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Molecular & Cellular Biomechanics 2025, 22(2), 1014.
https://doi.org/10.62617/mcb1014

Article

Research on the structural design of exoskeleton assisted transport robot combined with reinforcement learning algorithm under the background of artificial intelligence

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CITATION

Liu Z. Research on the structural design of exoskeleton assisted transport robot combined with reinforcement learning algorithm under the background of artificial intelligence. Molecular & Cellular Biomechanics. 2025; 22(2): 1014. https://doi.org/10.62617/mcb1014

ARTICLE INFO

Received: 5 December 2024
Accepted: 30 December 2024
Available online: 21 January 2025

Abstract: With the comprehensive interface between "Made in China 2025" and Industry 4.0, the handling mode of the handling system is constantly updated and developed, and a new type of handling mode, which is assisted by exoskeleton and other equipments to complete the handling work of workers, has been gradually applied. However, most of the existing exoskeleton-assisted robots are expensive and complicated in structure, which are not applicable to the actual needs of ordinary workers. Therefore, it is of great significance to design an exoskeleton-assisted handling robot that is applicable to the needs of ordinary workers. Based on this, this paper designs a relatively simple structure and low cost exoskeleton-assisted handling robot, and introduces the BN-Q-learning algorithm to give the control strategy of the robot, and finally simulates and analyzes the reliability of the handling robot, and the results show that the exoskeleton-assisted handling robot designed in this paper has a high reliability, and the force situation and the human body's joints are relatively well matched when handling heavy objects. The results show that the exoskeleton assisted handling robot designed in this paper is highly reliable, and the force situation when handling heavy objects matches the human body joints.

Keywords: artificial intelligence; exoskeleton robot; BN-Q-learning algorithm; structural design; virtual prototype simulation

1. Introduction

It is expected that by 2030, there will be 348 million elderly people over the age of 60 in China, accounting for 24.1% of the total population. Social development has entered a stage of rapid aging, which will lead to fewer and fewer physical workers of suitable age. Moreover, for the workers who have been engaged in physical labor for a long time, many workers have caused certain damage to their bodies in the process of work due to the long-term physical work and lack of protection in the work process.

As an important branch of service robot research, exoskeleton robot is a comprehensive technology that integrates a variety of disciplines to provide help for the wearer and can be easily worn on the human body. As a kind of robot coordinating with human body, exoskeleton robot can provide support and protection for human body in the process of movement, and can follow the human body coordinated movement, and enhance the human movement function during the movement. Therefore, a suitable exoskeleton assisted handling robot can be more flexible to adapt to the working environment of the wearer, provide strength assistance for the wearer in a more complex working environment, and protect the body damage that may be caused by the wearer during the work process.

As a comprehensive technology integrating a variety of disciplines, the current research on exoskeleton assisted robot has become a hot spot at home and abroad. Yamamoto et al. [1] optimized the mechanical system and sensing system of the wearable energy assisted suit designed, increased the torque provided by the drive system, and finally proved the feasibility of the design through experiments. Naito et al. [2] designed a spring as the power of semi-automatic exoskeleton upper limb power robot, and the test showed that the robot can provide more stable force assistance for the wearer in a specific working state. Ryu et al. [3] analyzed the kinematics and dynamics of the full-body exoskeleton assisting robot, and calculated that the exoskeleton model could bear most of the mass of the heavy objects carried by using the load distribution algorithm of the exoskeleton and the human model. Yu [4] discussed the commonly used control algorithms for lower extremity power assisting robots. The designed exoskeleton robot uses hydraulic system as driver, and chooses appropriate robot sensor and control system. Yu et al. [5] designed a new exoskeleton driving mechanism for the exoskeleton power assisting robot. Only when bending over to carry objects, the robot will start to help the back of the human body, making the force assistance more targeted. Zhao et al. [6] placed the robot sensor in the exoskeleton boot of the robot to optimize the design of the exoskeleton robot sensor system. Different sensors are selected for comparative analysis in view of the low accuracy and poor stability that may exist in the movement process. The results show that FlexiForce A201 sensor is more suitable for use as a sensor for lower extremity exoskeleton robots. Gao et al. [7] designed a wearable full-body exoskeleton assisted transport robot with relatively simple structure, which provides assistance to the waist when the human body bends over to carry heavy objects, and the elbow joint is designed as a self-locking mechanism. The simulation analysis and joint control simulation of the gait motion of the exoskeleton assisted transport robot were carried out. The research results show that the gait simulation movement of the designed exoskeleton assisted carrying robot is consistent with the actual data of the human body, which verifies the stability and reliability of the designed structure.

