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Mechanical Design and Preliminary Performance Evaluation of a Passive Arm-support Exoskeleton

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***Abstract*— In this study, a passive arm-support exoskeleton was designed to provide assistive aid for manufacturing workers. The exoskeleton has two operating states which can be altered using an unique ratchet bar mechanism with two blocks fixed on the ratchet bar. When the upper arm is elevated to the highest poiont, the pawl module will touch the lower block to allow the pawl separated, so that the arm can move freely without any resistance. When the upper arm is depressed to the lowest point, the pawl module will touch the upper block to make the pawl re-engaged, so that the upper arm can be locked at any vertical position. For purpose to improve the ergonomical property, the structural parameters of the exoskeleton were determined by particle swarm optimization. The designed exoskeleton was simulated in the Adams model to investigate its actual performance. A preliminary experimental study was conducted to evaluate the effectiveness of the designed exoskeleton on alleviating users' physical loads in holding heavy tools; the muscular activities on the shoulder muscle groups involved in the weights bearing, elicited by the surface electromyography (EMG) over the shoulder, were significantly reduced from three healthy subjects who carried hand-held tools. The simulation and experiment results show that the designed exoskeleton could effectively relieve the shoulder burden by transferring the bearing load to the waist, where the motion of the arm was not obstructed.**

Index Terms—upper limb exoskeleton, mechanism design, simulation, electromyography (EMG).

I. Introduction

With the rapid progress of industry, physical labor is still needed for intensive tasks that require workers to carry out. Repetitive and laborious work is not only hard for the workers, but also intensive work may lead to muscle fatigue and a high risk of injury. Workload-related musculoskeletal disorders (WMSD) are of a big concern in business development. The number of occupational diseases and cumulative traumatic diseases (CTD) caused by work overload is significantly increasing [1]. When workers carry loads, the muscles must provide sufficient force at the shoulder, elbow and trunk to

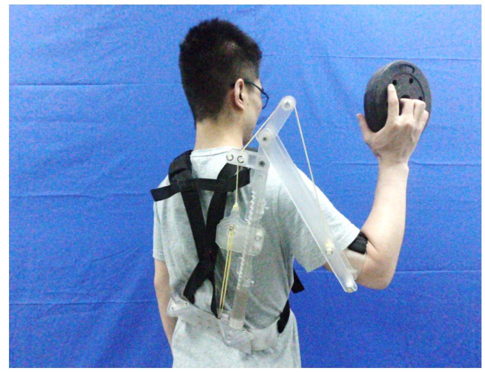

Fig. 1 A passive arm-support exoskeleton in this study

overcome the gravity and dynamic force of the load. Excessive loads or prolonged work leads to fatigue and even injury of muscles[2]. Exoskeletons have been proposed as a potential solution to solve the problem [3].

The exoskeleton incorporates a variety of disciplines such as robotics, human biomechanics, and cognitive science, which has attracted the attention of universities and research institutions. C. T. O'Neill *et al.* proposed a soft wearable robot for the shoulder, in which the actuator can be folded flat when not in use, which makes the robot almost invisible under clothing [4]. Y. Zhang *et al.* presented a soft upper-extremity passive robotic exosuit, in which the weight of loads is compensated by the cable and redistributed on the shoulders and thighs [5]. The Personal Lift Assist Device consists of elastic elements. The moments from the spinal column are shared between shoulders, pelvis, and knee [6-8]. J. Theurel *et al.* assess the physiological outcomes when using the Exhauss exoskeleton; the result showed that the burden on shoulder muscles was reduced [9]. B. K. Dinh *et al.* proposed a cable driven upper limb exosuit. It can provide assistive torque to the user's elbow[10,11]. Titan arm is an elbow exoskeleton designed for disabled or injured patients, therapists, and doctors. It uses a ratchet-based braking system that allows users to lift or hold loads [12].

