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RESEARCH AND DESIGN OF A MOVEMENT COORDINATION CONTROLLER IN THE HUMAN-MACHINE SYSTEM FOR ACTIVE ASSISTED EXOSKELETON ROBOT FOR MINING

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Abstract.
Miners face significant physical strain during their work due to the specific operating conditions of mining enterprises. They often have to move heavy objects, move around mine workings on foot with heavy equipment, and perform various production tasks in confined spaces and poor ventilation.
In this paper, a controller design for a wearable human-machine collaboration system was developed for a prototype of an active exoskeleton for the mining industry. The design of the developed controller with variable resistance for the efficient and stable implementation of walking assistance functions was based on the central pattern generator (CPG).
Thanks to the digital model of the controller and its subsequent verification, it was confirmed that the controller can effectively solve the problems of coordinating movements during the operation of the human-machine collaboration system. In addition, the test results showed that the controller is characterized by high reliability, low latency, and high recognition accuracy.
Moreover, for a limited volume of available sample, the initial recognition accuracy can reach more than 98% with low power consumption for computing tasks, which indicates the potential for using this controller in real conditions in mining enterprises.

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1 Introduction

When it comes to the mining industry, we can't help but think of the darkness deep underground, as well as the brave miners who work hard in extreme environments and make tremendous contributions to our society and economy. However, these miners face significant physical labor and health risks in their daily work. To improve this situation, we need innovative solutions to enhance the efficiency of miners [15], reduce labor intensity, and ensure their safety.

In this context, wearable exoskeleton robot assistive devices for mining have emerged. These exoskeleton robots are not only a technological feat, but also a revolutionary change in the way humans work. They combine knowledge from multiple fields such as mechanical engineering, electronic hardware, algorithm design, and biomechanics, aiming to provide practical assistance to miners. The application of mining exoskeleton robots provides strong support for miners, enabling them to easily move heavy objects and perform various tasks, such as using pneumatic picks. The application of this

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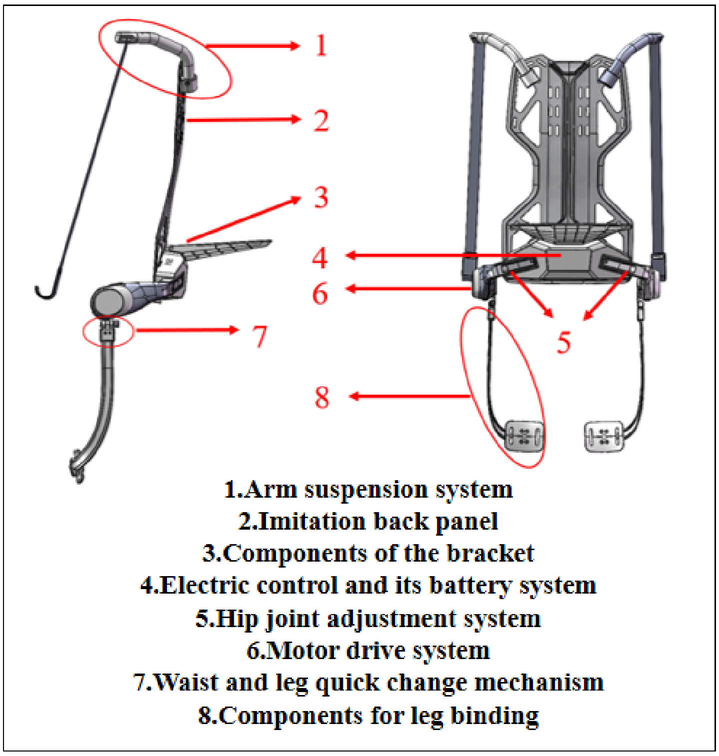
mechanical device can improve the physical fitness of operators in specific aspects such as load-bearing capacity and walking durability [1], while also improving the overall production efficiency of coal mining. Exoskeleton equipment is a type of equipment that combines mechanical structure and intelligent control technology. It mimics the human body structure and is worn by the human body, providing auxiliary strength and protection for the human body.

When the human body wears exoskeleton robots for weight-bearing operations, due to the complex underground road conditions and harsh working environment, the force situation of the exoskeleton human-machine system is also more complex and variable, making it difficult to control the stability of the exoskeleton human-machine system. Therefore, the research on human machine coordinated motion controllers for exoskeleton robots is of great significance, as it directly affects the assistance effect and safety of the human-machine system. Compared with traditional robots, in addition to controlling the device itself, the human body is also a part of the control system, that is, the human body is in the control loop. So, the control system of exoskeleton robots is also a difficulty and research hotspot in their application [2].



(a) Equipment composition unit

(b) prototype walking aid diagram

Fig. 1. Composition and walking aid diagram of an active assistive exoskeleton robot
Рис. 1. Состав и схема активного робота-экзоскелета

In order to effectively control exoskeletons, researchers have proposed many methods. For example, a typical layered control scheme for exoskeleton systems [3-4] involves high-level estimation of user walking intentions, mid-level conversion of user intentions into desired device states, and low-level implementation of desired device states by specific device controllers. In this control architecture, the wearer is not only the commander or supervisor of the system, but also a part of the control loop. For intent recognition algorithms, machine learning algorithms such as SVM and HMM (hidden Markov model) are often used. For example, Zheng et al. [7] used SVM method to recognize the lower limb movement status. To reduce the problem of recognition errors during the transition of movement status, they introduced the quadratic discriminant analysis (QDA) method to identify the movement patterns during the transition stage. Zhao Lina et al. [8] introduced the Hidden Markov Model (HMM) into lower limb motion intention recognition based on the characteristics of human motion patterns, and combined acceleration and plantar pressure signals to achieve pre-recognition of human gait. Researcher Wang Hailian [9] proposed a hybrid control strategy of three perception methods: ① EEG signal ahead recognition of action direction; ② Surface electromyographic signal recognition of lower limb movement patterns; ③ Fiber optic motion capture technology implements feedback on position and posture, and is ultimately integrated and applied to exoskeleton systems. This study constructed a central pattern generator (CPG) network structure and dynamic model for controlling dual hip exoskeleton robots, and designed a human-machine coordinated motion impedance controller based on this biomimetic model. The real-time assistance command generation and online real-time adjustment of trajectory based on human motion feedback were completed.

