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Design of a Humanoid Bipedal Robot Based on Kinematics and Dynamics Analysis of Human Lower Limbs*

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***Abstract*— This paper proposes a humanoid bipedal robot based on kinematics and dynamics analysis of human lower limbs. The robot has a high-torque hip joint which combines two-degree-of-freedom parallel mechanisms and a lightweight high-torque knee joint with variable damping. The introduction of prosthesis makes the robot much closer to the real human body. In this paper, the overall structural design and the machine construction of the bipedal robot are presented, and experimental research was implemented to validate the rationality of the structural design of the humanoid biped robot and the feasibility of the control system.**

I. Introduction

Humanoid bipedal robot is a comprehensive high-tech that integrates mechanism kinematics and dynamics, modern cybernetics, bionics, computer science and artificial intelligence and is widely used in contemporary scientific research. Research on humanoid biped robots has gone through a long development process, and the state of art is becoming increasingly advanced. In the early 1970s, Waseda University designed the world's first humanoid robot WABOT-1 [1]. In 1971, Kato Ichiro developed the WAP3 biped robot. The robot was driven by a device similar to artificial muscles and could walk stably on flat ground, slopes and stairs. Its development unveiled the research of the biped robots. In 1989, the WABIAN series of robots developed by Waseda University achieved a natural humanoid state and stable walking on complex roads [2]. HONDA company introduced a humanoid robot called ASIMO in 2000, which was the world's first robot that could walk upright with two legs [3]. In 2002, Tsinghua University developed the bipedal robot called THBIP-I. The robot has 32 degrees of freedom in the whole body of the robot, which could achieve complex and continuous actions such as stable forward and backward, sideways, and horizontal movement without cable. Soon after, Tsinghua University developed the second-generation robot THBIP-II. Based on the previous generation, it optimized the design of related mechanisms, reduced the size of the robot, and realized the development of robot miniaturization [4]. In 2004, the Korean Academy of Science and Technology developed the biped robots KHP-1, KHP-2 and the biped robot HUBO. HUBO was the world's first humanoid robot capable of working with two legs. NAO [5], a small humanoid robot developed by French company Aldebaran, has an inertial navigation device, and each foot is equipped with four pressure sensors. The information collected by sensors is used to adjust the attitude to achieve stable gait walking and movement performance. Yuji Tsusaka designed a wire-driven bipedal robot, and the architecture was accomplished by an innovative arrangement of actuators that reflected muscle concentrations [6]. Fei Sun designed a novel mechanical structure with two legs, two feet and a pelvis [7]. It has 12 degrees of freedom. The robot's body shape and mass distribution are similar to that of an adult to get an ideal stable walking movement. Boston Dynamics developed the biped robot Atlas in 2016 [8]. Atlas is a biped humanoid robot that can walk in the mountains and snow. It can adapt to a wide range of obstacles; Atlas can perform a large number of complex movements, and it is a coordinated movement of the whole body. It can walk stably and squat down to pick up the box. Its balance is not affected when it is disturbed by people. In 2019, Atlas also implemented more complex movements such as jumping and backflip.

The research on biped robots has developed rapidly in recent decades. These robots can achieve stable walking, climbing up and down the stairs, and other complex movements in diverse environments. However, these biped robots have a common feature. The main focus of these studies is the realization of smooth movement of the robots. Their gait movements are relatively fixed, which are quite different from the real gait movements of the human body. It is difficult to combine these robots with gait studies of the human body.

The aim of this paper is to design a humanoid bipedal robot based on kinematics and dynamics analysis of human lower limbs. First, the kinematics and dynamics of human lower limbs are analyzed in Section II. Further, the overall structural design of the biped robot is introduced in detail in Section III. Finally, we build the prototype and present the experiments in Section IV before concluding the paper in Section V.

II. Kinematics and Dynamics Analysis of Human Lower Limbs

A. Study on Human Lower Limb Size Parameters

Anthropometrics is a method of measuring the physical characteristics of the human body. Biomechanics are mainly concerned with the inertial characteristics of the body and its parts, which are called body segment parameters in the anthropometric subfield. The relevant characteristics are segment mass, segment center of gravity position, and segment mass moment of inertia. Many scientists have taken

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different approaches to determine human parameters, but the most important advancement and breakthrough was accomplished by W.T. Dempster [9]. Dempster created a table of parameters for each body part of the human body. Since the pioneering work of Dempster, body part parameter research has developed rapidly, especially represented by the two teams of Glauser and Chandler [10].