Passive systems are preferred in the construction and manufacturing industries. A number of passive exoskeletons are commercially available on the market. Some of them have been evaluated in actual factory applications, where real benefits have been found. Shoulder X is a shoulder-supporting exoskeleton for application in automotive, construction and shipbuilding. This device supports force incrementally when the user lifts his arm, which becomes near zero when the arm is lowered, allowing the user to rest arm naturally or reach for tools on their tool belt [13]. The Eksovest is a spring-loaded exoskeleton. this device can calculate arm load and support worker's arms to undertake tasks ranging from the height of chest to overhead. The lift force can be adjusted to fit

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application and operator preference [14]. Kubota showed an unpowered exoskeleton（ARM-1）at the International Robotics Exhibition. This device is purposed for fruit picking as well as activities where workers holding their arm above their shoulders for prolongered periods [15]. The AIRFRAME transfers the gravity of the arms from the shoulder to the center of the body, evenly distribute pressure to increase comfort [16-17]. J. L. Herder developed an arm exoskeleton ARMON for patients with neuromuscular diseases by employing a static balance mechanism fixed on a wheelchair to balance weight. The support force can be adjusted by an electric actuator to help patients complete daily activities [18]. T. Rahman designed the Wilmington robotic exoskeleton (WREX) for patients with weak upper limbs. It is a four-degree-of-freedom functional orthosis that counteracts gravity with rubber bands and attaches to a wheelchair [19].

An active exoskeleton such as the Titan arm can provide sufficient power, but the motor and battery become the bottleneck of weight reduction. This is one of the reasons why passive exoskeleton is used in some factories. Most passive exoskeletons use elastic elements to balance weight, such as Eksovest, Paexo, etc. In gravity-balanced exoskeleton, the structural parameters often correspond to a constant load. But in practice, a worker needs to use multiple tools. To fit variable tool weights while not affecting the free movement of the arm, the stiffness of the elastic element is generally chosen to be small, or it is necessary to change accessories between different tasks. This will limit the effectiveness of the assistance from the devices. This paper introduces a new arm-support exoskeleton for workers. The exoskeleton switch two different states using a ratchet bar. This device can support the upper arm at any height position when engaged, and move flexibly when separated. It can provide a stable support for multiple tools without changing any accessories. The exoskeleton was evaluated in Adams and sEMG tests. The results show that the proposed exoskeleton can provide a stable support for the upper limbs, relieving load on shoulder muscles.

II. THE WORKING PRINCIPLES OF THE EXOSKELETON

A. *Establishment of the shoulder Model*

Exoskeletons can provide resistance to movement if the joints of the system are misaligned with the wearer's joints[20,21]. It is necessary to have an accurate parametric model of the shoulder. Some researchers have found that as the humeral elevation, the position of the glenoid fossa is affected by the rotation and slip of the clavicleand shoulder blade. There is no fixed center of rotation[22]. This feature was taken into account in the design of the exoskeleton.

The shoulder model was used for calculating the kinematic parameters of arm in the reachable workspace. Klopcar *et al.* investigated the patterns of shoulder girdle elevation, depression, protraction, retraction, length changs and angular motion regarding the humeral elevation angle [23]. Their parameters were used for the current exoskeleton design.

The shoulder motion was equivalent to two rotations and one translation, as shown in Fig. 2. φ_{ed} is the projection angle of the shoulder girdle vector in the frontal plane. φ_{pr} is the projection angle of the shoulder girdle vector in the horizontal plane. d_{SG} is the length of the shoulder girdle vector. φ is the angle between the humerus vector and the body's vertical axis. The coupling between them is as follows:

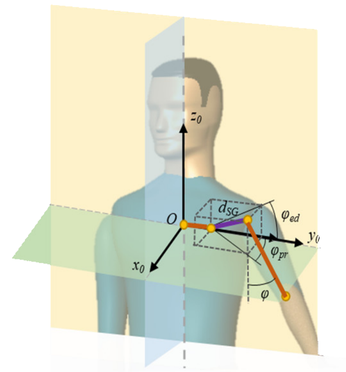


Fig. 2 Motion model of human shoulder

TABLE I DESIGN PARAMETERS OF HUMAN MODEL

Parameters	Value	Parameters	Value
Human height	1750mm	Human weight	60kg
Upper arm length	325mm	Upper arm weight	1.5kg
Lower arm length	255mm	Lower arm weight	0.75kg
Spine length	504mm	Hand weight	0.38kg

$$\varphi_{ed} = \begin{cases} -0.3\varphi & \varphi < 0° \\ 0° & 0° \leqslant \varphi \leqslant 30° \\ 0.36\varphi - 10.8° & \varphi > 30° \end{cases} \tag{1}$$

$$\varphi_{pr} = \begin{cases} 0.35\varphi & \varphi < 0° \\ 0° & 0° \leqslant \varphi \leqslant 70° \\ -0.22\varphi + 15.4° & \varphi > 70° \end{cases} \tag{2}$$

$$d_{SG} / d_0 = -1.6\times10^{-5}\varphi^2 + 3\times10^{-4}\varphi + 1 \tag{3}$$

The length of the segments is determined by the heights [24], and the detailed parameters of the model are shown in TABLE I.