2 System Composition

Based on the functional requirements analyzed earlier, this study developed a dual hip exoskeleton robot with 4 degrees of freedom as shown in Figure 1. When coal mine operators bend down to carry lighter objects, they can place the heavy objects on the gripper of the prosthetic arm suspension system as shown in Figure 1 (a). At this time, when bending down to carry heavy objects, the force of bending down to lift the heavy objects is mostly achieved by the reverse drive torque T of the motor, which can greatly alleviate waist fatigue of the human body. When coal mine operators carry heavy objects on their backs, they can place the heavy objects on a bracket, as shown in Figure 1 (b). During walking, the motor driving torque T can drive the human thighs to swing, thereby alleviating leg fatigue and improving the work efficiency of coal mine operators.

2.1 Structural composition

The exoskeleton robot designed in this study adopts a dual hip joint dynamic exoskeleton structure, which has good motion flexibility and stability. As shown in Figure 1, the exoskeleton device mainly consists of a prosthetic arm for handling functions, a bracket for carrying materials, and a power transmission component for assisting walking.

As a wearable device, the comfort and safety of wearing need to be considered first, so the overall design of the device adopts a anthropomorphic structural design. Based on the analysis of human motion biology [5] and gait data [12], design the size, joint degrees of freedom, and biomimetic structure of the exoskeleton. To simplify the design of mechanical systems while still ensuring that the robot can work collaboratively with the wearer. Each hip joint has a total of 4 degrees of freedom, including active flexion/extension and passive abduction/adduction, to accommodate the movement of the thighs. In order to be compatible with wearers ranging from 1.55 meters to 1.85 meters, the thigh length is designed for quick replacement, and the waist width is designed for stepless adjustment. Moreover, in order to better transmit force and fit the waist of the human body, the back panel is designed with a humanoid curved shape.

2.2 Drive and Sensor Systems

Related studies have shown [6] that during normal walking in the human body, the hip and knee joints consume the most energy, and the hip joint is greater than the knee joint. Therefore, in the actual work of coal mine workers, the flexion/extension of the hip joint needs to provide the maximum muscle energy. Therefore, in the design process of exoskeleton robots, the active driving joint is designed on the hip joint. The power unit adopts a high energy density three-phase brushless DC motor module, and adopts FOC control algorithm to achieve position, speed, and torque three loop control.

In order to measure joint angles, encoders were installed on the double hip joints of the exoskeleton, and an incremental optical encoder with a resolution of 2000 counts per revolution was used, installed on the motor shaft. IMU is installed on the main structure and constructed using a low-cost MPU-6500 six axis motion tracking sensors. The sensor combines a 3-axis gyroscope and a 3-axis accelerometer in a small package and provides high-resolution measurements (with a gyroscope range of ± 2000 °/s and an accelerometer range of ± 16g). These real-time collected sensors information serve as inputs to the control system, outputting real-time action instructions to drive the system, and ultimately providing real-time assistance to the wearer.

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2.3 Control and Communication System Architecture

The main controller and battery pack are arranged inside the backpack, and the joint controllers and motors are integrated and arranged near the active hip joint. In order to achieve high-speed real-time control, we have developed a dedicated main control circuit board and used CAN communication bus to achieve data communication between the main control node and the electronic control node. The communication rate is set to 1Mbps, and the update frequency of the main controller is 1000Hz, which means that the exoskeleton central motion control system adopts a distributed control structure. It mainly consists of a main control computer and a Controller Area Network (CAN) bus controller (such as a joint drive module). Each drive joint servo control system is connected to the CAN bus interface card through a CAN bus interface circuit. This robot control system has good scalability, convenient disassembly, and good maintainability. Distributed systems require minimal computing resources from the main control computer, and each controller has a light computational burden. The main control computer only needs to focus on trajectory planning, while the distributed controller is responsible for trajectory tracking. Each controller completes position, speed, current feedback, and output pulse width modulation (PWM) drive signals based on control commands from the main control computer, enabling the motor to run to the specified position.

A hierarchical control system was constructed based on the structure of human information perception, decision-making, and motion control, as shown in Figure 2. From top to bottom, it consists of the upper decision-making layer, the middle control and signal conversion layer, and the lower control and driving layer. The function of the entire control system is to provide appropriate assistance to the wearer at appropriate times while ensuring coordinated and smooth movement between the exoskeleton robot and the wearer.

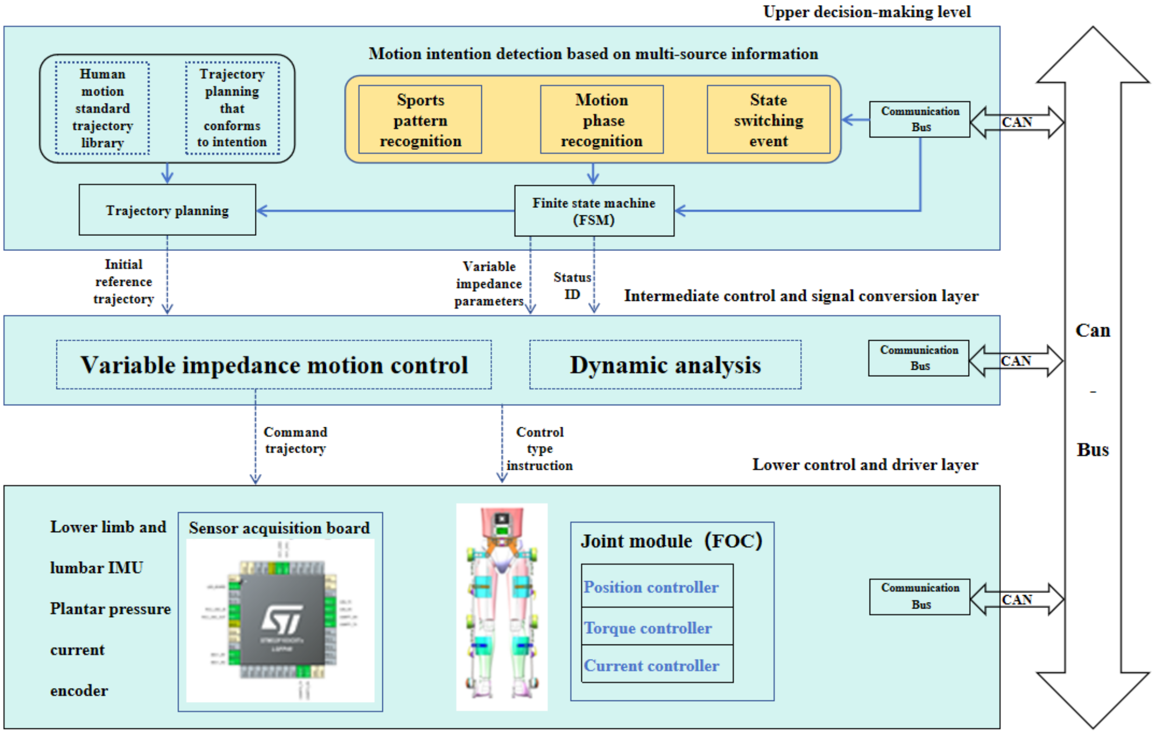

Fig. 2. Hierarchical Control System Architecture
Рис. 2. Иерархическая структура системы управления