Based on the research by Dempster, Clause, and Chandler, Gongbing Shan and Christiane Bohn proposed the use of regression coefficients to determine the parameters of various parts of the human body. Their research showed that human parameters could be determined by the following linear regression equation,

$$\psi = \beta_0 + \beta_1 \cdot BM + \beta_2 \cdot BH \tag{1}$$

ψ is the predicted human parameter, BM is the mass of the human body and the unit is *kg*, BH is the height of the human body and the unit is *cm*, β_0, β_1, β_2 are regression coefficients.

According to the design purpose of the humanoid biped robot in this paper, the overall design parameters of the robot are *185cm* and *80kg* (refer to the WHO BMI index of the healthy human body to determine this standard, and its normal value is *18.5-24.9*). Based on the above research and the national standard of "Chinese Adult Human Body Size", the lower limb size parameters of the robot are shown in Table I.

TABLE I.

LOWER LIMB SIZE PARAMETERS OBTAINED BY REGRESSION EQUATION METHOD

	Mass (kg)	*Length (cm)*
feet	1.18	26.32
Calf	2.93	43.20
Thigh	11.35	45.32

	$I_X (kg \cdot cm^2)$	$I_Y (kg \cdot cm^2)$	$I_Z (kg \cdot cm^2)$
Calf	310.38	306.90	39.48
Thigh	1975.43	1973.46	368.20

B. Kinematics and Dynamics of the Hip and Knee Joints

This paper uses Opensim to analyze the kinematics and dynamics of hip and knee joints during a gait walking cycle. Opensim is a powerful software that is widely used in human motion analysis. By using the human skeletal muscle model of Opensim, we can analyze the muscle force and joint force during human movement, create simulations based on the movement data, and perform inverse kinematics and dynamics simulations. The Opensim lower limb skeletal muscle model is shown in Fig. 1.

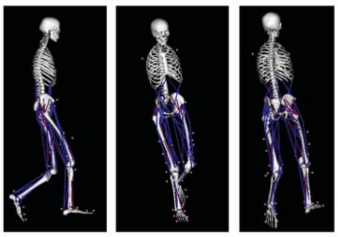

Fig. 1. Opensim lower limb muscle model

This section uses the human skeletal muscle simulation model provided in Opensim and the experimental data of the normal walking gait database "3DGaitModel2354" to perform hip and knee kinematics and dynamics analysis during a gait walking cycle. The kinematics and dynamics analysis of the hip and knee joints are finished and the driving parameters of the humanoid biped robot are determined based on it. The results obtained through the analysis of experimental data are shown in Table II, which provides the standard for the structural design and hardware selection of the robot.

TABLE II.

ANALYSIS OF MAIN MOTION PARAMETERS OF HIP AND KNEE JOINTS

	Max. angle (deg)	*Min. angle (deg)*	*Max. Angular velocity (deg/s)*	*Max. Torque (N • m)*
Hip joint	22.14	-21.19	182	59.14
Knee ioint	0.94	-69.77	400	55.72

III. STRUCTURAL DESIGN OF HUMANOID BIPED ROBOT

A. Structural Design Standards

The humanoid biped robot designed in this paper focuses on the movement and control of the hip and knee joints, and does not consider the motion of the ankle joints. A passive energy storage feet is used in the robot. The human body parameters of 185cm in height and 80kg in weight are used to determine the design standards of every part based on the analysis of human lower limb parameters. Servo motors are used to reach the requirements of precise position, speed, torque control and feedback. The motion ranges of the hip and knee joints of the humanoid biped robot in this paper are designed to realize normal gait movement.

The structural design standards of the humanoid biped robot are as follows:

1. Thigh: Mass *11.4kg*, length *45cm*, center of mass position *20cm*, Moment of inertia I_x $1975kg \cdot cm^2$, I_y $1975kg \cdot cm^2$.

2. Calf: Mass *2.9kg*, length *43cm*, center of mass position *17cm*, Moment of inertia I_y $310kg \cdot cm^2$.

3. Passive foot: Mass *1.1kg*, Length *26cm*.

4. Hip joint: Maximum torque *70N·m*, Maximum rotation speed *40r/min*, Range of flexion and extension angle $(-15^o \sim +60^o)$, Range of adduction and abduction angle $(-10^o \sim +30^o)$.