To sum up, a lot of research has been carried out on exoskeleton assisted robots at home and abroad, from the single-function upper limb exoskeleton assisted robot and lower limb exoskeleton assisted robot, to the full-body exoskeleton assisted robot that can meet the needs of wearers with more functions [8–10]. Compared with lower limb power robot, the whole-body exoskeleton power robot has a more complex structure and control mode, and its main purpose is to provide help for the human body in the process of upper limb and lower limb movement. Although the research of exoskeleton assisted robot has achieved a lot of results, the control mode and structure of the designed exoskeleton robot are mostly relatively complex, which makes the cost of the exoskeleton assisted robot more expensive, and is not suitable for the actual needs of ordinary workers in society. Based on this, this paper presents a design study for exoskeleton-assisted handling robots using the BN-Q-learning algorithm.

The research organization and innovation of this paper are: based on the analysis of human movement, the main design principles of safety, anthropomorphism and versatility of exoskeleton assisted handling robot are summarized. Under the guidance of the design principles, the main structure of the upper limbs, lower limbs and back support of the exoskeleton assisted transport robot is designed. According to the designed main structure, the key components are designed. The control strategy of the robot is given by introducing the BN-Q-learning algorithm, and in order to verify the reliability of the handling robot, virtual prototype simulation is used to establish the driving function of the handling action of each joint for simulation and analysis.

2. Overall design of exoskeleton assisted handling robot

2.1. Design principles

According to the actual needs of ordinary workers, the main functions of the designed exoskeleton assisted handling robot should be the handling assistance function and the supporting role of heavy objects in the process of gait movement [11]. The design of the exoskeleton assisted handling robot should follow the following design principles:

(1) Safety principle, the design of the exoskeleton assisted handling robot needs to work closely with the human body in the actual work process.
(2) Anthropomorphic principle, the designed exoskeleton structure should be able to work closely with the human body.
(3) The principle of universality, because the designed exoskeleton assisted handling robot structure needs to be worn together with different human bodies in the actual work process, the designed exoskeleton assisted handling robot needs to fully take into account the versatility of the designed structure.

2.2. Basic dimensions of the human body

Considering that the designed handling robot needs to be worn, the robot structure size should be designed according to the human body size. The human size data referred to in this paper comes from GB10,000-88, and the specific data is shown in **Table 1**.

Table 1. Chinese adult male body size table.

Percentiles	10	50	90	95	99
4.1.1 Height (mm)	1611	1686	1764	1789	1830
4.1.2 Weight (Kg)	50	57	66	70	78
4.1.3 Upper Arm (mm)	294	313	333	339	350
4.1.4 Forearm (mm)	221	237	254	259	269
4.1.5 Thigh (mm)	440	469	500	509	532
4.1.6 Calf (mm)	346	372	399	407	421

2.3. Exoskeleton assisted handling robot frame

According to the above design principles and the basic size of the human body, the overall design framework of the exoskeleton assisted handling robot given in this paper is shown in **Figure 1**.

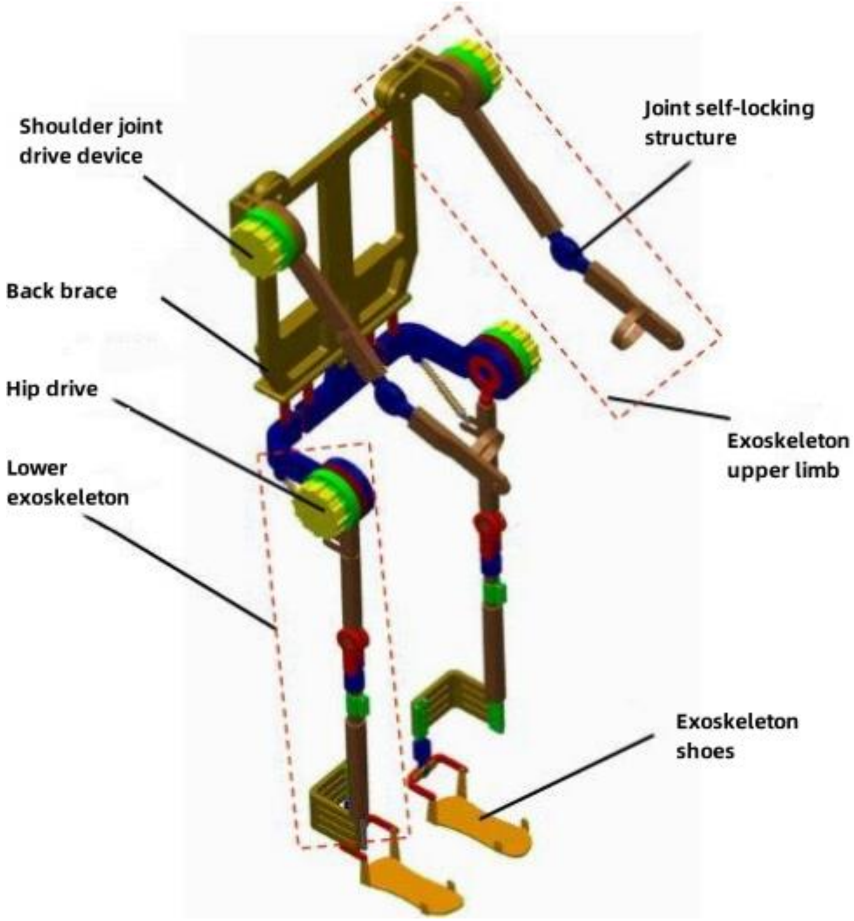

Figure 1. Frame of exoskeleton assisted carrying robot.