The upper decision-making layer is the core of the entire control system, mainly completing tasks such as identifying human motion intentions, state switching based on finite state machines (FSMs), and online joint trajectory planning. The switching of FSM from one state to another requires the wearer's movement intention as the triggering condition. Moreover, in order to achieve flexible control of exoskeleton robots and timely assist control, the wearer's movement intention must also be accurately identified. The main function of the intermediate control and signal conversion layer is to call the corresponding dynamic model based on the identified motion states and generate real-time and online command curves for each joint motor. These trajectory curves serve as inputs to the lower control layer, and the motion control of the exoskeleton robot joints is achieved through the rotation vector control FOC algorithm integrated within each joint module. The FOC control algorithm in this system adopts a three-loop control structure of position, speed, and torque. In order to facilitate the switching of multiple motion modes, this system can freely switch between multiple motion modes through preset switch commands.

3 Establishment and Analysis of Human Exoskeleton Coupling Model

The human exoskeleton system is a human-machine coupling system, in which humans act on the entire control loop. In order to develop human-machine coordinated motion control algorithms, it is necessary to establish a suitable mathematical model to describe the coupling relationship between the exoskeleton and the human body. This chapter will introduce the derivation and analysis of the human exoskeleton coupling model.

3.1 Gait cycle and phase division

In natural gait, the angle change of the hip joint is a periodic curve, but the period and amplitude of the curve will change with changes in stride length and stride frequency. During walking and jogging, the angle curves of the left and right hip joints exhibit periodicity and consistency. Except for a phase difference of half a cycle, the peak and period of the two angle curves are basically consistent. During walking, a single gait cycle T includes standing and swinging phases, with standing phase accounting for about 60% and swinging phase accounting for about 40%. The trend of hip joint angle variation is stable, as shown in Figure 3.

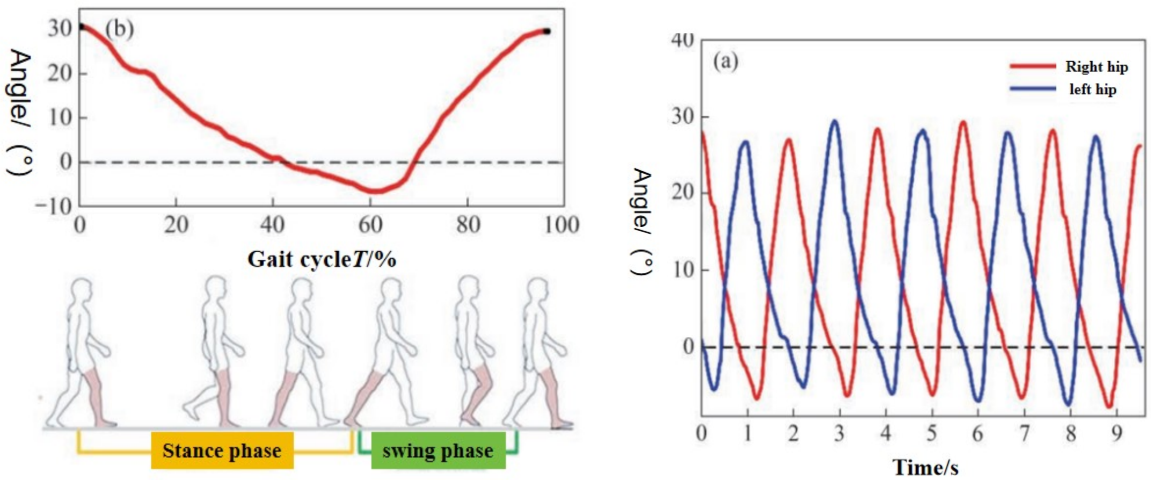

Fig. 3. Periodicity of Gait Cycle
Рис. 3. Цикл походки

Human gait analysis is the basis for assisting in the formulation of control strategies. Taking human gait analysis as an example, Figure 4 presents several gait phase analysis diagrams of the human body from an upright state to walking. This study divides a complete gait cycle into four phases, namely the right foot forward bipedal support phase (RDS), left foot swing phase (LS), left foot forward bipedal support phase (LDS), and right foot swing phase (RS).