B. *The principle of the exoskeleton*

The exoskeleton consists of two rods worn on the human back. The rotation of the upper arm is transformed into the linear motion of the pawl module through two pulleys and a rope. A special ratchet bar mechanism was proposed, as shown in Fig. 3. The pawl module is divided into two states

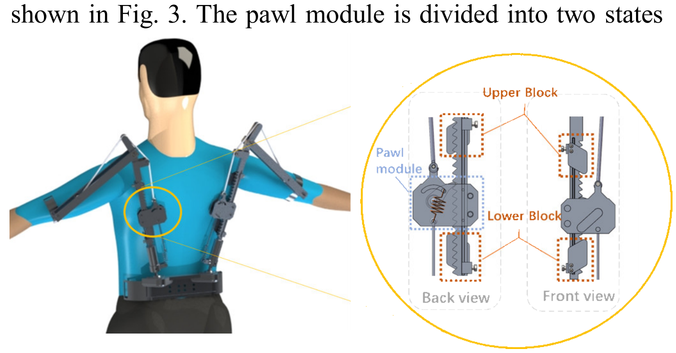


Fig.3 The main mechanism of the exoskeleton

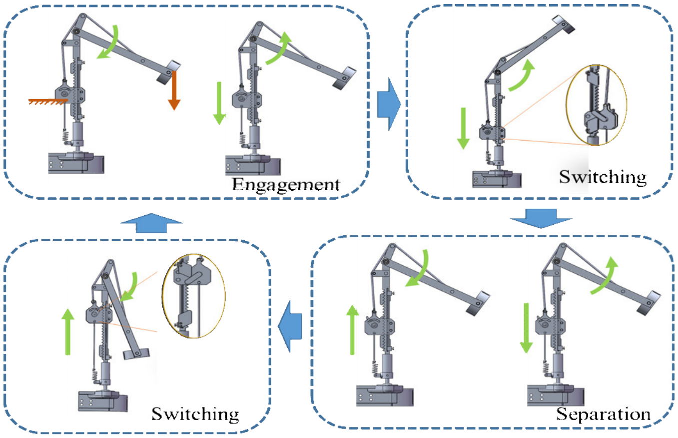


Fig. 4 Exoskeleton states switching process

(engagement and separation). The state change is triggered by the upper and lower blocks, and fixed position can be adjusted by screws.

The state of the exoskeleton changes with the position of the pawl, as shown in Figure 4. When the pawl module is engaged, the upper arm can only be elevated, whereas the depressed arm will be hindered by the pawl. In this state, the arm support function of the exoskeleton can be achieved. When the upper arm is elevated to the highest height, the pawl module touches the lower block, and the pawl is separated. The upper arm can move freely without any resistance in the separated state. When the upper arm is depressed to the lowest height, the pawl module touches the upper block, and the pawl is re-engaged.

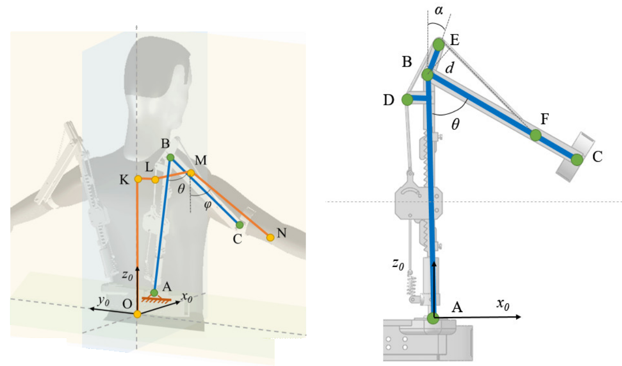
III. Structure Optimization

A. Optimization of the support rod

The exoskeleton is worn on the back of the human body. In order to reduce its size while providing sufficient assistance, it is necessary to optimize its main parameters.

