

# Design and Simulation of Exoskeleton Robot

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## ABSTRACT

Based on the research of lower limb exoskeleton robots and extensive literature review, combined with human anatomy and kinematics, a four-degree-of-freedom lower limb exoskeleton robot was designed, and its three-dimensional model was established using UG software. In the design of the exoskeleton robot, it is required to have a simple structure, zero sensitivity in response speed, and be easy to realize automatic control. The exoskeleton robot designed in this paper uses electric push rods as the driving elements, and the dimensions of each part of the robot are obtained from the national standard human body size table; based on the analysis of the human gait cycle, and using cubic polynomial interpolation to plan the spatial posture of each joint; Adams was used to simulate the movement of the exoskeleton robot, and the motion curves of each joint were obtained.

## KEYWORDS

Lower Extremity Exoskeleton; Structural Design; Gait Analysis; Kinematics Simulation.

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## 1. INTRODUCTION

External skeletons can function to protect living organisms. They provide a structure that shields and supports the soft bodies of creatures from external injuries [1]. Humans have long ago learned to utilize artificial skeletal armor for bodily protection, particularly critical during combat where external skeletons play a significant role. With the advent of new technologies, powered external skeletons have been increasingly employed in medical and military fields [2]. In healthcare, societal progress correlates with a deteriorating trend towards an older population structure, turning this demographic shift into a societal challenge [3,4].

Research on lower limb exoskeleton robots began in the 1980s, with development led by the United States, the United Kingdom, and Japan [5]. In 2004, the University of California, Berkeley, developed a mechanical suit, the Berkeley Lower Extremity Exoskeleton, as shown in Figure 1(a). The Berkeley mechanical suit's legs have 7 degrees of freedom, with 3 degrees at the hip joint, 1 degree at the knee joint, and 3 degrees at the ankle joint. Hydraulically driven, it can achieve 4 degrees of freedom including hip flexion/extension, abduction/adduction, knee flexion/extension, and ankle flexion/extension. Ekso Labs developed a bionic leg mechanism called Ekso Bionics [6], as shown in Figure 1(b). The exoskeleton's mechanical structure adopted a biomimetic design, powered by DC motors, enabling upright walking with the assistance of this equipment. To promote the industrialization of robots, Professor Shuai Mei from Beihang University collaborated with Beijing Da'ai Robot Company to successfully design two rehabilitation robots: the bipedal AiLegs and the mobile platform AiWalker, as shown in Figure 1(c,d).