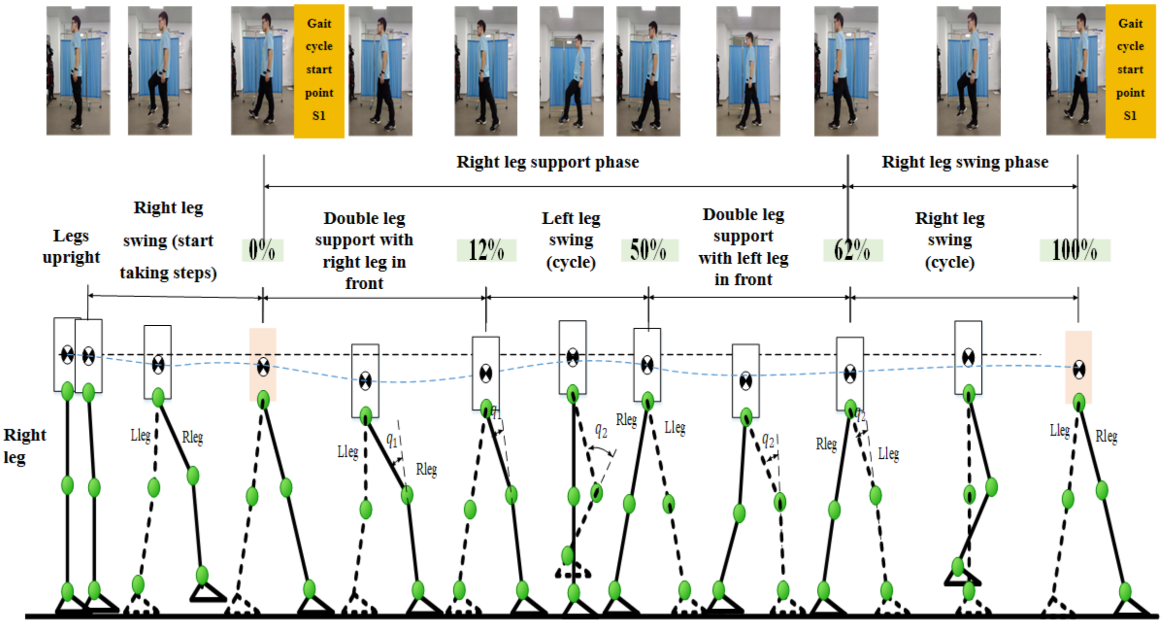

Fig. 4. Gait Phase Division
Рис. 4. Разделение походки по фазам

3.2 System biomechanical model

As an intelligent wearable device exoskeleton assistance system, the closed-loop feedback control system of the entire human-machine system requires the collaboration of two dynamic control systems (human motion control system and exoskeleton control system). In order to achieve a common goal, these two systems need to adapt to each other. People are also included in the control loop, known as Man In the Loop (MIL). For hip joint waist handling and assistive exoskeletons, it belongs to a single joint robot in terms of structure, which can be simplified into a fixed joint and a connecting rod hinged composition, as shown in Figure 5.

Calculate the dynamic equation using the Lagrangian method as follows (1). Among them, L is the Lagrangian, defined as the difference between the kinetic energy KE and the potential energy PE of a moving body or system, namely $L = KE - PE$.θ is a generalized coordinate system,$\dot{\theta}_i = \partial\theta_i/\partial t$ is the generalized velocity.

$$\tau = \frac{\partial}{\partial t}\left(\frac{\partial L}{\partial \dot{\theta}_i}\right) - \frac{\partial L}{\partial \theta_i} = \left(I_c + m{l_c}^2\right)\ddot{\theta} + mg\,sin(\theta)\,l_c \quad (1)$$

The above dynamic formula describes an ideal dynamic model, but in practical systems, the friction force of joints also needs to be considered. After considering the friction force, the dynamic formula is:

$$\tau - \tau_f = \left(I_c + m{l_c}^2\right)\ddot{\theta} + mg\,sin(\theta)\,l_c \quad (2)$$

Among them τ_f is the friction torque at the joint. The friction force formula at the joint can be established through Coulomb friction and viscous friction:

$$\tau_f = k_c + k_v\dot{\theta} \quad (3)$$

Among them k_c is the Coulomb friction coefficient and k_v is the viscous friction coefficient. By substituting the above equation into the kinetic formula, it can be obtained that:

$$\tau = \left(I_c + m{l_c}^2\right)\ddot{\theta} + k_v\dot{\theta} + mg\,sin(\theta)\,l_c + k_c \quad (4)$$

Through the above motion equations, we can calculate the joint torque required to complete this motion based on real-time collected angle and angular velocity sensor data, providing necessary information for servo control of subsequent movements.

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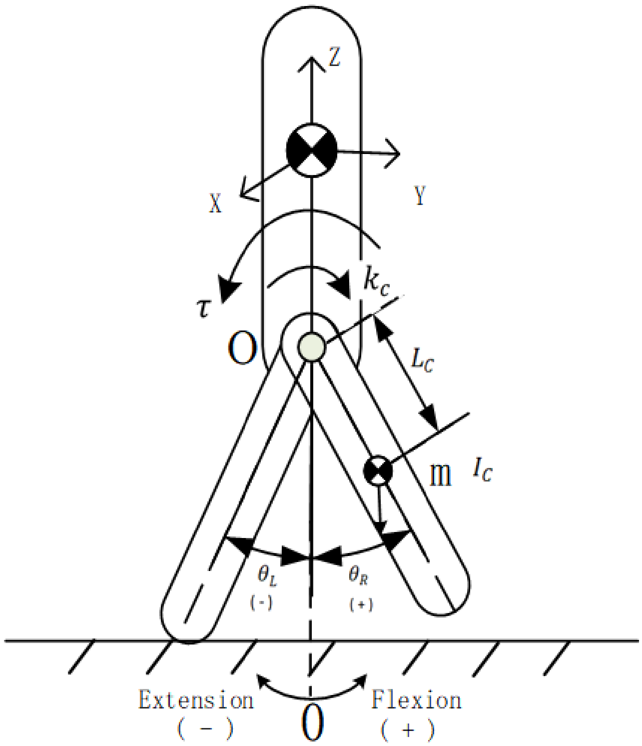

Fig. 5. Simplified model for force analysis of exoskeleton robots
Рис. 5. Упрощенная модель для силового анализа робота-экзоскелета

4 Control system design and simulation

The lower limb wearable enhanced exoskeleton robot is a highly coupled system between humans and machines. In order to achieve flexible motion control and achieve reliable assistance control for the wearer, it is necessary to accurately identify and predict the wearer's motion intention in real time. Then, design an intelligent and efficient control algorithm to achieve precise control of the exoskeleton.

4.1 Simulation system for human-machine coupling system

The design of control systems begins with precise human-machine physical models. Its complex dynamic model can be modeled through data-driven (i.e. system identification) or based on mechanical principles.

This study adopted a Central Pattern Generator (CPG) specialized neural network architecture and combined it with a variable impedance controller to develop a human-machine coordinated motion controller. Finally, the various mode states are integrated into a complete control system using a finite state machine (FSM) [13]. This study used MATLAB/SIMULINK to develop simulation models for various possible working conditions. The left figure in Figure 6 shows a multi joint universal human exoskeleton coupling system control simulation platform. By using this model, the force and motion relationships of human-machine systems can be studied offline, and dynamic systems can be simulated and analyzed before being put into use. System parameters can be adjusted in a timely manner, providing important data for practical scenario use and exoskeleton control, ultimately achieving the goal of rapid development. The human-machine model on the right side of Figure 6 shows the motion modeling of the human-machine system using the Simscape tool. The advantage is that the mathematical model can be associated with the model constructed by Solidworks, and the connection between various modules, joint driving, and information sensing are also very convenient. For universality, models including hip, knee, and ankle joints were modeled here.