The rod AB is the main support rod of the exoskeleton; the rod BC is the exoskeleton arm, as shown in Figure 5(a). The point A is fixed to the exoskeleton belt, and spherical hinge motion pair is adopted. The point B is the hinge point between the exoskeleton arm and body. An arm bracket is fixed at point C to achieve force transmission. Points O, K, L, M, N are parametric models of the human body, the rod LM is the shoulder girdle, the rod MN is the upper arm. In order to make the exoskeleton fit the human body during arm movements and reduce its space occupation in the back and underarms, the angle of the exoskeleton should be approximately the same as the angle of the upper arm. This also reduces the potential safety hazards of collision with other objects in the actual environment. Therefore, it is necessary to ensure that the difference between θ and φ should be as small as possible during the motion, as shown in Fig. 5(a).

The major parameters of the human body and the motion information of the upper arm can be obtained from section II. The length of the MC is set as the three-quarter of rod MN based on the size of the elbow. The coordinates of point A are set to [x_a y_a z_a], and x_a, z_a are constants. θ can be calculated using the cosine formula.



(a) (b)

Fig. 5 Human-exoskeleton coupling model

$$\theta = \arccos \frac{BA^2 + BC^2 - \left((x_c - x_a)^2 + (y_c - y_a)^2 + (z_c - z_a)^2\right)}{2 \cdot BA \cdot BC} \tag{4}$$

The space of arm movement is defined as P, and the difference between θ and φ is defined as:

$$\delta = \sqrt{\sum_{n \in P} \left(\varphi(\mathrm{n}) - \theta(\mathrm{n})\right)^2} \tag{5}$$

δ is always a positive value, since no exact match in the kinematics of both mechanisms exist. However, a small value of δ indicates that the smaller difference in their angles, and the exoskeleton is closer to the human body. In order to minimize δ, a optimal solution is sought by using Particle Swarm Optimization. The optimal mathematical model is:

$$\begin{aligned} &\min \quad \delta(X) \quad X = [AB, BC, y_a]^T \\ &s.t. \quad g_1(X) = AB + BC \geq AC \\ &\qquad\; g_2(X) = AB + AC \geq BC \\ &\qquad\; g_3(X) = BC + AC \geq AB \end{aligned} \tag{6}$$

where AB, BC, y_a with the ranges of $400 < AB < 450$, $300 < BC < 350$, $50 < y_a < 152$, limited by the body segment size and exoskeleton structure.

By the simulation using MATLAB, the calculation result is as follow:

$$\{AB = 422mm, BC = 300mm, y_a = 152\mathrm{mm}\}$$

B. Optimization of rope position

In order to realize the effective transfer of rope tension and reduce the strength requirement of rods, we optimize the fixed position of the rope. Since rod AB and BC are hinged, the rope motion occurs in a single plane, so the optimization is studied in the two-dimensional plane, as shown in Fig. 5(b).

The length AB and BC can be obtained from section III(A). The ranges of BE, BF and α is limited to $50 < BF < 250$, $50 < BE < 100$, $-20° < \alpha < 20°$. Thus the coordinates of each point at any φ（n） can be obtained. The torque of the rope at 1N/m stiffness can be calculated as follows:

$$M_{k=1} = \frac{\left|\overrightarrow{FE}(n) \times \overrightarrow{FB}(n)\right|}{\left|\overrightarrow{FE}(n)\right|} \bullet \left(\left|\overrightarrow{FE}(n)\right| - \left|\overrightarrow{FE}(0)\right|\right) \tag{7}$$

Limited by the actual structure, the distance of the linear motion of the pawl module is limited to less than 100mm. In order to maximize $M_{k=1}$, the optimal solution is sought by using Particle Swarm Optimization. The optimal mathematical model is:

$$\begin{aligned} &max \quad M_{k=1}(X) \quad X=[BF,BE,\alpha]^T \\ &s.t. \quad g_1(X)=\left|\overrightarrow{FE}(\mathrm{n})\right|-\left|\overrightarrow{FE}(0)\right|\leq 100 \end{aligned} \tag{8}$$

By the simulation using MATLAB, the calculation result is as follow:

$$\{BF=216(mm), BE=56(mm), \alpha=19°\}$$

IV. Simulation Analysis

A. Mechanical stress analysis

Mechanical stress analysis was implemented to ensure safety and stability. The exoskeleton model was built with SolidWorks software, and the finite element analysis was performed by the Simulation program. The boundary conditions were shown in the figure 6(a). A compressive force of 50N was applied on the arm bracket, and the spherical hinge joint was fixed. Polycarbonate (PC) materials were selected for analysis. Figure 6(b) shows the calculation results. The maximum stress of the exoskeleton is 61.3MPa, which is less than the strength of the material. This results indicating that the designed structure and material can provide stable support.

