Article

Research on structural design of exoskeleton assisted transport robot based on artificial intelligence

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Abstract: With the comprehensive docking of "Made in China 2025" and Industry 4.0, the handling mode of the handling system is constantly updated and developed, and a new handling mode which is assisted by exoskeletons and other equipment to complete the handling work is gradually applied. However, most of the existing exoskeleton assisted robots are expensive and complex in structure, and are not suitable for the actual needs of ordinary workers, so it is of great significance to design an exoskeleton assisted handling robot suitable for the needs of ordinary workers. Based on this, this paper designs a relatively simple structure, relatively low cost of exoskeleton assisted transport robot. The simulation analysis of the reliability of the robot is carried out, and the results show that the exoskeleton assisted robot designed in this paper has high reliability, and the force condition of carrying heavy objects is more matching with each joint of the human body.

Keywords: artificial intelligence; exoskeleton robot; assisted handling; 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. Ishii (2004) 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 [1]. Naito (2008) designed a spring as the power of semi-automatic exoskeleton upper limb power robot, through the test shows that the robot can provide a more stable force assistance for the wearer in a specific working state [2]. Ryu (2012) 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 [3]. Yu (2014) 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 [4]. Yu(2015) designed a new exoskeleton driving mechanism for the exoskeleton power assisting robot [5]. 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 (2015) places the robot sensor in the exoskeleton boot of the robot to optimize the design of the exoskeleton robot sensor system [6]. 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 (2018) 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 [7]. 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, PID control is used in this paper to design and study the exoskeleton assisted handling robot.

The research organization and innovation points of this paper are as follows: on the basis of the analysis of human movement, the main design principles of safety, personification and universality of exoskeleton assisted handling robot are summarized. Under the guidance of the design principles, the main structure of the upper limb, lower limb and back support of the exoskeleton assisted carrying robot is designed. According to the designed main structure, the key parts of the robot are

designed. In order to verify the reliability of the handling robot, the virtual prototype is used to simulate and establish the driving function of each joint.

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**.
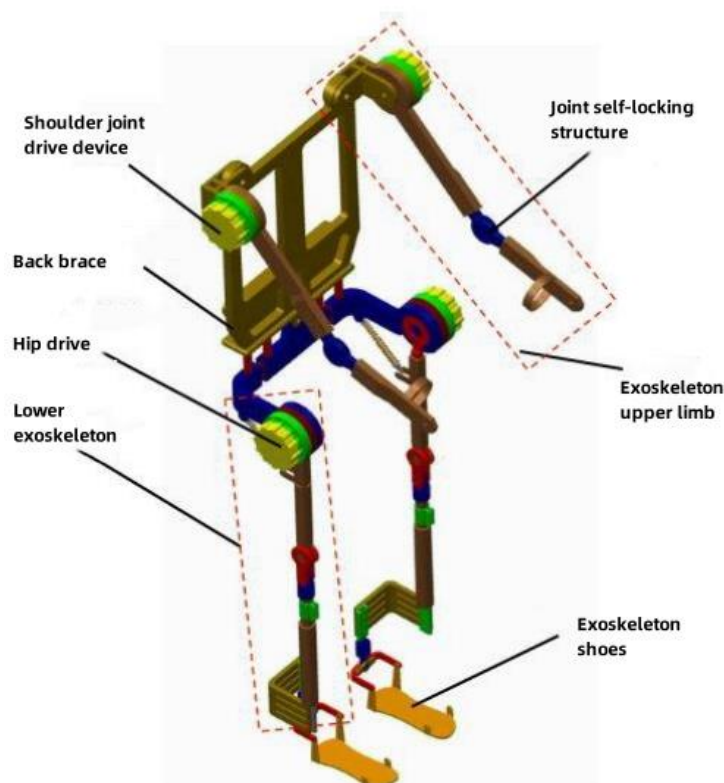
Figure 1. Frame of exoskeleton assisted carrying robot.

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.