5. Knee joint: Maximum torque *70N·m*, Maximum speed *80r/min*, Range of motion angle $(0^o \sim +140^o)$.

6. Reserve enough space for adding passive modules (Counterweight module, rope structure, damping, spring and so on).

B. Overall Structural Design of the Humanoid Biped Robot

The main content of this paper is the structural design of the biped robot. The biped robot in this paper has three degrees of freedom. The hip joint has *2* degrees of freedom and the knee joint has *1* degree of freedom. Combining the analysis of human lower limb parameters, an innovative structural design scheme is proposed: a high-torque hip joint that combines two-degree-of-freedom parallel mechanisms was designed; a high-torque knee joint combined with passive energy storage ankle joint was designed. In this paper, the overall structural design and the machine construction of the biped robot were completed. The overall 3D model of the designed humanoid biped robot is shown in Fig. 2.

Fig. 2. Overall 3D model of the humanoid biped robot

C. High-torque Two-degree-of-freedom Hip Joint Design

1) Overall structural design of the hip joint. To realize the two degrees of freedom of the hip joint, a design idea using a two-degree-of-freedom parallel mechanism was adopted. It has the advantages of compact structure, small motion inertia, small cumulative error, and easy inverse solution. The high torque output characteristic of the hip joint is achieved by using servo motors (the maximum torque can reach *70N·m*). Another advantage of this hip joint design is that all the heavy-weight parts including motors, reducers, counterweight modules are designed to be installed above the waist so that the overall mass distribution of the robot is closer to the real human body. The specific structure is shown in Fig. 3.

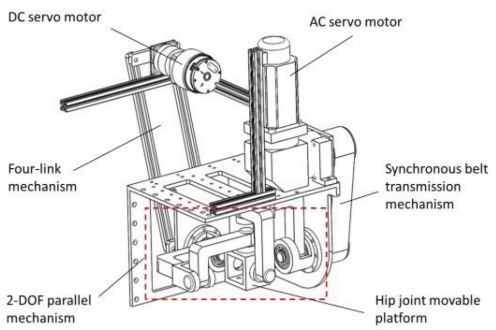

Fig. 3. Specific structure of the hip joint

2) Specific structural design of the hip joint. 2-DOF parallel mechanism consists of hip joint links, hip joint movable platform, deep groove ball bearings and cylindrical pins, and its schematic diagram is shown in Fig. 4. The hip joint moving platform is located at the intersection of the axis of the first hip joint shaft and the axis of the second hip joint shaft. According to the structural relationship of the links, the rotation of the first hip joint shaft can drive the rotation of the hip joint moving platform on the sagittal plane, and the range of motion angle can reach $-15^o \sim +60^o$. The rotation of the second hip joint shaft can drive the rotation of the hip joint moving platform on the coronal plane, and the range of motion angle can reach $-10^o \sim +30^o$. The hip joint movable platform is connected with the thigh connecting plate.

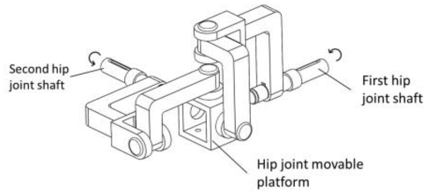

Fig. 4. Schematic diagram of 2-DOF parallel mechanism

The torque of the AC servo motor is transmitted to the hip joint through the synchronous belt transmission mechanism and the 2-DOF parallel mechanism. The torque of the DC servo motor is transmitted to the hip joint through the four-link mechanism and the 2-DOF parallel mechanism. Through the structural design as shown in Fig. 3, the motion control of flexion and extension of the hip joint on the sagittal plane can be realized by controlling the AC servo motor, and the motion control of adduction and abduction of the hip joint on the coronal plane can be realized by controlling the DC servo motor.

D. High-torque Variable-damping Knee Joint Design

1) Overall structural design of the knee joint. The design of the knee joint is very important for the humanoid biped robot. This paper combines the idea of crank-link mechanism to complete the design of knee joint. The specific structure is shown in Fig. 5. The high-torque output characteristic of the knee joint is achieved by using AC servo electric actuator. The single-degree-of-freedom movement of the knee joint is achieved by controlling the telescopic length and speed of the AC servo electric actuator. The biggest features of the knee joint design are light weight (the mass of the knee joint is *0.65kg*), high torque output (the maximum torque can reach *75N·m*), variable damping and compact structure.