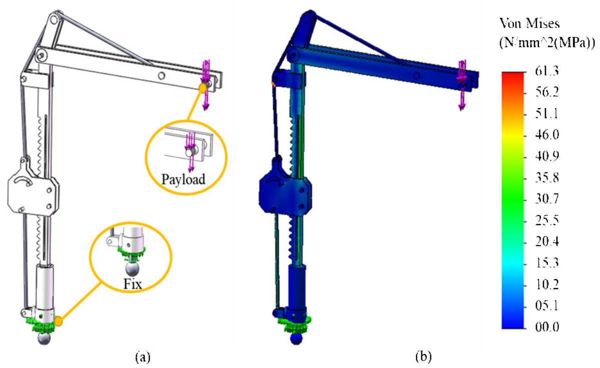


Fig. 6 Finite element analysis results. (a) boundary conditions.(b) stress distribution.

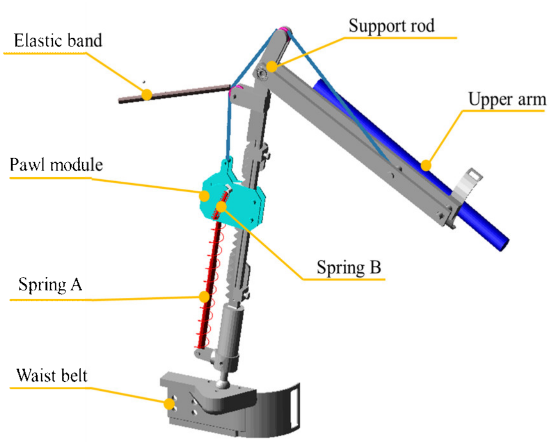


Fig. 7 Exoskeleton model in Adams

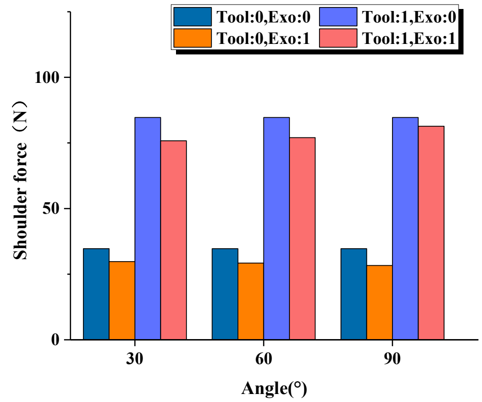


Fig. 8 Shoulder joint force amplitude in the engagement state. Tool: 0/1 represents whether the Tool is held, Exo: 0/1 represents whether the exoskeleton is worn.

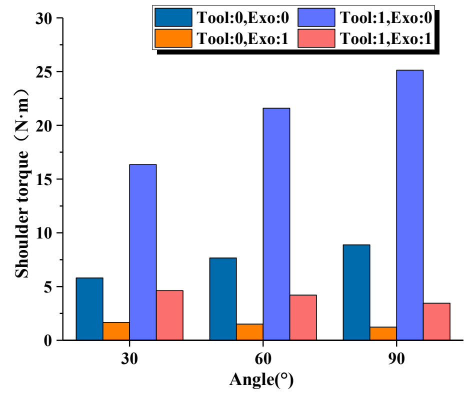


Fig. 9 Shoulder joint torque in the engagement state. Tool: 0/1 represents whether the Tool is held, and Exo: 0/1 represents whether the exoskeleton is worn.

B. Dynamics Simulation

In order to analyze the interaction between the exoskeleton and the human, a three-dimensional model based on optimal parameters was established in Adams software, as shown in Fig. 7. Consider the symmetry of the left and right arms, only the right arm was used for simulation. The blue bar simulates the upper arm, and the position of the shoulder is determined by the formula in section II(A). The mass of the upper arm is set to 2kg. Taking into account the weight of common tools, we set the tool load to 5kg and add it to the end of the arm. The spring A is used to ensure that the pawl is in one of the two states (engagement or separation). The spring B is used to ensure that the ratchet module can slide down the track when the arm is raised. When the pawl module is engaged, the exoskeleton can provide support at any height positions.