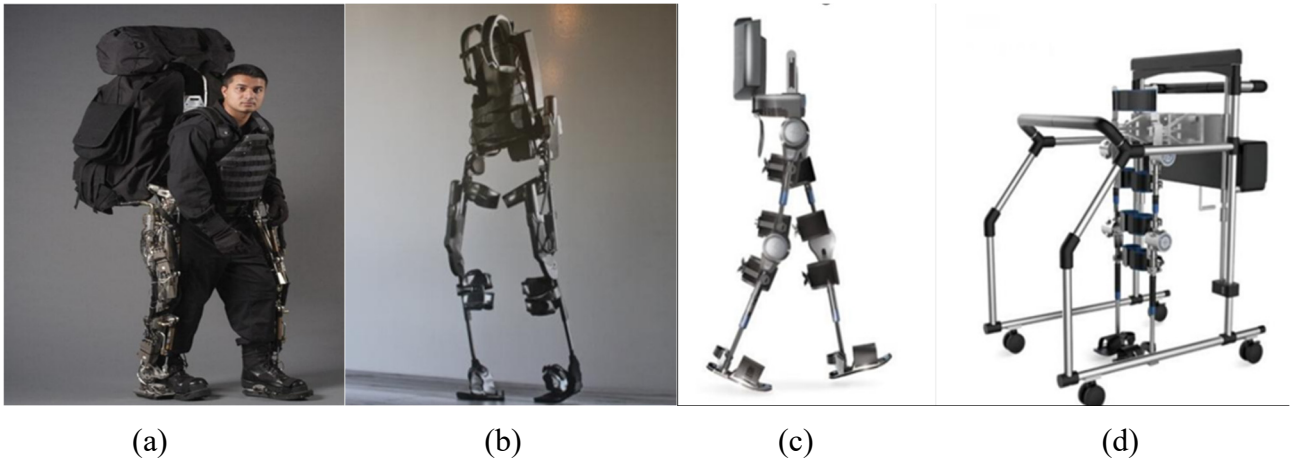


Figure 1. Lower extremity exoskeleton robots

## 2. STRUCTURE DESIGN OF LOWER LIMB EXOSKELETON ROBOTS

### 2.1. Analysis of the Human Lower Limbs

When standing upright, rotation around the vertical axis is referred to as "internal and external rotation," rotation around the coronal axis is called "flexion and extension," and rotation around the sagittal axis is termed "adduction and abduction." The primary movements during walking or running are accomplished in the sagittal plane.

Joint degrees of freedom are a paramount concern in the design of exoskeleton robots; appropriate degrees of freedom can enhance the flexibility of the exoskeleton and the comfort of the wearer. One side of the human body's lower limbs has seven degrees of freedom, achieved through the hip, knee, and ankle joints. Among these, the hip joint connects the pelvis to the thigh and allows for internal and external rotation, flexion and extension, adduction and abduction; the knee joint connects the thigh to the shank, typically considered to have only flexion and extension; the ankle joint connects the shank to the foot, allowing for internal and external rotation, flexion and extension, adduction and abduction.

### 2.2. The Structure Model of Lower Limb Exoskeleton Robot

The lower limbs are composed of three major joints. To ensure the normal walking of the exoskeleton robot and the safety of the wearer, the degrees of freedom (DOF) of the lower limb exoskeleton robot must be consistent with the human body, Modeling is shown in Figure 2.

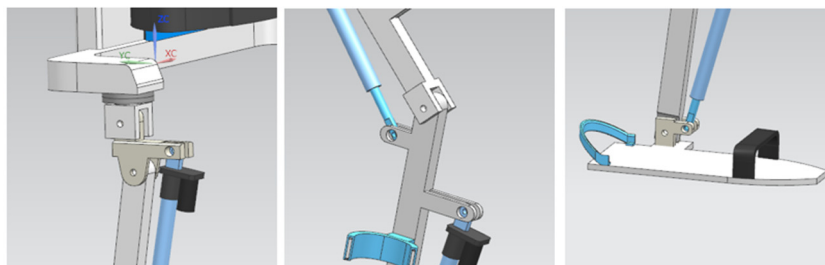


Figure 2. Joint Modeling Diagram

The hip joint is a spherical joint. The thigh has three DOF at the hip joint: flexion, extension, adduction, and rotation. Among them, flexion and extension are the most important DOF for forward movement in humans. In design, it would be very inconvenient for the wearer to turn, so this paper mainly considers two DOF: flexion-extension and rotation.

The knee joint is an elliptical gliding joint. When the knee joint is partially flexed, the lower leg can rotate slightly inward and outward. When the knee joint is fully extended, the lower leg cannot rotate inward or outward. This kind of DOF can be ignored in the design of the exoskeleton structure; the knee joint is approximately equivalent to a hinge joint, with only one flexion-extension DOF.

The ankle joint, also known as the talocrural joint, is a gliding joint. At the ankle joint, there are 3 DOF. These joints have a small range of motion but play an important role in maintaining body balance. For the sake of simplifying the structure at the ankle joint and reducing the difficulty of later processing, this paper only considers the flexion-extension DOF of the ankle joint.

### **2.3. The Driving Method of the Lower Limb Exoskeleton Robot**

The driving method of the drive system determines the reaction speed, response speed, and walking speed of the wearer. In this paper, the lower limb exoskeleton robot's hip joint, knee joint, and ankle joint all adopt electric push rod driving methods. The electric push rod is a type of electric actuator composed of an electric motor, push rod, and control device, which can achieve centralized control. After passing through the deceleration device, the electric motor drives the motion of the lead screw nut, converting the rotary motion of the electric motor into the linear motion of the lead screw, and completing the reciprocating motion by controlling the forward and reverse rotation of the motor. The electric push rod has small volume, high precision, good synchronization, and excellent self-locking performance.