(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.
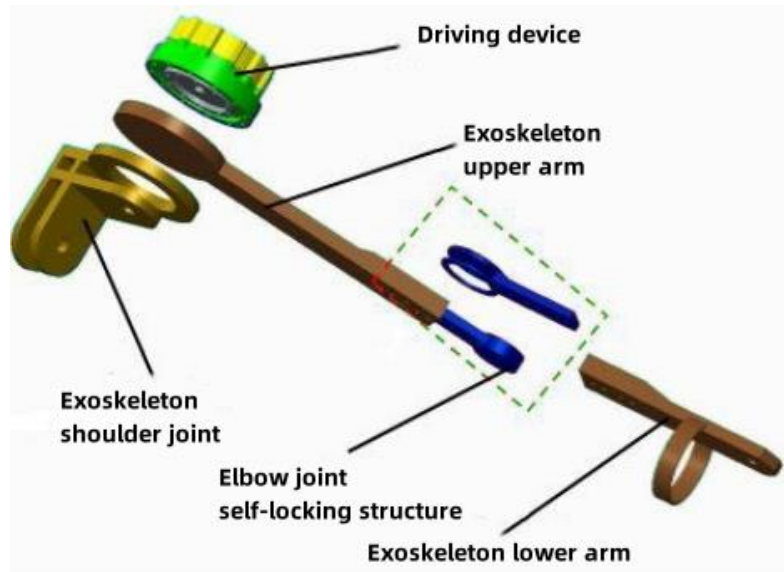
Figure 2. The structure diagram of upper limb.

(**2**) **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.
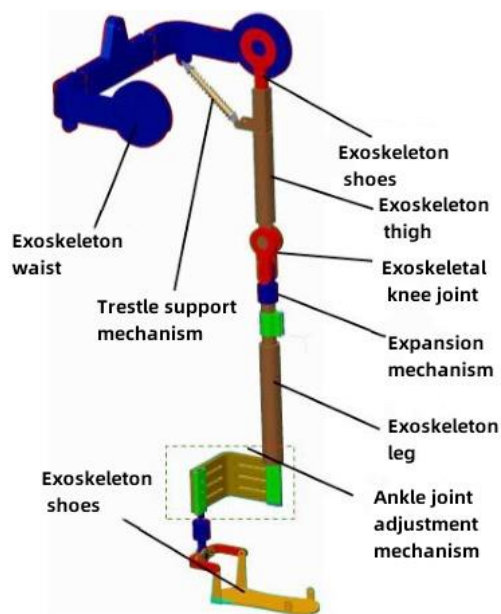
Figure 3. The structure diagram of lower limb.

(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.
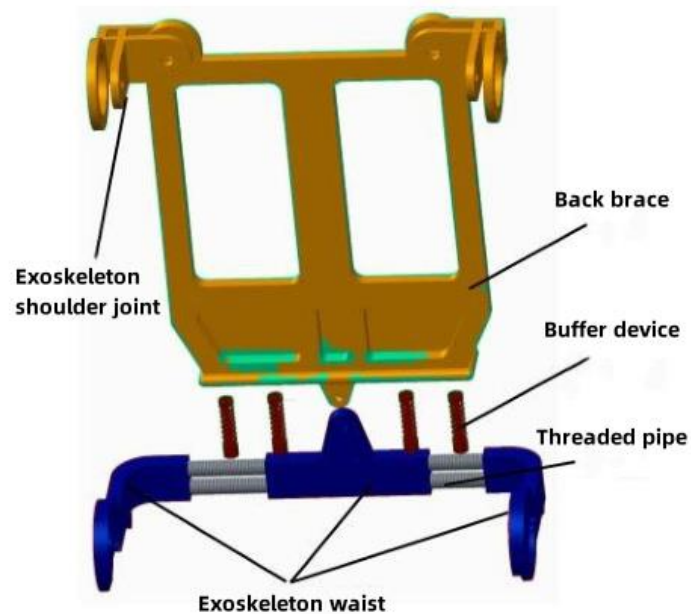

Figure 4. The structure diagram of back bracket.

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.
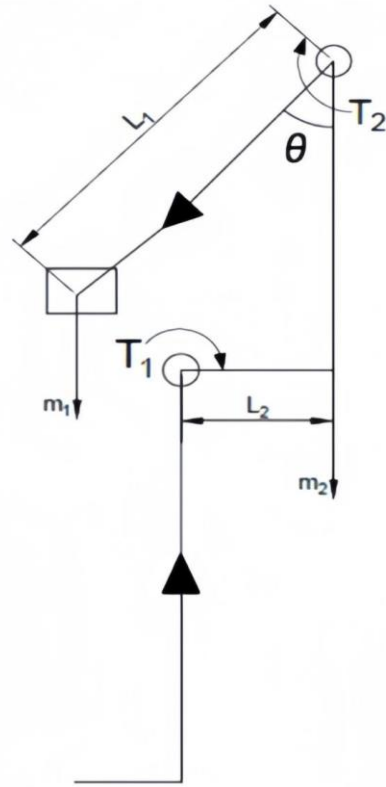
Figure 5. The figure of heavying objects.