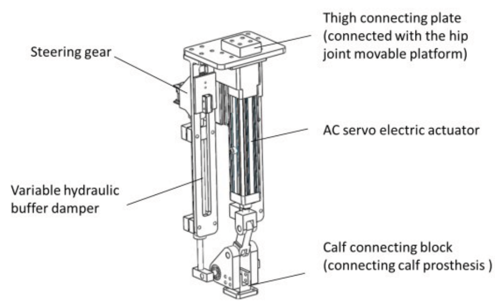

Fig. 5. Specific structure of the knee joint

2) Principle of knee joint structural design. The motion angle of the knee joint designed in this paper ranges from 0^o to

$+140^o$. A simplified model of the knee joint structure is shown in Fig. 6.

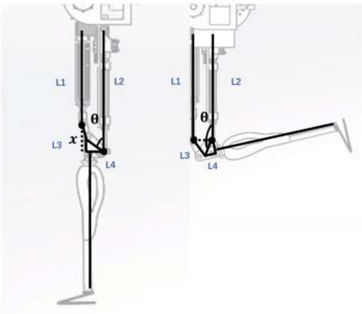

Fig. 6. Simplified model of the knee joint structure

L1 is the AC servo electric actuator, *L2* is the connecting rod composed of the variable hydraulic buffer damper and the fixing plate, *L3* is the knee joint link, and *L4* is the calf connecting block. θ represents the angle formed by the upper side of the calf connection block and the vertical plane, and the designed angle range is $+40^o \sim +180^o$. According to the structural relationship, it can be deduced that the knee joint's motion angle range is $0^o \sim +140^o$. x represents the elongation length of the AC servo electric actuator. According to the determined geometric relationship of the mechanical structure, it can be known that there is a certain corresponding relationship between x and θ, and the corresponding relationship can be flexibly adjusted by changing the distance between *L1* and *L2* or changing the length of *L3* and *L4*. According to the design requirements of the humanoid biped robot at this stage, the distance between *L1* and *L2* is *60mm*, the length of *L3* is *60mm*, and the effective length of *L4* is *60mm*. The corresponding relationship between x and θ is

$$x = 60\sqrt{3} - 60\left(\cos\theta + \sqrt{2sin\theta - sin^2\theta}\right) \tag{2}$$

Considering the structural relationship between the calf connection block and the knee joint motion, it can be concluded that the corresponding relationship between the knee joint motion angle and the elongation length x of the AC servo electric putter is shown in Fig. 7.

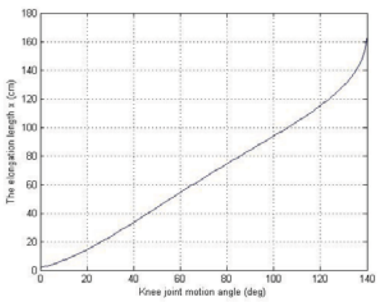

Fig. 7. Relationship between knee joint motion angle and the elongation length x

3) Variable-damping structure design. During normal human gait movement, the maximum knee joint force that the knee joint bears is about four times as heavy as the body weight. In order to reduce the impact damage to the knee joint when the robot is walking, a variable hydraulic buffer damper is selected in the design, and its installation position in the biped robot is shown in Fig. 8. The damping of the variable hydraulic buffer damper can be adjusted by the knob at the end, and the knob is connected to the steering gear through a designed connection plate. According to the experimental test, the damping of the damper can be adjusted flexibly by controlling the rotation of the steering gear.

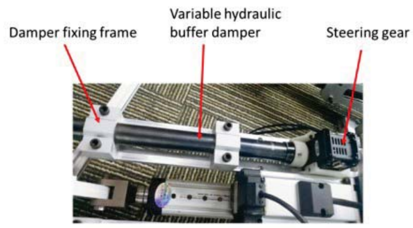

Fig. 8. Installation position of the variable hydraulic buffer damper

In summary, the design of the knee joint makes full use of the spatial position of the thigh structure, which makes the overall structure more compact. The design concept of the crank-link mechanism not only realizes the lightweight of the knee joint, but also makes the knee joint have the characteristics of adjustable damping and shock absorption.

E. Overall Parameters of the Humanoid Biped Robot

According to the design standards of the humanoid biped robot, this paper has completed the robot's structural design, strength check and parts selection, and the machine construction of the biped robot was finished. Fig. 9 shows the prototype of the humanoid bipedal robot.