### **2.4. Three-dimensional Modeling of Lower Limb Exoskeleton Robots**

The exoskeleton robot designed in this article is drawn in the 3D software UG. It starts with drawing based on the main body dimensions mentioned earlier, integrating the hip joint and the main body into one piece while preserving the rotational freedom of the vertical axis of the hip joint. The blue parts of the components are cushions to ensure the comfort of the human waist, and the black parts are devices used for tightening during wear. The circular parts of the components enable hip joint rotation, and the connected parts are specifically designed to install the drive device, ensuring that the extension length of this connector is not too short to prevent interference during motion. In this article, the projected distance between the centers of the connectors is 49mm, as shown in Figure 3(a).

The thigh part is drawn according to known data in terms of size and structurally designed to include the installation position for the drive device, with a distance of 16mm from the center to the boundary. Considering the range of motion angles of the knee joint, neither of the two installation positions needs to extend too far, as shown in Figure 3(b).

The dimensions of the calf part have also been provided, with a reserved space for installing the drive element. The distance between the center and the boundary at the connection with the thigh is also 16mm. Attention should be paid to the connection between the calf and the ankle joint, where the design requires a longer extension of 56mm, as shown in Figure 3(c). Both the thigh and calf are designed with structures to support the human leg, and the blue parts of the components have reserved positions for strap installation on both end faces, allowing for strap selection based on the user's leg size.

The dimensions of the foot part have been determined, with specific structural designs as shown in Figure 3(d). The installation position for the drive device also needs to extend a certain distance to avoid interference; in this article, the extension distance is 15mm. The black parts of the components are used to secure the front part of the human foot, while the blue parts at the back are used to secure the heel. Additionally, when designing, it is only necessary to focus on one side first, as the other side can be realized through the "mirror geometry" command.

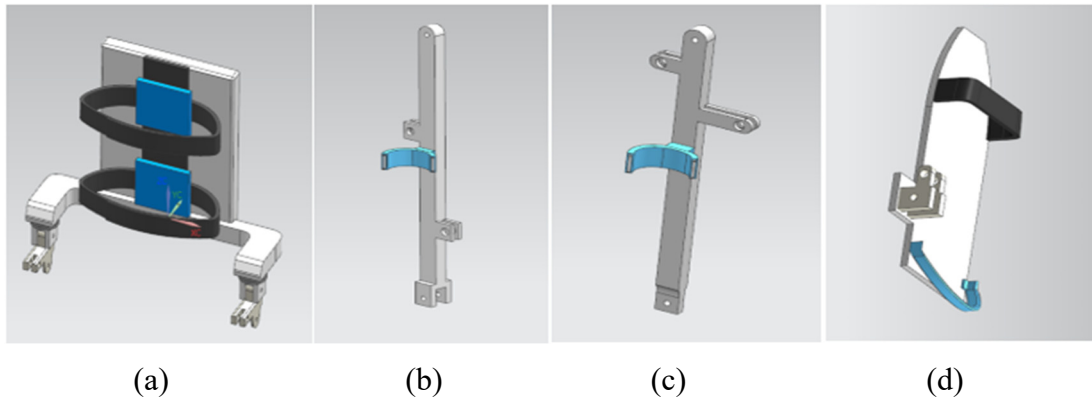


Figure 3. External skeletal robot structure diagram

### 3. GAIT PLANNING FOR LOWER LIMB EXOSKELETON ROBOTS

#### 3.1. Human Motion Gait Analysis

The movement of human lower limbs is periodic. A gait cycle refers to the process where the same foot, from heel strike, steps onto the ground again. The posture and behavioral characteristics of human walking are achieved through the synchronized movement of major joints in the body, moving in a designated direction. There is a 20% duration of double support, where both legs are supporting, and the rest of the time is spent on single support. Since the movement process between the left and right legs is identical, it suffices to study a single side of the lower limb. At the beginning of standing, the left toes touch the ground while the right heel is about to touch the ground; during the middle of standing, the left toes leave the ground, the right foot touches down, the right leg takes on the supportive role, the left leg swings, and the front and back legs switch; towards the end of standing, the left foot touches the ground, and the right toes are about to leave the ground; at the beginning of the swing phase, the right toes leave the ground, and the right leg swings forward; during the middle of the swing, the left foot touches the ground, and the front and back legs switch; towards the end of the swing, the right heel touches the ground, the left toes touch the ground, repeating the next cycle of movements [7].