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 formula of the torque exerted by T_1 can be obtained:

$$T_1 = L_2 \times m_2 \times G \qquad (1)$$

In the formula, 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 formula of the torque subjected to T_2:

$$T_2 = L_1 \times sin(\theta) \times m_1 \times G \qquad (2)$$

In the formula, 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:

$$P_{des} = T_{des} \times \theta_{des} \qquad (3)$$

In the formula, T_{des} is the expected torque and θ_{des} is the expected speed.

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 can not be too large, in this regard, this paper chooses to use the harmonic reducer, its transmission ratio is:

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

In the formula, 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.
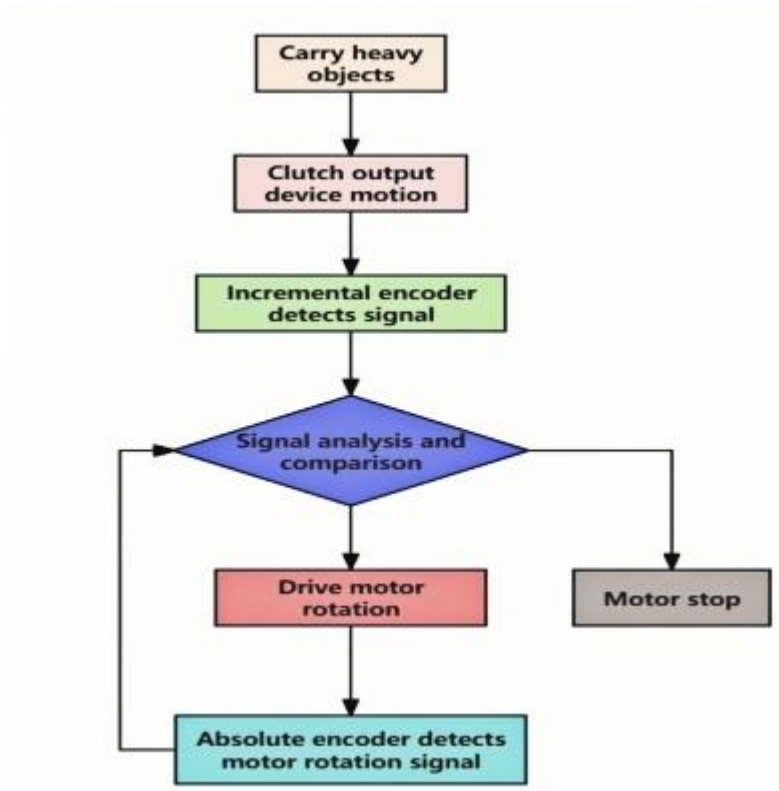
Figure 6. The schematic of control flow chart.

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 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 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.
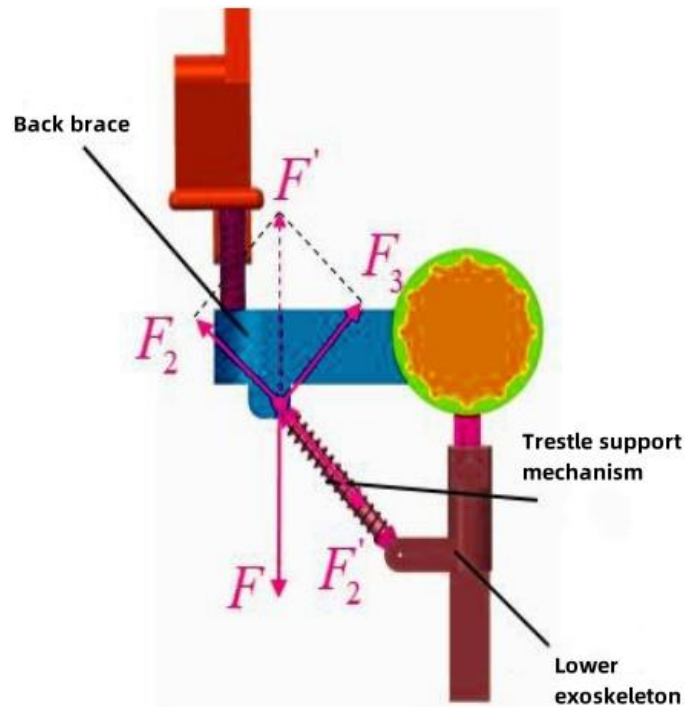
Figure 7. The chart of force analysis chart.

4. Simulation of virtual prototype of exoskeleton assisted handling robot

4.1. Establishment of model

Considering that the design of the carrying robot structure has more parts, so when the more complex assembly is imported into 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 waist is omitted.