In the structural design of the exoskeleton assisted carrying robot, because the exoskeleton needs to be used with the human body, according to the above analysis of the main joints of the human body, it is necessary to first determine the degree of freedom of the joints of the designed structure. In the process of determining the size of the exoskeleton limbs and back of the exoskeleton power carrying robot, the size data mainly refer to the Chinese adult male human body size table, because the body size difference of different wearers needs to be considered, so that the exoskeleton robot can be applied to most people, so the limbs and back supports of the exoskeleton power carrying robot can be adjusted [12]. The scope of the size selection standard is in line with the body size of 10% to 99% of people in society, which covers the size of the vast majority of adult men in China, and also meets the design principle of the universality of the exoskeleton power carrying robot.

2.3.1. Design of upper limb structure

The upper limb structure design of the exoskeleton assisted transport robot is shown in **Figure 2**. The designed exoskeleton upper limb structure mainly consists of exoskeleton joints, exoskeleton limbs, elbow joint self-locking structure and driving device. The size of the exoskeleton assisted handling robot should cover the size range of 10% to 99%. Therefore, according to **Table 1**, the size range of the upper arm of the exoskeleton is 294 cm to 350 cm, and the size range of the lower arm of the exoskeleton is 221 cm to 269 cm.

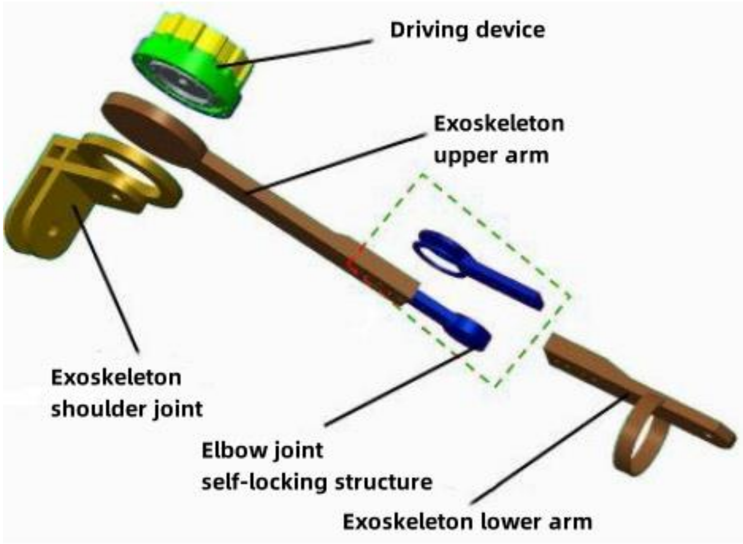

Figure 2. The structure diagram of upper limb.

2.3.2. Design of lower limb structure of exoskeleton

The lower limbs of the designed exoskeleton assisted handling robot are shown in **Figure 3**. One end of the exoskeleton thigh adjustment mechanism is connected with the exoskeleton waist rotation, and the other end is connected with the exoskeleton knee joint through the bearing rotation [13]. Since the inner side of the exoskeleton lower limb is designed to be hollow, the lower end of the telescopic structure can be inserted into the exoskeleton lower limb and connected together by bolt fixation. According to the previous analysis, the size of the exoskeleton assisted handling robot needs to cover 10%~99% of the size range. Therefore, according to **Table 1**, the size range of the exoskeleton thigh is 440 cm~532 cm, and the size range of the exoskeleton calf is 346 cm~421 cm.

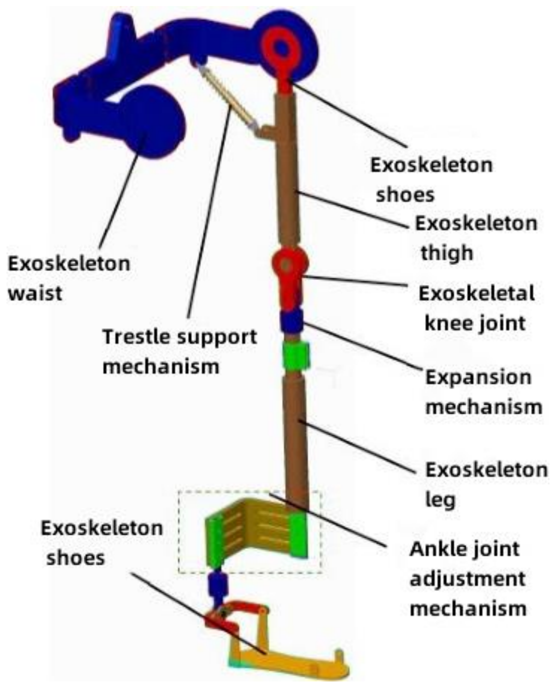

Figure 3. The structure diagram of lower limb.