#### 3.2. Three-Point Planning Method

The three-point planning method is adopted, which includes the start of a single leg swing, the highest point of a single leg swing, and the landing of a single leg swing, as shown in Figure 4. The moment when the swing starts is denoted as  $t_0$ , a complete cycle of a single leg swing is denoted as  $T$ , and the time taken for the swinging leg to reach its maximum height off the ground is denoted as  $t_h$ . It is assumed that at this time, the sole of the foot is parallel to the horizontal plane.

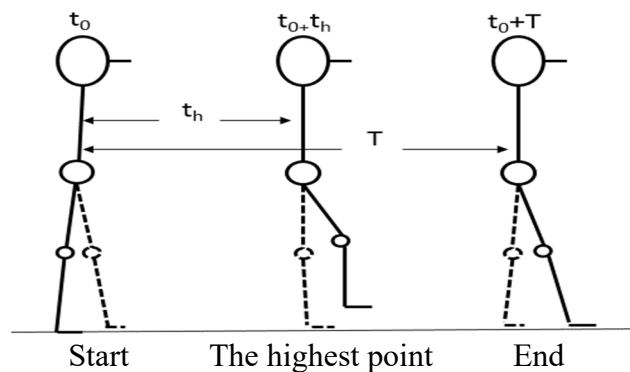


Figure 4. Three-Point Planning Method

### (1) Rajectory of the ankle joint

When planning the joints, take the heel of the supporting leg as the origin, the swing leg is the right leg in the direction of progress, and the supporting leg is the left leg in the direction of progress. Assume that the sole plane of the swing leg is always perpendicular to the calf. According to Figure 4, suppose at this moment it is in the  $k$ -th swing, the stride length of a step is  $s$ , at time  $t_h$  the distance from the starting point is  $L_h$ , the height of the ankle joint above the ground is  $H$ , and the angle between the sole of the swing leg and the horizontal plane during the swing is  $\theta(t)$ , we get:

$$\theta(t) = \begin{cases} 0, & t = kT \\ 0, & t = kT + t_h \\ 0, & t = (k+1)T \end{cases} \quad (1)$$

$$x(t) = \begin{cases} ks, & t = kT \\ ks + L_h, & t = kT + t_h \\ (k+1)s, & t = (k+1)T \end{cases} \quad (2)$$

$$z(t) = \begin{cases} l, & t = kT \\ H, & t = kT + t_h \\ l, & t = (k+1)T \end{cases} \quad (3)$$

Since at the moments  $kT$  and  $(k+1)T$ , the entire supporting leg is always on the ground, we can obtain the constraint condition:

$$\begin{cases} \dot{\theta}(kT) = 0 \\ \dot{\theta}((k+1)T) = 0 \end{cases} \quad (4)$$

$$\begin{cases} \dot{x}(kT) = 0 \\ \dot{x}((k+1)T) = 0 \end{cases} \quad (5)$$

$$\begin{cases} \dot{z}(kT) = 0 \\ \dot{z}((k+1)T) = 0 \end{cases} \quad (6)$$

### (2) Trajectory of the hip joint

Before gait planning, it is constrained that the upper body's torso remains perpendicular to the ground. The Z-value of the hip joint is a constant and equals the sum of the lengths of the calf and thigh plus the distance from the ankle joint to the horizontal plane. When planning the hip joint, only the X-axis coordinate value needs to be considered.

$$x(t) = \begin{cases} ks + \frac{s}{4}, & t = kT \\ ks + \frac{s}{2}, & t = kT + t_h \\ ks + \frac{3s}{4}, & t = (k+1)T \end{cases} \quad (7)$$

Fixed boundary constraints are added:

$$\begin{cases} \dot{x}(kT) = 0 \\ \dot{x}((k+1)T) = 0 \end{cases} \quad (8)$$

It has been determined that during walking, the corresponding ankle joint and hip joint Cartesian coordinate values can be obtained using the three-point planning method, and the values of other joints can also be obtained.