### 4.2. 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.

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).*

4.3. 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 8** below.
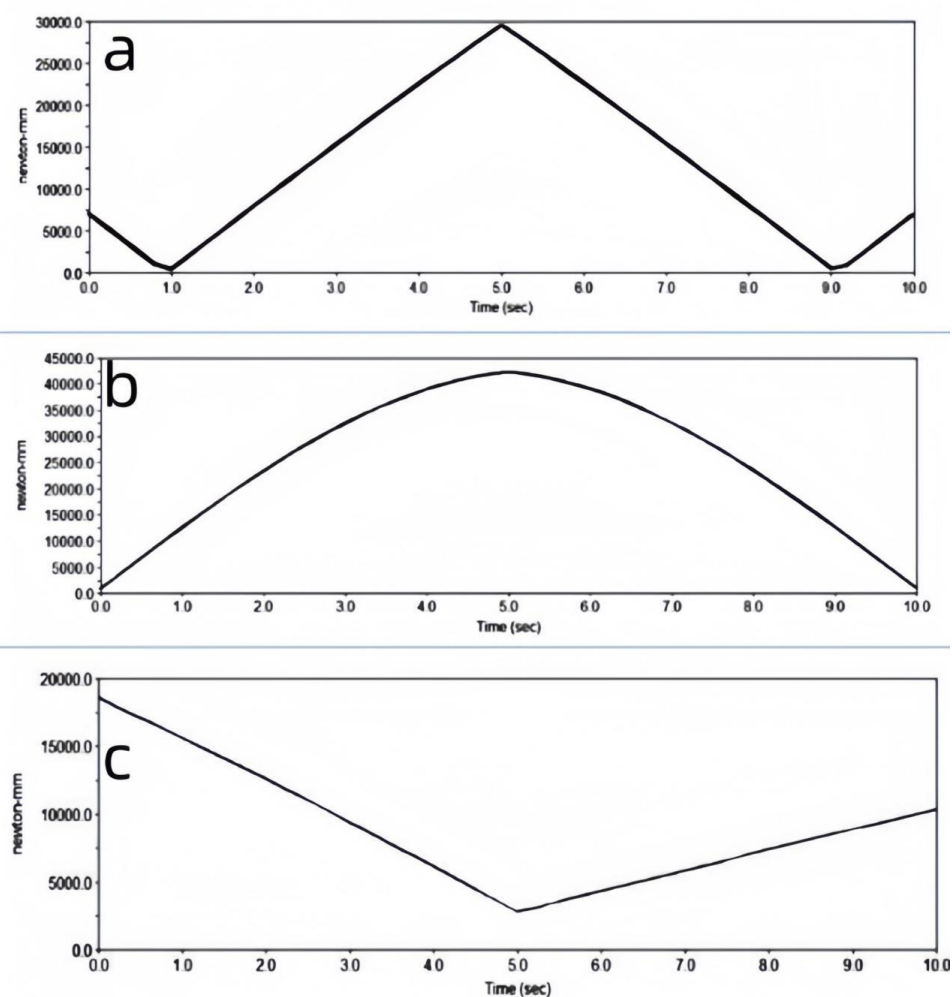
Figure 8. Carrying motion torque, **(a)** knee joint torque; **(b)** hip torque; **(c)** shoulder joint torque.

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 18 nm, 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.

5. Conclusion

In summary, on the basis of analyzing the research of exoskeleton robot at home and abroad, this paper designs a set of exoskeleton assisted handling robot which is suitable for the actual needs of ordinary workers. The overall design framework and key parts of the robot are given, 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 stress conditions of 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 practicability and can provide help for the human body to carry heavy objects. Compared with previous studies, the exoskeleton assisted handling robot designed in this paper has low cost, simple structure, and is suitable for mass production, which has important practical significance for reducing the burden of workers.

On the whole, this paper establishes the exoskeleton assisted handling robot based on artificial intelligence, and carries on the simulation analysis to its reliability, which achieves the established human research purpose. However, in this paper, the virtual prototype mainly simulated the handling action of the exoskeleton robot, and the simulation scene was relatively simple, which failed to fully cover various complex situations that the robot may encounter in actual work. To some extent, this limits our full understanding and evaluation of robot performance. In future research work, it is also necessary to simulate the exoskeleton assisted handling robot in more complex work scenarios, for example, to simulate the situation of the robot carrying out handling operations in a small space, or to simulate the challenges of walking and handling on uneven terrain. Through these more realistic simulation tests, we can have a deeper understanding of the performance of the robot in the face of complex environments, so as to carry out targeted optimization design and improve its stability and reliability in various scenarios.

Conflict of interest: The authors declare no conflict of interest.

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