2.3.3. Design of lower limb

The design structure of the exoskeleton back system is shown in **Figure 4**. The back system is mainly composed of an exoskeleton shoulder joint, an exoskeleton waist, a support buffer device and a threaded pipe [14]. The exoskeleton waist is connected together by threaded tubes, which rotate into the exoskeleton waist mechanism during the connection process.

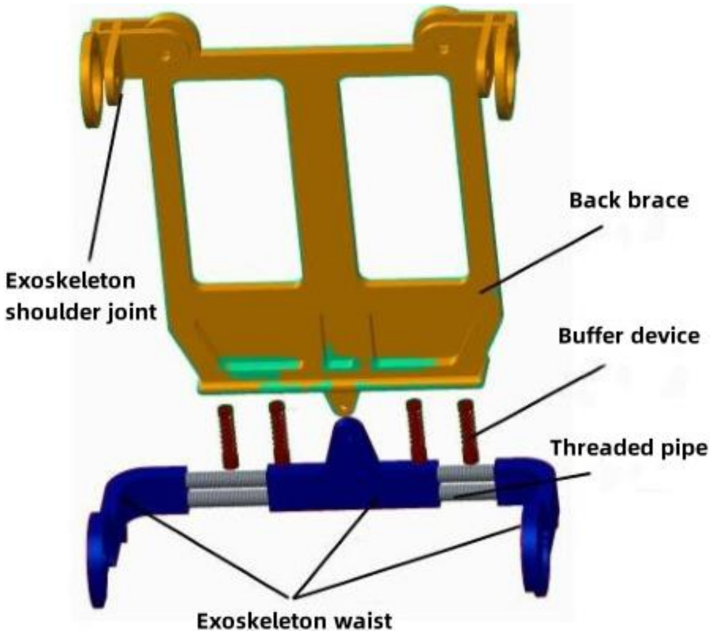

Figure 4. The structure diagram of back bracket.

3. Key structure design of exoskeleton assisted handling robot

3.1. Drive system design

The drive system of exoskeleton assisted handling robot mainly provides auxiliary power for people when heavy objects are carried. Exoskeleton assisted handling robot is a wearable mechanical mechanism that integrates sensing, control, information and mobile computing technologies, and its drive system is the core component of the robot, which directly affects the performance and application range of the robot. The common driving force modes of exoskeleton assisted handling robot include hydraulic drive, pneumatic drive and motor drive, among which the motor drive has the advantages of simple structure, fast response, high efficiency, convenient use and maintenance, so this paper chooses to use the motor drive mode. The force on people when carrying heavy objects is shown in **Figure 5** below.

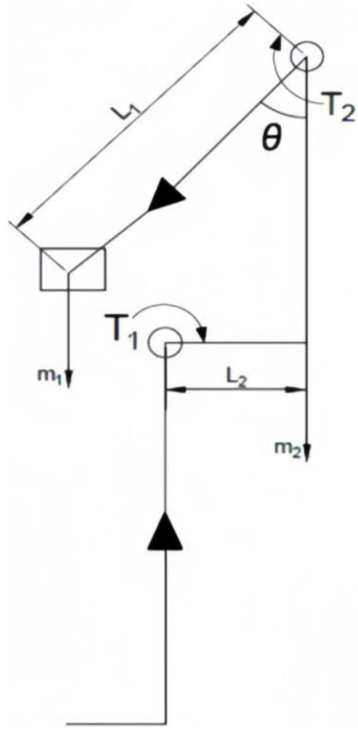

Figure 5. The figure of heavying objects.

In this paper, the hip joint moment is set as T_1 and the shoulder joint moment is set as T_2. From this, the expression equation of the torque exerted by T_1 can be obtained:

$$T_1 = L_2 \times m_2 \times g \tag{1}$$

In the equation, L_2 is the width of the back support, m_2 is the weight of the back support, and g is the gravitational acceleration coefficient.

The expression equation of the torque subjected to T_2:

$$T_2 = L_1 \times sin(\theta) \times m_1 \times g \tag{2}$$

In the equation, L_1 is the arm length, m_1 is the weight mass, and θ is the shoulder joint Angle.

The driving joints of the exoskeleton assisted handling robot are driven by direct current. After the power supply is connected to the motor, the motor will consume energy in the form of useful work, heat generated by the motor movement and friction of the motor. Among them, the expression of the motor useful work is:

$$P_{des} = T_{des} \times \theta_{des} \tag{3}$$

In the equation, T_{des} is the expected torque and θ_{des} is desired angular velocity.