### (3) Start-up planning

The phase from a stationary state to continuous walking is called the start-up phase, during which initial state values such as posture and speed for continuous walking can be obtained. In the design,

at time  $t_h$ , the maximum height of the ankle off the ground is  $H$ , the distance of the stride is  $s/2$ , the step length is also  $s$ , and the single leg swing period continues to use  $T$ , then the ankle has

$$\begin{cases} z(kT) = l \\ z(kT + t_h) = H \\ z((k+1)T) = l \end{cases} \quad (9)$$

$$\begin{cases} x(kT) = ks \\ x(kT + t_h) = L_h \\ x((k+1)T) = ks + s \end{cases} \quad (10)$$

Additional constraints:

$$\begin{cases} \dot{x}(kT) = 0 \\ \dot{z}((k+1)T) = 0 \end{cases} \quad (11)$$

$$\begin{cases} \dot{x}(kT) = 0 \\ \dot{z}((k+1)T) = 0 \end{cases} \quad (12)$$

The hip joint becomes the value in the forward direction during motion, it can be obtained:

$$\begin{cases} x(kT) = ks + \frac{s}{6} \\ x(kT + t_h) = ks + \frac{s}{2} \\ x((k+1)T) = ks + \frac{5s}{6} \end{cases} \quad (13)$$

The hip joint becomes the value in the forward direction during motion, it can be obtained Among them, the reason for adding  $s/6$  is that if the angle values of each joint in the initial state of starting to walk are  $90^\circ$ , the center of gravity of the human body will move backward, falling on the heel of the sole of the foot, there will be a tendency to fall. Adding  $s/6$  moves the center of gravity of the person forward. Add constraints:

$$\begin{cases} \dot{x}(kT) = 0 \\ \dot{z}((k+1)T) = 0 \end{cases} \quad (14)$$

According to the cubic spline interpolation method, we have obtained the Cartesian coordinate values of the hip joint and ankle joint. The angle of the knee joint can be derived from the D-H method in Chapter 4 based on the hip joint and ankle joint.

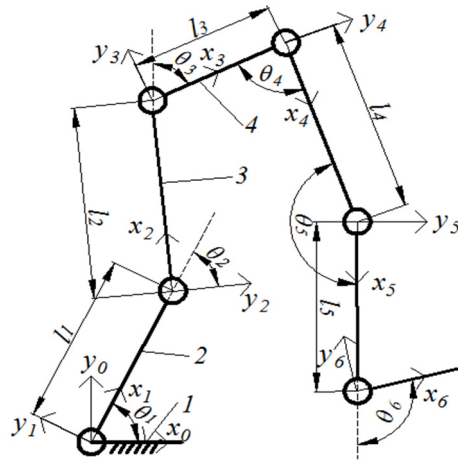
## 4. KINEMATICS ANALYSIS AND SIMULATION

### 4.1. Kinematics Analysis

The forward kinematics solution in robotics defines how to determine the position and posture of the end-effector of an industrial robot within a fixed coordinate system, given knowledge of each joint type, dimensions of adjacent joints, and their relative motions. Introduced by Denavit and Hartenberg in 1955, this method has since become the standard for representing and modeling robots, known as the D-H method, and has been extensively utilized. The procedure includes: 1) Establishing a global coordinate system and local coordinate frames; 2) Identifying link parameters and joint variables, such as link length ( $L_n$ ), link twist angle  $\alpha_i$ , joint translation  $d_n$ , and joint rotation angle  $\theta_n$ ; 3) Computing the pose transformation matrix for each link [8].