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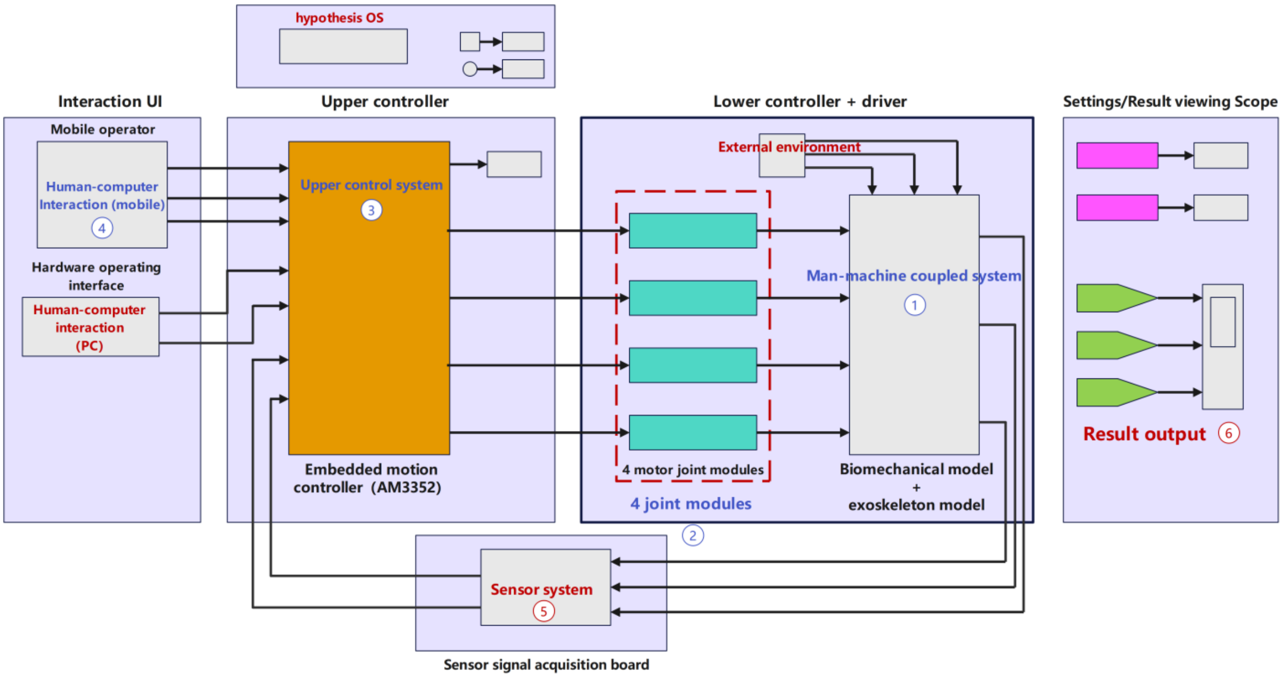

Fig. 6. Simulation model of human exoskeleton coupling system based on SIMULINK
Рис. 6. Модель системы взаимодействия между человеком и экзоскелетом на основе SIMULINK

In order to achieve motion control of exoskeletons, classic control algorithms or modern control theories can be chosen for controller design. For example, PID (Proportional Integral Differential) controller is a classic feedback control algorithm. It can adjust the output based on the state error of the exoskeleton to approach the target state. The PID controller is simple and easy to use, but parameter adjustments need to be made according to specific application scenarios. Fuzzy control is a control method based on fuzzy logic. It can handle uncertainty and fuzziness and is suitable for controlling exoskeleton robots in complex environments. Fuzzy control requires building a fuzzy rule library and conducting fuzzy inference based on input states. Neural network is a computational model based on biological neurons. By training neural networks, we can achieve adaptive control of exoskeletons. Neural network control is suitable for complex nonlinear systems, but requires a large amount of training data and computational resources. This study comprehensively considers the robustness of control and the real-time performance of computation and proposes a variable impedance control algorithm based on motion pattern generator (CPG).

4.2 Design of Variable Impedance Controller Based on CPG

The existing hip joint assistance algorithms can be mainly divided into two categories based on gait phase estimation methods [14], namely oscillator-based methods and finite state machine (FSM) based methods. In oscillator-based methods, the gait period (0-100%) is continuously estimated by an adaptive oscillator. In FSM based methods, gait events, such as foot landing/toe off (or standing/swinging phase), are detected discretely by FSM conversion rules. Although the two groups have significant features in gait recognition, they follow a common feedforward-based control rule: 1) Firstly, estimate the gait stage and parameters (such as speed, leg swing time) based on the user's previous steps; 2) Then generate auxiliary torque. The assistance switching under different sports modes is presented with continuity through a low-pass filter to ensure the continuity of torque commands.

CPG is a neural network that can generate rhythmic neural signals. It can simulate the basic patterns of human gait and adaptively adjust based on external feedback. This section constructs the central pattern generator CPG network structure and dynamic model for controlling dual hip exoskeleton robots, and designs a human-machine coordinated motion impedance controller based on this biomimetic model, completing the generation of real-time assistance commands and real-time online adjustment of trajectories based on human motion feedback.

1) Dual hip joint CPG neural network model

The advantage of a CPG controller is that it can generate coordinated rhythmic activity patterns, such as walking, running, etc., without external rhythmic inputs. It can also adjust the control output in real-time based on the feedback signals from sensors. This study used a Matsuoka oscillator model based on neural oscillator networks [10-11]. This network can adjust the shape and symmetry of the output signal through its own state variables.

The Matsuoka oscillator mathematical model is a mathematical equation used to describe the dynamic behavior and interaction of each neuron or neural oscillator in a CPG network. The dynamic differential equation of a single neuron in this model is represented by the following three nonlinear first-order differential equation systems.

$$T_r \frac{dx_i}{dt} + x_i = -\sum_{j \neq i} a_{ij}[x_i]^+ - b_i f_i + S_i + (-1)^{i-1} P_k \tag{5}$$

$$T_a \frac{df_i}{dt} + f_i = [x_i]^+ \tag{6}$$

$$g(x_i) = [x_i]^+ = max\,(0, x_i) \tag{7}$$

In the formula, i=1,2⋯; $g(x_i)$ is the output of the i-th neuron;x_i is the internal state variable of the i-th neuron; f_i is the state variable representing self inhibition of neurons (fatigue strength variable of the i-th neuron) ;$b_i$is the degree of self inhibition (fatigue strength coefficient); S_i is the steady-state input variable for the i-th neuron; a_{ij} is the weight coefficient of the connection between the jth neuron and the i-th neuron; T_r is the signal rise time constant (internal state time constant);T_a is the time constant for neuronal fatigue or adaptation; P_k is to input an external signal of the k-th neural oscillator, such as a sensor signal; The function max $(0, x_i)$ represents taking the maximum value between 0 and x_i.