According to the working principle and working characteristics of the exoskeleton assisted handling robot, the driving joint is matched with the human body, so the size of the reducer cannot be too large, in this regard, this paper chooses to use the harmonic reducer, and its transmission ratio is:

$$i = -\frac{z_1}{z_2 - z_1} \tag{4}$$

In the equation, z_1 is the number of rigid gear, z_2 is the number of flexible gear.

The control flow chart of the drive device of the exoskeleton assisted handling robot is shown in **Figure 6**. The absolute encoder is connected with the disk motor to detect the rotation Angle of the motor, and the Angle signal of the motor rotation is transmitted to the control device, which is compared with the Angle signal measured by the incremental encoder.

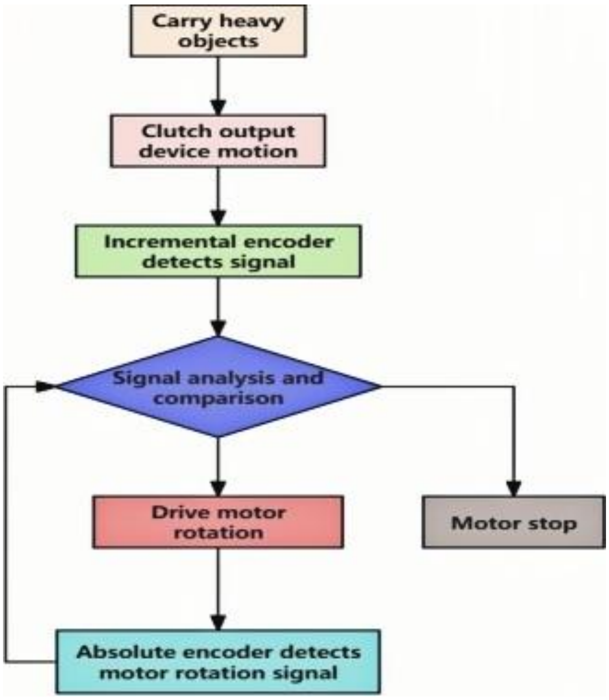

Figure 6. The schematic of control flow chart.

When the motor rotates, the speed of the motor is changed by the harmonic reducer, through which the torque is transmitted to the clutch input and output devices. The function of the clutch input and output device is that when the human body bends over to carry heavy objects, the clutch input and output device is not stuck together, only when bending to a certain Angle, the clutch input and output device will be stuck together. The incremental encoder is connected with the clutch output device. When the human body bends over, the clutch output device is driven to move. The incremental encoder is used to detect the Angle signal of the clutch output device, and the measured Angle signal is transmitted to the control device.

3.2. Elbow joint self-locking mechanism design

Considering that the upper limb is mainly responsible for the support of heavy objects, the exoskeleton elbow joint is designed as a self-locking mechanism. In ergonomics, the Angle range of the human elbow joint is 90° ~ 180° when the human upper limb supports the heavy object, so the self-locking Angle of the exoskeleton elbow joint needs to be designed to be the same as the Angle when the human upper limb supports the heavy object [15–17]. The exoskeleton elbow joint self-locking mechanism is mainly composed of external connecting parts, toothed stop blocks and spring pieces. The external connectors on both sides are fixedly connected with the upper arm of the exoskeleton and the lower arm of the exoskeleton, and the movement of the exoskeleton arm can drive the movement of the external connector.

When the self-locking mechanism is in the initial position, the joint Angle is 180°. During the bending of the exoskeleton arm, the exoskeleton arm drives the bending of the external connector. In the process of reducing the joint Angle from the initial Angle of 180°, the two toothed stop blocks are subject to a certain amount of spring, and the teeth on the external connector are jammed by the toothed stop block, so the elbow joint can only move in the direction of the elbow joint Angle reduction, and the opposite direction is the self-locking direction. When the human body is carrying heavy objects at this time, the exoskeleton elbow joint is self-locking, and the main force is borne by the exoskeleton and the self-locking joint.

3.3. Design of support mechanism

In order to improve the reliability and stability of the structure between the back support of the exoskeleton and the lower extremity of the exoskeleton, the support mechanism is used at the hip joint of the back support and the lower extremity of the exoskeleton. The support mechanism mainly relies on its internal spring to provide support for the back bracket, so as to assist the support of the lower extremity of the exoskeleton to the back bracket and the entire upper extremity of the exoskeleton [18]. Compared with the support of the exoskeleton lower limbs to the back bracket alone, the reliability and stability of the joint structure can be improved. The force analysis of the back bracket at the support mechanism is shown in **Figure 7**. The reaction force F' received by the back support F, F' decomposes the force F and force$_3$ F_2 along the direction of the support mechanism and its vertical direction, and the relationship expression is as follows:

$$F' = \sqrt{F_2^2 + F_3^2} \tag{5}$$

The reaction force of the component force F_2 is F'_2, and the effect of the force F'_2 is to squeeze the support mechanism of the support, which produces the effect of a forward force on the lower limbs of the external skeleton. When walking in a gait, a forward pushing force is generated. And the support mechanism is composed of vibration damping spring, so that the support mechanism can not only assist the support of the human back bracket and assist the human gait movement, but also reduce the vibration and impact of the exoskeleton hip joint associated with the support mechanism during movement.