Lower-limb exoskeleton robots can be viewed as a series of robotic components comprising a waist protector, thigh and shank links, feet, and their interconnecting joints. Each link of the robot is thus reduced to a rigid component, with the waist protector projecting onto the sagittal plane during

ambulation. The movements of the hip, knee, and ankle are simplified into rotary pairs, using the sole of the stance foot as the foundation and the swing foot as the terminal effector. The kinematic model and its corresponding coordinate system are depicted in Figure 3-2. The coordinate frame for each link is positioned at the joint, with the Z-axis perpendicular to the plane of the paper, directed outward; the X-axis extends along each link; the Y-axis is normal to the plane defined by the X and Z axes [9].



1-Foot 2-Shank Link 3-Thigh Link 4-Waist

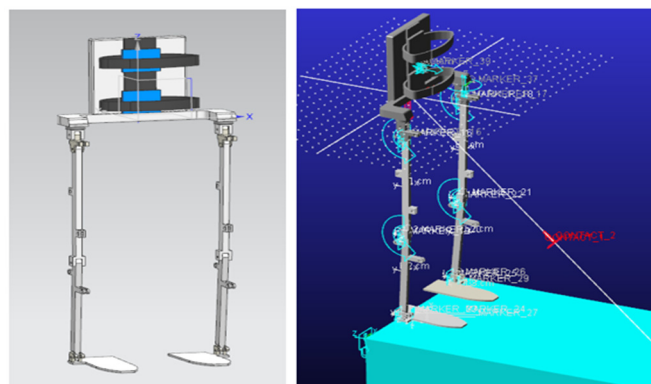
**Figure 5.** Kinematic Model of Exoskeleton Robot

D-H Coordinate Transformation Technique:

$$T_1^{i-1} = R(z_{i-1}, \theta_i)Trans(z_{i-1}, d_i)Trans(x_i, l_i)R(x_i, \alpha_i) \tag{15}$$

#### 4.2. Lower Limb Exoskeleton Robot Motion Simulation

Through motion simulation, we can more intuitively determine the correctness of the robot design and the movement trajectory of each component during operation. This paper uses Adams software for the motion simulation of the exoskeleton robot. The professional modules of Adams include Adams/car, Adams/engine, Adams/rail, etc. We can use the modeling module provided by Adams to establish the model of the exoskeleton robot or draw the model in other modeling software, export it as a ".x.t" format file, and then import it into Adams. After importing, we can set the material and mass of each part, the fixed constraints between parts, and reduce the coordinate systems between parts.

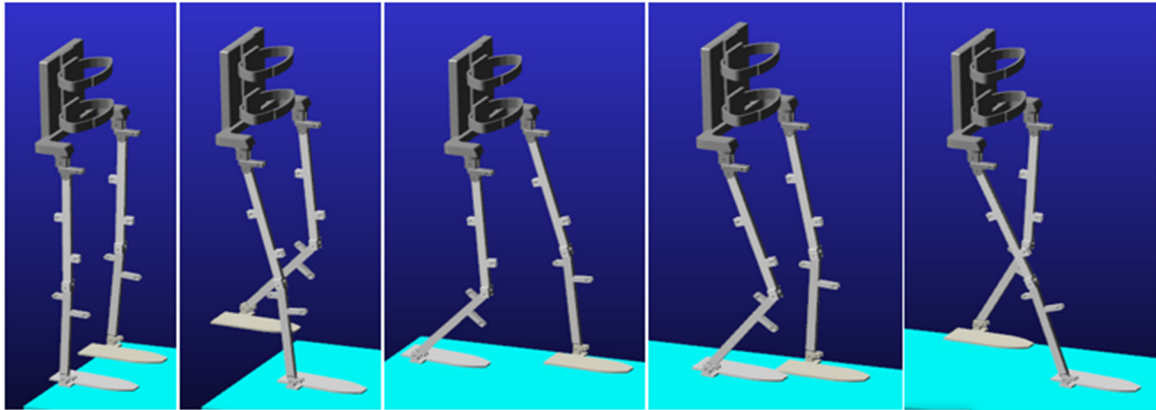


**Figure 6.** Simplified model diagram and kinematic pair, setting diagram of the drive

Before importing the model drawn by UG into Adams software, it is necessary to simplify the model, highlight some main components, and treat those parts without relative motion as a whole. The

exoskeleton robot designed in this paper mainly moves within the sagittal plane and only considers movement on flat ground; movements on other planes are not considered. Rotational pairs are set for the hip joint, knee joint, and ankle joint to simulate the flexion and extension movements of the joints; parallel pairs are set to keep the back always parallel to the ground, and a translational pair is set for the waist; a cuboid is established as the ground for the exoskeleton robot to walk on, and the ground is set as fixed; the left and right feet are also set with parallel pairs to be parallel to the ground to prevent dragging during movement, and they are set to contact with the ground, as shown in Figure 6.

