obtained. The research can provide important theoretical basis for the selection of hydraulic cylinder.

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