2) CPG based adaptive impedance controller

This system uses a CPG based adaptive impedance controller to generate motor torque commands. The CPG network takes joint angles as input and outputs torque commands. This command serves as the input for the human-machine positive dynamics model and outputs motion data, namely the desired joint angle and angular velocity trajectory. The feedback motion sensor data and the generated motion information are used as inputs to the impedance controller, and finally output motor force control commands. This method adopts a human-machine coupling model to design a motion controller, which can achieve better human-machine coordination and safety. At the same time, it adopts a central mode model that simulates human periodic motion, which can better and quickly adapt to external changes. Compared to iterative learning algorithms, low-cost and low computing power processors can be used to achieve real-time assistance.

Figure 7 shows the control system architecture of the human-machine coupling system.

4.3 Simulation analysis

Convert the differential equations 5-7 of the hip joint controller into differential equations and construct its simulation model in Simulink as shown in Figures 8 and 9.

The coupling mode and strength parameters are determined through simulation as shown in Table 1. The hip joint angle is used as an input for the adaptive oscillator module to estimate gait phase. The gait phase is used by the torque generation module. As long as the user walks, all activated degrees of freedom are torque controlled. The start and end of walking assistance are determined by the state of the left and right foot FSM. The assistance size parameter is modulated by walking speed and walking gait mode. For example, producing smaller torque at lower speeds.

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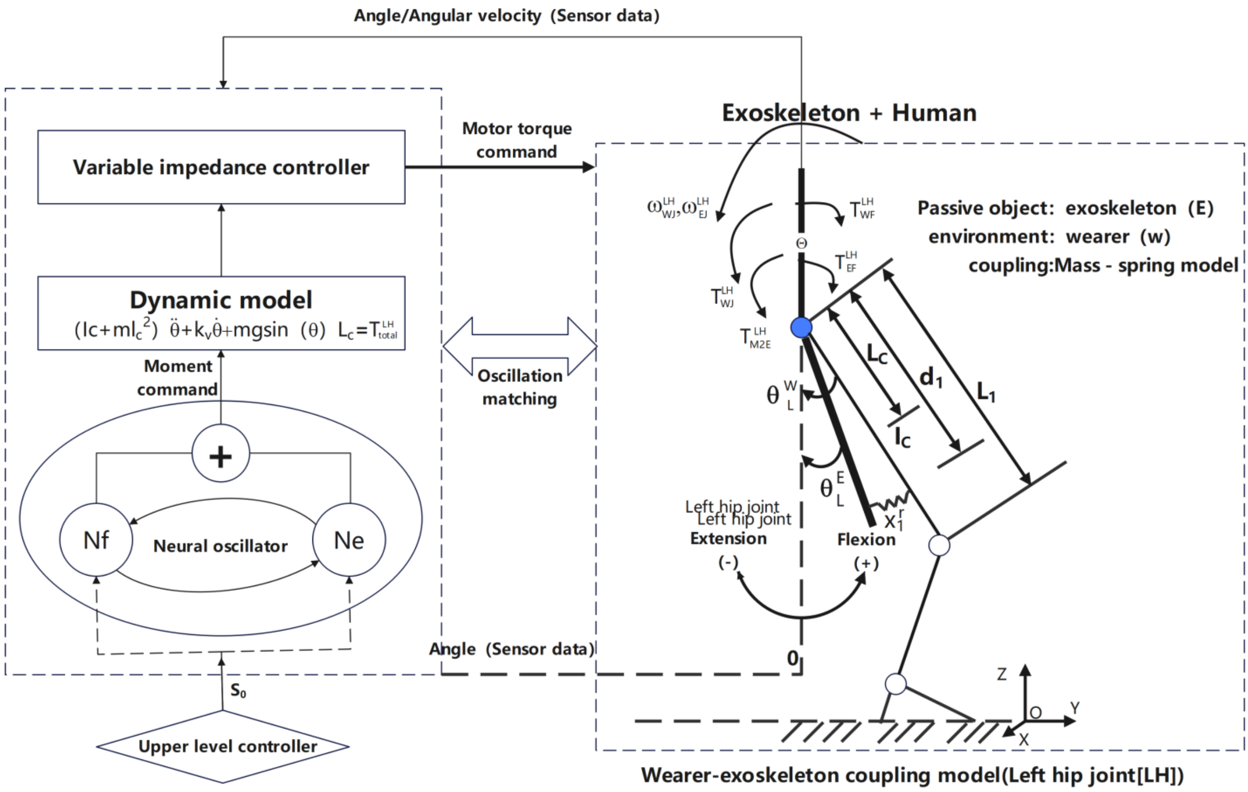

Fig. 7. Architecture of CPG based adaptive impedance control system

Рис. 7. Структура адаптивной системы управления переменного сопротивления на основе CPG