The overall height of the robot is *1.25m*, the total width of the robot is *380mm*, the total width of the robot is *700mm*, the mass of the passive foot is *0.98kg*, and the remaining quality will be determined according to the actual situation. The most critical design of the biped robot in this paper is the parameters of the thigh and the calf. The actual length of the thigh is *455mm*, the total mass is *7.5kg*. The length of the calf is *420mm*, and the total mass is *2.0kg*. The design of the robot reserves enough space for adding counterweight modules to adjust the center of mass and moment of inertia of each part. The parameters of the completed robot can meet the design requirements of this paper.

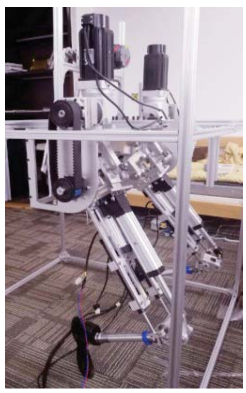

Fig. 9. Humanoid bipedal robot prototype

IV. Experimental Research on Humanoid Biped Robot

In this paper, the structural design of the humanoid biped robot was completed, and an experimental prototype of the robot was constructed. The robot experiments in this section verified the rationality of the structure design of the humanoid biped robot and the feasibility of the control system construction.

A. The Control System Design

Based on the characteristics of the humanoid biped robot designed in this paper, a distributed control system design is adopted. The control system is divided into a main control module, a motion execution module and a sensor module. The structure of the control system of the robot is shown in Fig. 10.

The main control module is the core of the humanoid biped robot control system and it is used to establish a human-computer interaction system, detect the motion status of the biped robot, perform gait planning based on the real-time feedback information of the sensor module, and send control instructions to the motion execution module to complete the coordinated control of each joint motor to control the movement of the humanoid biped robot.

The motion execution module consists of a multi-axis motion controller, servo drivers and motors. The main function is to control the motors to realize joints motion according to the control instructions of the main control module, so that the robot can stably walk, and transmit the relevant state information of the robot to the main control module.

The sensing module consists of IMUs and pressure sensors. The main function is to collect data through sensors and feed back to the main control module in real time, so as to realize the feedback adjustment function of the biped robot.

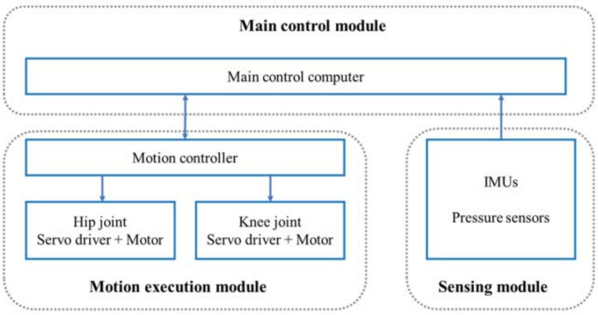

Fig. 10. The structure of the control system of the robot

B. Basic Experiments of the Humanoid Biped Robot

The main purpose of the experimental research is to realize two-degree-of-freedom motion control of the hip joints and single-degree-of-freedom motion control of the knee joints. A support frame was constructed to support the robot.

1) Knee joint motion control experiment. The movement of the knee joint was realized by controlling the AC servo electric actuator. The movement process of the knee joint is shown in Fig.11, and the range of motion angle $\boldsymbol{\rho}$ reached 0^o~$+90^o$ (Maximum range of motion angle during normal human gait walking). The maximum motion angle of the knee joint could reach the designed standard of $+140^o$. The motion control of flexion and extension of the knee joint were realized successfully.

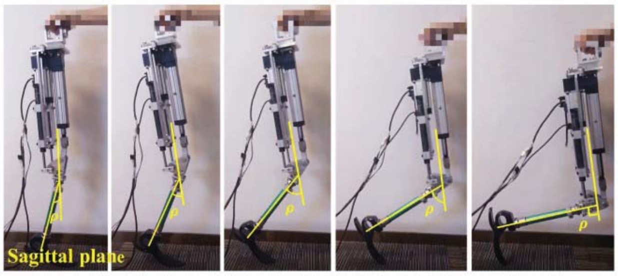

Fig.11. The motion process of the knee joint

2) Hip joint motion control experiment. The movement of the hip joint on the sagittal plane was realized by controlling the AC servo motor. The movement process is shown in Fig. 12, and the range of motion angle θ reached -15^o~$+60^o$. The motion control of flexion and extension of the hip joint were realized successfully.