The exoskeleton is adjusted to the engagement state in Adams, and the internal force of the shoulder caused by arm gravity at three fixed angles are analyzed. When the shoulder is elevated 30, 60 and 90 degrees, the state of wearing exoskeleton and non-wearing exoskeleton were simulated as shown in Fig. 8 and Fig. 9. The force and torque amplitudes required for the shoulder joint are compared under different conditions. The results show that the exoskeleton can reduce the shoulder force slightly, while the torque is significantly reduced. It shows that the proposed exoskeleton can provide effective assistance, and it may relieve muscle fatigue since shoulder torque is produced by muscles

V. Preliminary Experiment

Emlpoying the optimized parameters, a right arm exoskeleton was fabricated as shown in Fig. 10. An experiment platform for evaluating the exoskeleton performance in reducing physical workload was developed. Electromyography (EMG) signals of three muscle goups on the shoulder were collected to analyze muscle activities in different task conditions.

A three-kg weight was chosed as the maximum handheld load. Three support positions of the exoskeleton were selected as 32, 55 and 76 degree, evenly separating the range of exoskeleton arm. The Posterior Deltoid (PD), Middle Deltoid (MD), and Anterior Deltoid (AD), which are the major muscles during the elevating of arm[4], were monitored to evaluate the effectiveness of the exoskeleton. Three surface electromyography (sEMG) sensors were placed on the lengthwise direction of the muscle on the right arm. The positions of the electrodes were shown in Fig. 11.

Three healthy male subjects were tested in experiment. Their physical parameters are shown in TABLE II. Subjects were asked to hold three loads (0, 1.5, 3kg) with and without exoskeleton, and keep their shoulder at three different fixed angles (30, 60, 90 degrees). The exoskeleton angles (32, 55, 76 degrees) are different from the shoulder angles, due to the difference in kinematics between the human body and the exoskeleton, and the discontinuity of the engagement angle caused by the ratchet structure. The raw sEMG signals were rectified, filtered (10Hz-100Hz), and intercepted. The mean value of sEMG was used to represent the muscle activation. The percentage reduction of sEMG when wearing exoskeleton was calculated. Three muscle signals of subject A when

Fig. 10 Experiment platform

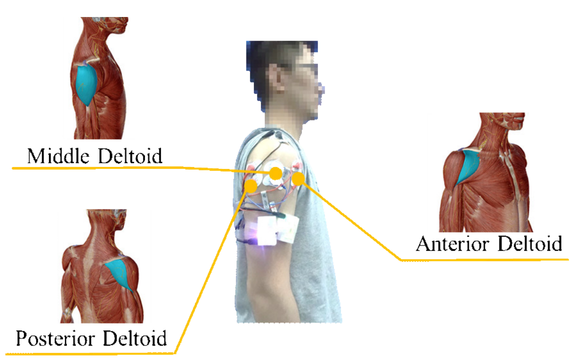


Fig. 11 sEMG electrode placement

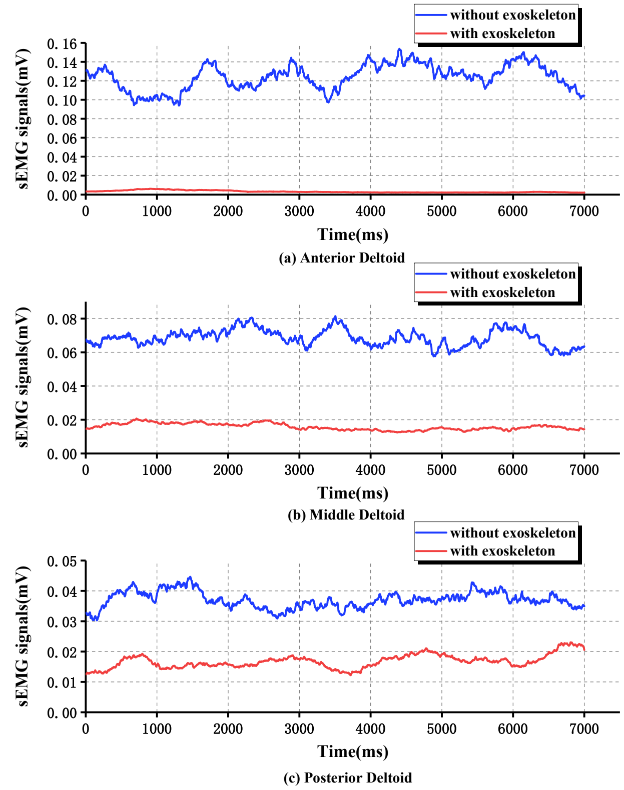


Fig. 12 (a)-(c) Three muscle sEMG signals of subject A under 3kg load at 32 degrees