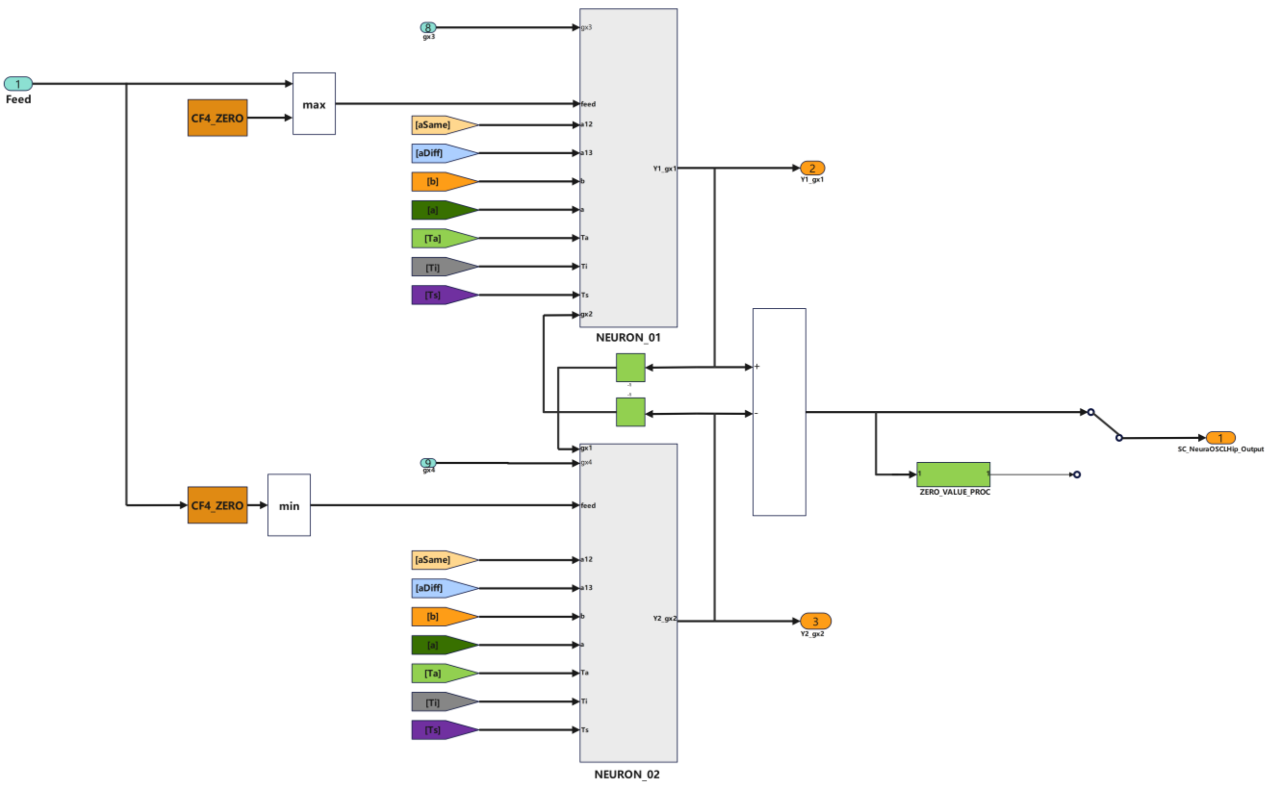

Fig. 8. Simulation model of unilateral hip joint oscillator

Рис. 8. Модель генератора колебаний одной стороны тазобедренного сустава

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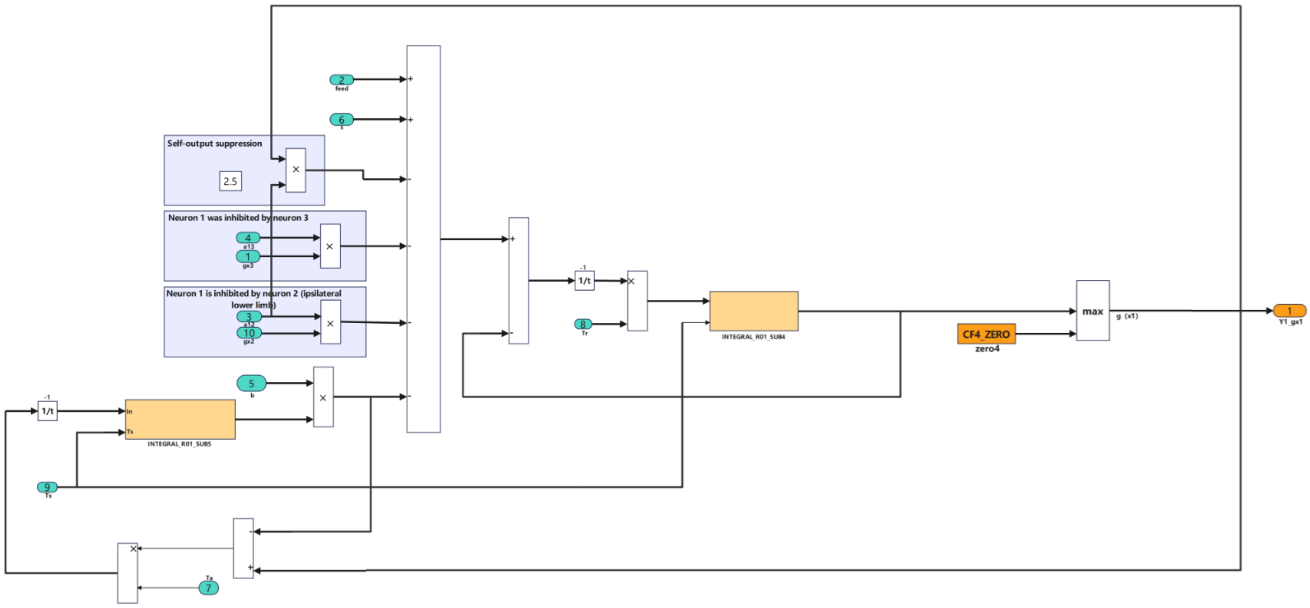

Fig. 9. Simulation model represented by the difference equation of hip flexor neurons
Рис. 9. Модель разностного уравнения нейронов сгибания бедра

Table 1. Controller Parameter Values
Таблица 1. Значения параметров контроллера

Parameter symbols	Parameter significance	Value
T_r	Signal rise time constant	0.04
T_a	Neuron fatigue or adaptation time constant	0.5
$b_1 = b_2 = b$	fatigue strength coefficient	2.5
p_0	Neuron steady-state input variables	10
$a_{13} = a_{31} = a_{42} = a_{24}$	The connection weight coefficient of neurons	1
$a_{12} = a_{21} = a_{43} = a_{34}$	The connection weight coefficient of neurons	2

Figure 10 shows the result graph of real-time assistance trajectory curve generation using dual hip joint angles as inputs to the CPG network. From the graph, it can be seen that during the flexion movement of the lower limbs of the human body, except for the initial stage, stable assistance curves are generated in real-time during the stable gait cycle. The red dashed line in the following figure represents the starting time of the assistance theory. The statistical results show that the recognition accuracy at the start of assistance reaches over 98%. The bottom figure of Figure 10 also shows the identification ID results through gait phase, and it can be seen that good prediction results have been achieved. Under the limited sample size, the recognition accuracy of each phase is 100%.