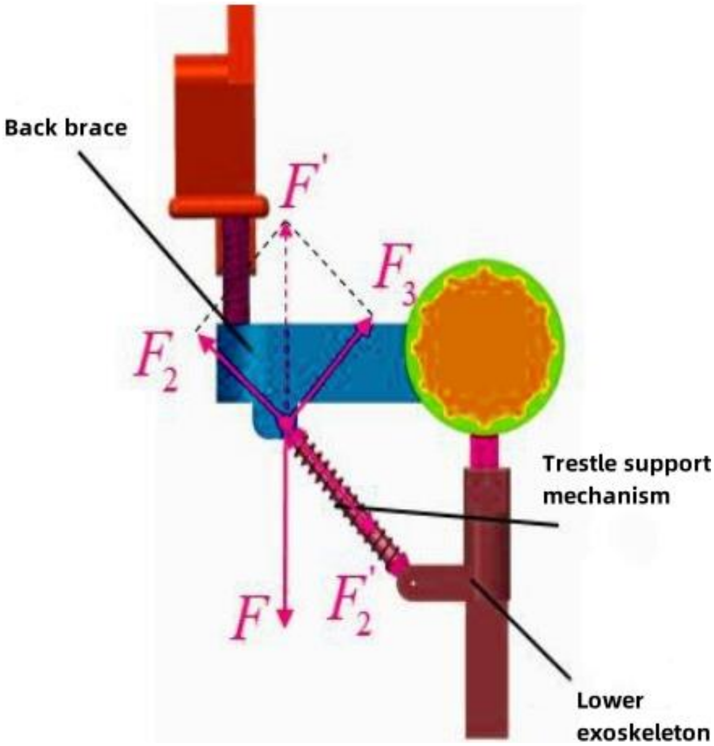

Figure 7. The chart of force analysis chart.

4. Exoskeleton handling robot control strategy

4.1. Q-learning algorithm

The Q-learning algorithm solves the optimal policy for the Markov process using the time difference method and Bellman's equation. The process of solving the Markov optimal policy can be understood as the data collection and processing of the unknown environment in which the robot is located using the value function method, and based on the processed data, the robot is made to take the optimal action to maximize the value of rewards and penalties obtained by the robot.

$$V^{\pi}(s_t) = \sum a \in A\, \pi(a|s_t) Q(s_t, a_t) \tag{6}$$

$$Q(s_t, a_t) = R_s^a + \gamma \sum s' \in S\, P_{ss'}^a V^{\pi}(s_t') \tag{7}$$

$$V^{\pi}(s_t) = \sum a' \in A\, \pi(a|s_t) \left[R_s^a + \gamma \sum s' \in SP_{ss'}^a V^{\pi}(s_t') \right] \tag{8}$$

In the equation, $V^{\pi}(s_t)$ is state value function; $Q(s_t, a_t)$ is State Action Value Function; $\pi\ (a|s_t)$ is action selection strategies.

Based on the above equation, the value function is used to replace the state value function in reinforcement learning for evaluation. The relationship between the two is shown in **Figure 8** below.

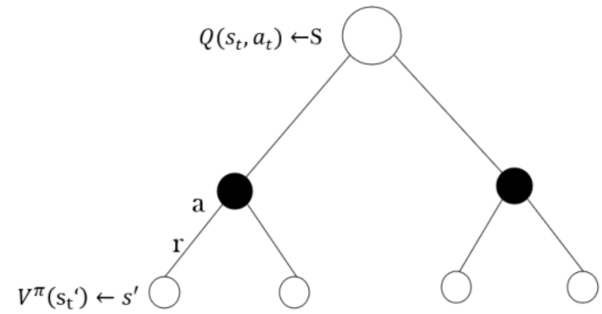

Figure 8. Relationship between value function and state value function.

4.2. BN algorithm

In this paper, we propose to improve the Q-learning algorithm by adding artificial neural networks. By adding an artificial neural network to the Q-learning algorithm, the algorithm is regarded as a nonlinear information processing system that can handle discrete or abnormal input information. In this paper, the artificial neural network is added to replace the Q-value table in Q-learning algorithm, and the improved algorithm can use the environment information obtained by the robot through external sensors as the input of the neural network, and the output will generate the next action of the robot. The structure of the Q-learning algorithm with the artificial neural network is shown in **Figure 9** below.