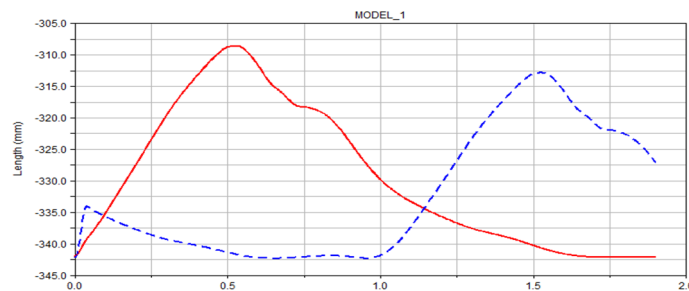
After setting up, carry out motion simulation, set the number of steps to 150, and then observe the results as shown in Figure 7.



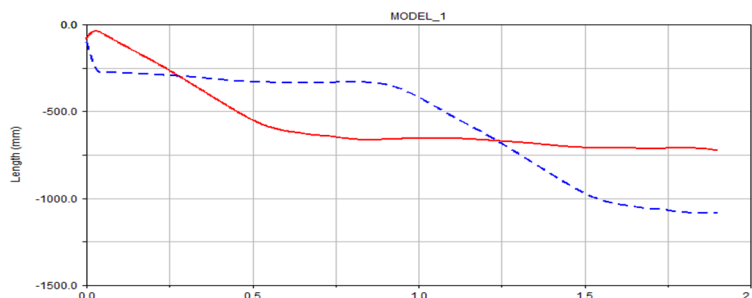
**Figure 7.** Gait diagram of the exoskeleton robot

### 4.3. Simulation Results

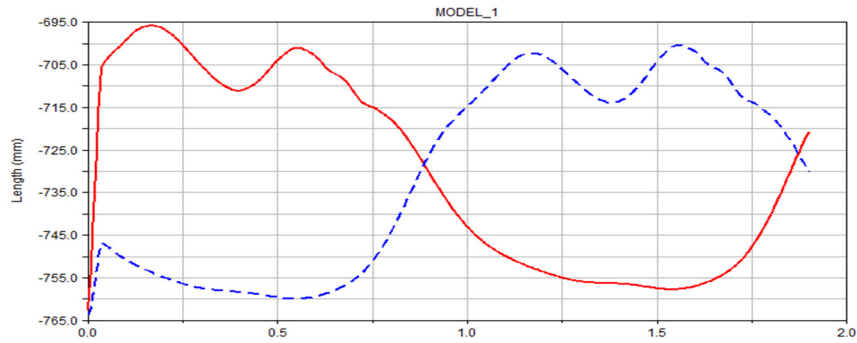
After the simulation is run and results are obtained, select the centroid of each connecting rod to generate trajectory images. Since there is no lateral movement, the displacement on the X-axis will not change, and only the position changes on the Y-axis and Z-axis need to be considered. The changes in the coordinates of the centroid motion trajectory of each part are shown in the figure, where the solid line represents the left leg and the dotted line represents the right leg.