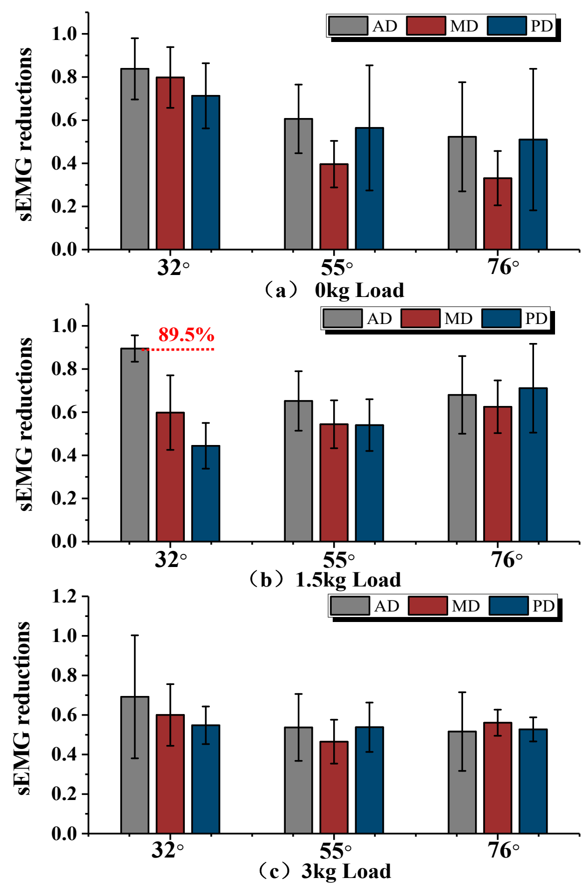


Fig. 13 sEMG reductions under three different loads

TABLE II EXPERIMENTAL SUBJECT

Subjects	Sex (F/M)	Age(yr)	Height (mm)	Weight (kg)	Arm length (mm)
A	Male	23	1750	65	290
B	Male	27	1800	65	300
C	Male	21	1700	65	295

holding a 3kg load at 32 degrees are shown in Fig. 12. The test result of sEMG reductions and standard deviation from three subjects are shown in Fig. 13.

Positive reductions of muscle activities were observed under different task conditions, which indicates that the designed exoskeleton can significantly relieve shoulder burden. The EMG signals in all three muscles decreased by more than 30%. At 32 degrees, the exoskeleton demonstrated a noticeable benefit to AD muscle, with the maximum reduction of 89.5%. When the angle increases, the reduction of sEMG was reduced. Antior, middle, posterior muscle signals decreased by more than 50% under 1.5kg and 3kg loads at 76 degrees, which is associated with a common posture when working with hand-held tools.

VI. Conclusion and Future Work

A passive arm-support exoskeleton has been designed for assembly workers, construction workers, and others who need to lift their arms for a long time. This device is characterized by the use of a passive mechanism to achieve the mutual conversion of two states. This device supports the upper arm and relieves the burden on the shoulder joint.

To evaluate the effect of the designed exoskeleton, a 3D model was built using the Adams software. The actual stress of the exoskeleton during the movement of the human body was analyzed. The results show that the designed exoskeleton can provide effective assistance.

The shoulder sEMG signals under different task conditions were collected to evaluate the effect of the designed exoskeleton. The results showed that the proposed exoskeleton can effectively lower shoulder muscle activies.

The exoskeleton for the right arm has been completed, and the application for both arms needs further analysis, such as the interference and coupling of bilateral exoskeletons. In future work, we will optimize the strap structure to improve the comfort of the exoskeleton. Stronger, lighter materials will be tested, and the exoskeleton for both arms will be assembled. More complex task conditions will be investigated, making the design more practical and reliable.

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