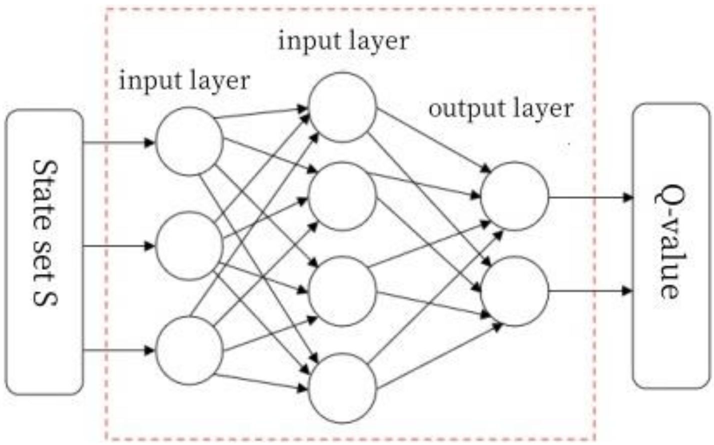

Figure 9. Q-learning algorithm incorporating artificial neural network structure diagram.

In this paper, the gradient and data processing speed of the neural network cannot achieve the effect after joining the neural network; in order to obtain greater learning efficiency to improve the training speed so the BN layer is introduced in the artificial neural network, the BN layer is used before the activation function layer in the artificial neural network. In this paper, we use a strategy similar to weight sharing to treat all samples as whole neurons. The input layer is followed by each layer of the network because the parameters are updated when training is performed, and updating the parameters causes changes in the input data of the later layers. Therefore, a preprocessing operation is performed before the input of each layer, which is normalized to have a normalized mean of 0 and a variance of 1. After processing, the input is fed into the next layer for computation, and the problem of changing data distribution is solved after processing. The essence of the improved algorithm is that the normalization is performed before each layer of the network after the input layer before entering the next layer of the network.

4.3. BN-Q-learning algorithm for path planning

In this paper, an algorithm that fuses the BN algorithm and the Q-learning algorithm is proposed as a way to solve the problem of path planning for robots in static environments. The artificial neural network is transformed by BN and the BN layer network is placed in front of the artificial neural network activation function layer. The activation function equation before the BN layer is added is:

$$z = g(W \times u + b) \tag{9}$$

When treated with a BN layer the forward conduction is calculated as:

$$z = g(BN(W \times u + b)) \tag{10}$$

The paranoia parameter b does not play a role in the BN layer and can be omitted, thus yielding Eq:

$$z = g(BN(W \times u)) \tag{11}$$

The BN-Q-learning algorithm execution steps are:

(1) The Q-value robot state, actions and neural network parameters are first initialized;

(2) Input the information about the current state of the robot's environment into the artificial neural network to select the action that can maximize the Q-value and execute it;

(3) Generate new environment state information s_{t+1} and reward/punishment values r_t. Learning is repeated if the robot collides during the path planning process;

(4) Loop this process until the robot reaches the target point.

5. Simulation of virtual prototype of exoskeleton assisted handling robot

5.1. Establishment of model

Considering that the design of the carrying robot structure has more parts, so when the more complex assembly is imported into Automatic Dynamic Analysis of Mechanical Systems (ADAMS), due to the compatibility of 3D design software and ADAMS, it is easy to cause distortion of the assembly structure, so some non-core parts are properly simplified to improve the simulation speed [19]. Mainly for the exoskeleton assisted handling robot to achieve the main handling action simulation, so this simulation only in the virtual prototype model after the import of the human body, the freedom of the human coronal plane is omitted, the exoskeleton foot only retains the movement in the median of the human body, the exoskeleton upper limb and the exoskeleton lower limb are combined together. At the same time, the back of the human exoskeleton is combined together, and the freedom movement of the human waste is omitted.

5.2. Set the transport simulation driving function

According to the analysis of human body carrying movement, the main driving joints of human body are hip, knee, shoulder, elbow and ankle. Based on this, this paper establishes STEP function in ADAMS to drive each joint in the established virtual prototype model. The specific step drive function established is shown in **Table 2** below [20].

Table 2. Handling simulation driving functions.

Driving joints	Driving function
Ankle joint	STEP (time, 0,0,0.01, - 5 * PI / 180) + STEP (time, 5,0,5.01, 10 * PI / 180)
Knee joint	STEP (time, 0, 0 d, 0.01, 20 d) + STEP (time, 5, 0 d, 5.01, and 40 * PI / 180).
Hip joint	STEP (time, 0,0,0.01, PI / 180-30 *) + STEP (time, 5,0,5.01, 60 * PI / 180)
Shoulder joint	STEP (time, 0,0,0.01, 8 * PI / 180) + STEP (time, five,0,5.01-20 * PI / 180)
Elbow joint	STEP (time, 0,0,0.01, 5 * PI / 180) + STEP (time, 5,0,5.01, - 5 * PI / 180).