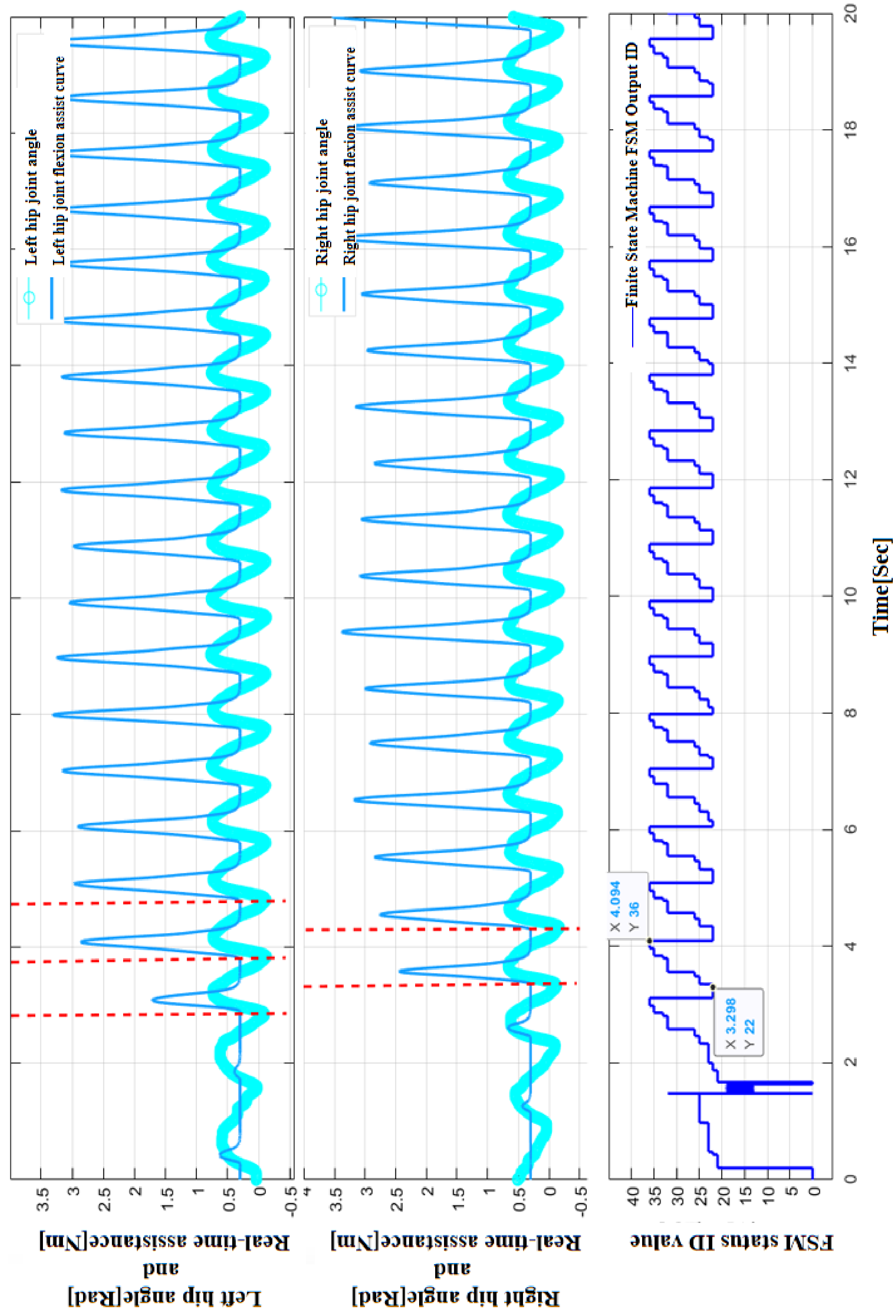

Fig. 10. Power curve generation and finite state machine ID

Рис. 10. Построение кривой мощности и идентификатор равномерного переключения состояний

5 Conclusion

This article mainly focuses on the development of an active assistive exoskeleton robot for mining operations. The system is expected to improve the efficiency of workers and reduce the risk of musculoskeletal diseases, thereby maintaining their physical health.

The design of the controller for this active assistive exoskeleton robot, as a wearable human-machine coupling system, is the first challenge to be overcome. This paper mainly focuses on the implementation of efficient and stable walking assistance functions, and designs a variable impedance controller based on the Central Mode Generator (CPG) network. Through simulation and real machine verification, it has been proven that the controller can efficiently achieve human-machine coordinated motion control tasks. Meanwhile, the experimental results show that the controller has good robustness, low latency, and high recognition accuracy.

In the future, we plan to test the performance of exoskeleton robots in actual coal mining operating environments. By collecting and analyzing experimental data, we can further optimize control algorithms and improve the stability and adaptability of exoskeletons. Moreover, we hope to apply exoskeleton robots to a wider range of fields, such as other heavy labor industries, rehabilitation medicine, and emergency rescue. Through continuous research and innovation, we can create a healthier and more efficient working and living environment for humanity.

Conflicts of Interest

The authors declare no conflict of interest.

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ИССЛЕДОВАНИЕ И РАЗРАБОТКА КОНТРОЛЛЕРА КООРДИНАЦИИ ДВИЖЕНИЙ В СИСТЕМЕ «ЧЕЛОВЕК-МАШИНА» ДЛЯ АКТИВНОГО ЭКЗОСКЕЛЕТА ДЛЯ ГОРНЫХ РАБОТ

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Ключевые слова: экзоскелет для горной промышленности; система человеко-машинного взаимодействия; центральный генератор упорядоченной активности; контроллер с переменным сопротивлением, моделирование.

Аннотация.
Шахтеры в процессе производственной деятельности сталкиваются со значительными физическими нагрузками из-за специфических условий функционирования горных предприятий. Зачастую необходимо передвигать тяжелые предметы, перемещаться по горным выработкам пешком с тяжелым снаряжением и выполнять различные производственные задачи в условиях ограниченного пространства и плохой вентиляции.
В рамках данного исследования для прототипа экзоскелета активного типа для горной промышленности был разработан дизайн контроллера для носимой системы взаимодействия человека и машины. В основу дизайна разработанного контроллера с переменным сопротивлением для эффективной и стабильной реализации функций помощи при ходьбе был положен центральный генератор упорядоченной активности (ЦГУА).
Благодаря цифровой модели контроллера и ее последующей верификации было подтверждено, что контроллер может эффективно решать задачи координирования движений при функционировании системы взаимодействия человека и машины. Кроме того, результаты испытаний показали, что для контроллера характерны высокая надежность, низкая задержка и высокая точность распознавания.
При этом для ограниченного объема доступной выборки первоначальная точность распознавания может достигать более 98% при низком энергопотреблении для проведения вычислительных задач, что указывает на потенциал применения данного контроллера в реальных условиях на горных предприятиях.

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