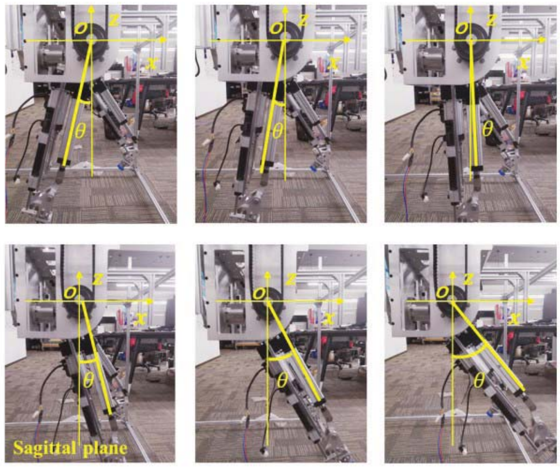

Fig.12. The motion process of the sagittal plane of the hip joint

The movement of the hip joint on the coronal plane was realized by controlling the DC servo motor. The movement process is shown in Fig 13, and the range of motion angle $\boldsymbol{\tau}$ reached -10^o~$+30^o$. The motion control of adduction and abduction of the hip joint were realized successfully.

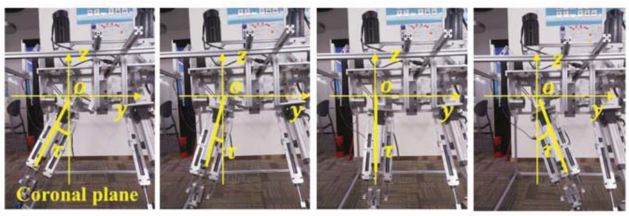

Fig.13. The motion process of the coronal plane of the hip joint

According to the joint motion control experiment, it can be concluded that the structural design of the hip and knee joints of the humanoid biped robot is reasonable, the movement of the joints is flexible, and the range of motion angle and output torque of the joints can reach the designed standards. There is no interference between the mechanical parts and the mechanical assembly is compact. The motion control of the 2-DOF hip joints and the 1-DOF knee joints can be successfully achieved by controlling the servo motors.

V. DISCUSSION AND CONCLUSION

In recent years, research on humanoid biped robots has developed rapidly. A large number of existing robots can achieve many complex movements. However, these biped robots have a common feature. The main focus of these studies is the realization of smooth movement of the robots. Their gait movements are relatively fixed, which are quite different from the real gait movements of the human body, and it is difficult to combine these robots with gait studies of the human body. Pneumatic artificial muscles are widely used in the design of humanoid biped robots, and the biped robot designed by Yang Liu is one of the representatives [11]. But the driving torque of this type of robots is small, and the robots driven by the rope mechanism also have the same problem. Many humanoid robots use series elastic actuators as the power source [12], but the joints of this type of robots are too heavy and the structure of the joints is relatively not compact enough. The link mechanism is also widely used in the joint design of robots, which has a very typical application in the design of human prosthetic knee joints [13].

Based on the current research status of biped robots, this paper innovatively proposed to build a humanoid biped robot based on the analysis of the kinematics and dynamics of human lower limbs. The parameters of the robot were similar to the parameters of real human lower limbs. A hip joint with a two-degree-of-freedom parallel mechanism was designed. It can output large torque by using servo motors as the power source. A high-torque knee joint with the compact structure was designed, which overcomes the problems of overweight and oversized knee joints, and the damping of the knee joint is variable.

The overall structural framework of the robot has been constructed. To achieve the same center of mass and moment of inertia of each part of the lower limb as the real human body, it is necessary to design some counterweight modules in the next step. The robot design also reserves the space for adding passive modules and more passive modules will be designed to make the robot closer to the real human body.

In the future, more in-depth experimental research will be conducted on the humanoid biped robot that has been constructed to make the robot achieve more complex movements such as standing, walking, running and so on. During the experimental research, the designed robot will be optimized iteratively, and a comprehensive experimental platform for the humanoid biped robot will be established, which will have the ability to perform normal gait experiments, pathological gait analysis experiments, fall and anti-fall experiments, lower limb electromechanics product inspection and development functions.

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