5.3. Analysis of simulation results

The analysis of moving motion of virtual prototype mainly analyzes the angular velocity, angular acceleration and torque of each joint of the virtual prototype model established in the process of moving motion. After the ADAMS simulation, enter the ADAMS post-processing module to obtain the simulation result analysis diagram of the torque of each joint during the handling process, as shown in **Figure 10** below.

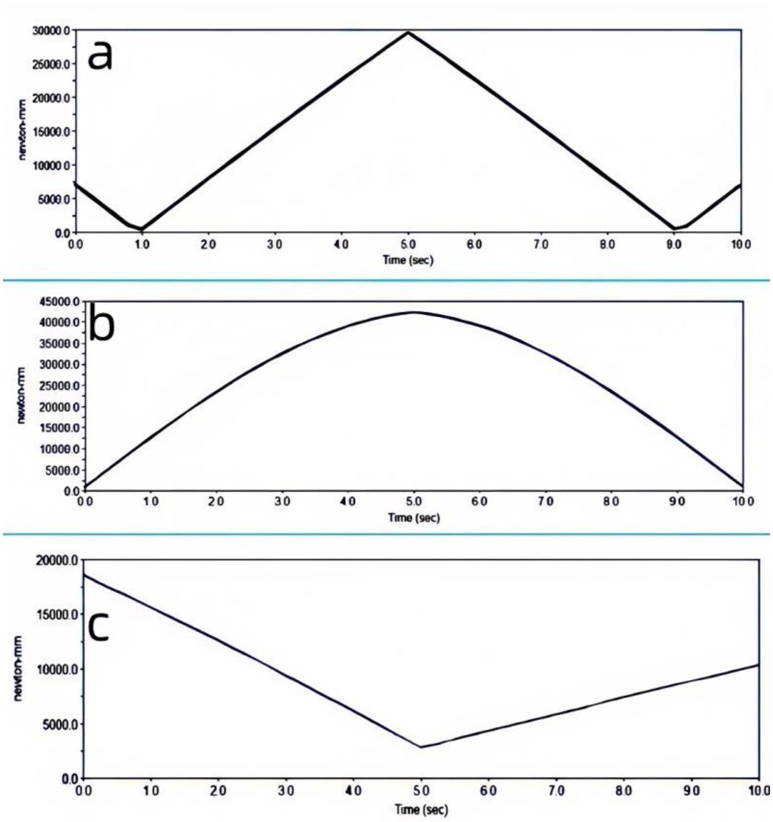

Figure 10. Carrying motion torque. **(a)** knee joint torque; **(b)** hip torque; **(c)** Shoulder joint torque.

Through the data analysis of the figure above, it can be seen that when carrying heavy objects, the maximum torsion of the knee joint is 30 nm, the maximum torque of the hip joint is 45 nm, and the maximum torque of the shoulder joint is 18Nm, which is basically consistent with the stress of each joint when the human body is actually carrying heavy objects, which also verifies the good practicability of the exoskeleton assisted handling robot designed in this paper. It can help the human body carry heavy objects.

6. Conclusion

In summary, this paper designs a set of exoskeleton-assisted handling robot suitable for the practical needs of ordinary laborers on the basis of analyzing the research on exoskeleton robots at home and abroad. The overall framework of the design of the handling robot and the design process of the key parts are given, the control strategy of the robot is given based on artificial intelligence, and the performance of the robot is simulated and analyzed. The results show that the artificial intelligence-based exoskeleton-assisted handling robot designed in this paper is basically consistent with the force on each joint when the human body actually carries heavy objects, which also verifies that the exoskeleton-assisted handling robot designed in this paper has good practicality and can provide help for the human body to carry heavy objects. Compared with the existing research, the exoskeleton assisted transport robot designed in this paper has low cost and simple structure, which is suitable for mass production and of great practical significance for reducing the burden of laborers.

As a whole, this paper establishes an exoskeleton assisted handling robot based on artificial intelligence, and simulates and analyzes its reliability, which achieves the established human research purpose. However, in the virtual prototype, this paper mainly simulates the handling action of the exoskeleton robot, and the simulation scenario is relatively simple, which fails to fully cover the various complexities that the robot may encounter in the actual operation. To a certain extent, this limits our comprehensive understanding and evaluation of the robot's performance. In the future, we need to simulate the exoskeleton-assisted handling robots in more complex work scenarios, for example, simulating the handling operation of the robots in a small space, or simulating the challenges of walking and handling on uneven terrain. Through these closer to the actual simulation test, it is necessary to use more advanced artificial intelligence technology, in-depth understanding of the performance of the robot in the face of complex environments, so as to optimize the design, improve its stability and reliability in a variety of scenarios.

Ethical approval: Not applicable.

Conflict of interest: The author declares no conflict of interest.

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