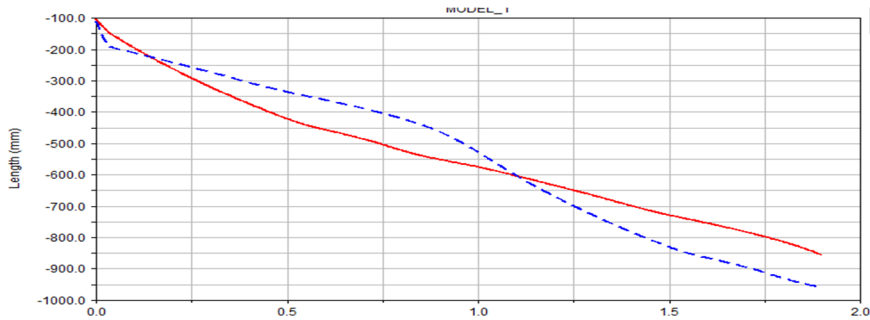
**Figure 8.**Thigh Center of Mass Y-axis Variation Chart



**Figure 9.**Thigh Center of Mass Z -axis Variation Chart

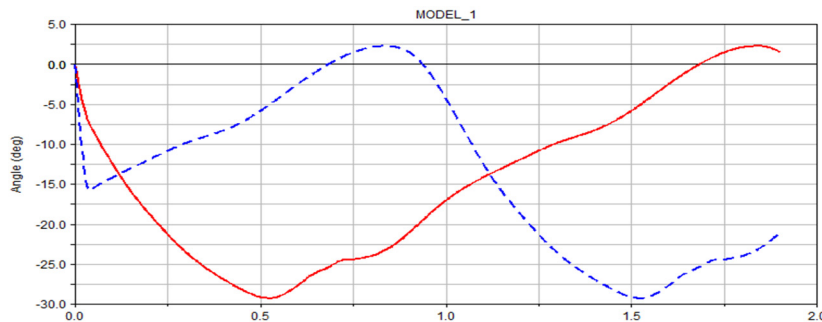


**Figure 10.** Calf Center of Mass Y -axis Variation Chart

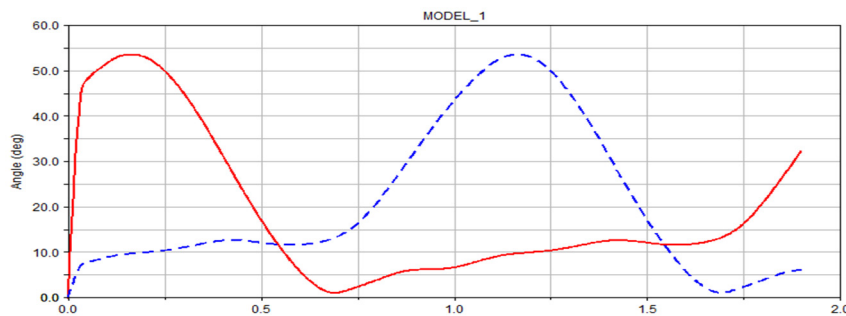


**Figure 11.** Calf Center of Mass Z -axis Variation Chart

From the motion trajectory of the centroid in the above figure, it can be seen that there is a rapid movement of the centroid before 0.1 seconds. This is because both the left leg and the right leg need to adjust their posture to prepare for walking. Comparing the motion trajectory of the centroid of the left leg and the right leg, the difference is not obvious, the trajectory coincidence is very high, and the movement process is stable. To further validate the rationality of the gait design, analyze the curve of joint angle changes during the driving process.



**Figure 12.** The angle change curve of hip joint rotation during the driving process



**Figure 13.** Angle Change Curve of Knee Joint Rotation Drive

Based on the supervision change curve of the hip joint and knee joint, it can be seen that there was also a significant change in angle before 0.1 seconds, which is for the same reason - to prepare for walking. Combining the analysis of the angle changes at the hip joint and knee joint, as well as the

trajectory changes of the center of mass of the thigh and calf, it can be seen that the exoskeleton robot moves smoothly during walking, and both the center of mass change curve and the angle change curve show periodic changes.

## 5. SUMMARY

This article reviews the development of exoskeleton robots both domestically and internationally. Based on observations and research on the human leg, the characteristics of the lower limb exoskeleton robot are obtained, namely the structure of the hip joint, knee joint, and ankle joint. The three-dimensional model of the robot was drawn using UG. Gait analysis was performed on the exoskeleton robot, fully understanding the movement form of the exoskeleton robot, and kinematic and dynamic analyses were conducted on the exoskeleton robot.

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