Design and Optimization of a Wearable upper Limb Exoskeleton based on Adams

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Abstract. A wearable upper limb exoskeleton for factory assembly positions was designed. The trajectory and dynamics of the worker's arm during assembly was analysed. According to the power demand, the corresponding torque drive was designed at the shoulder joint. Then the corresponding scheme was designed. The effect on joint drive force was simulated on Adams. As shown by the result, pre-compression force and spring stiffness have a great influence on the driving effect. Finally, with the work of additional required force moment for the shoulder joint as the objective function, the two parameters of spring stiffness and pre-compression force were optimized. Compared to not wearing the exoskeleton, the energy consumption of the exoskeleton was reduced by 90%.

1. Introduction
As a way to enhance human strength and assist human body training, Exoskeleton is widely used in military, medical, rescue and daily life [1-4]. The types of exoskeleton mainly include military exoskeletons [5], lower limb exoskeleton [6], Waist-assistive exoskeleton [7], upper limb exoskeleton [8], etc. However, most of the exoskeleton is a human-machine intelligent system integrating mechanical, electrical, sensor and space control [9, 10]. It is expensive, complicated in design and large weight and it is difficult to meet the demand for the current market. Especially for modern manufacturing industrial assembly, workers need to wear and move quickly for a long time, which is obviously not suitable for the job. Based on the analysis of kinematics and dynamics of upper limb joints during assembly work, a lightweight and flexible wearable upper limb exoskeleton is designed.

2. Trajectory of upper limb
The upper limb exoskeleton should always follow the spatial position of the human arm and provide matching assistance as much as possible to meet the requirements of the worker. Therefore, it is important to calculate the trajectory and power demand of the upper limb bones during the assembly work. As shown in Figure 1, from top to bottom are the three positions of the handing tool operation, swing arm after operation and swing arm completion. When handing tool operation, the forearm is at an angle of 90 degrees to the upper arm and the upper arm is at an angle of 90 degrees to the vertical. When swing arm completion, the forearm is at an angle of 180 degrees to the upper arm and the upper arm is at an angle of 30 degrees to the vertical. During the swing arm, the angle between the forearm and the upper arm and the angle between the upper arm and the vertical direction change uniform.
3. Dynamics of upper limb
During the swing arm, the shoulder and elbow joints are mainly used to withstand the force moment generated by the gravity of the tool and arm. The wrist joint withstands less torque due to the small force of the palm. According to the measurement, a male with a height of 170 cm has an upper arm length of about 240 mm, an upper arm mass of about 1.026 kg, a forearm length of about 290 mm, a forearm mass of about 1.387 kg. The weight of the hand tool is 1 kg. The model shown in Figure 2 is created in Adams. Both the upper arm and the forearm are modeled as a uniform mass link. Fixed to the forearm, the hand tool is modeled as a 1 kg ball. The shoulder and elbow joints are considered as two rotating joints.

![Figure 1](image1.png)  **Figure 1.** The trajectory of upper limb.

![Figure 2](image2.png)  **Figure 2.** Dynamics model of upper limb.

According to the above model, the force moment required for the rotation angle of the shoulder joint and the elbow joint with the upper arm can be obtained as shown in Figure 3. As can be seen from the figure, the torque requirement of the shoulder joint is much larger than that of the elbow joint. The torque curve of the shoulder joint is in the form of a parabola, which increases first and then decreases. The maximum torque occurs when the angle of rotation is approximately 30 degrees and the maximum value is 10564 N· mm.

![Figure 3](image3.png)  **Figure 3.** The force moment required for the rotation angle of the shoulder joint and the elbow joint with the upper arm.

4. Joint drive design of upper limb exoskeleton
The shoulder joint is mainly stressed during the assembly work of the worker, so it is necessary to design the support torque as close as possible for the shoulder joint. As shown in Figure 4, the upper limb exoskeleton provides a support plate that is bound to the upper arm to serve as a lifting arm and a rotational joint is designed to provide sufficient torque at the shoulder joint.

Since the torque curve of the shoulder joint is in the form of a parabola and the torque provided by the rotating joint should be as close as possible to this curve, the internal structure of the rotating joint is designed as a crank-link mechanism, as shown in Figure 5. The brace is fixed at an angle to the crank. When the crank rotates around the shell, the piston slides down the channel of shell and compresses the spring. The spring force provides a moment for the rotating joint.
5. Simulation and optimization of joint driving force effect

5.1. Simulation and optimization of joint driving force effect

According to the internal structure of the rotating joint and the trajectory of the arm, an equivalent mechanical analysis model can be established on Adams, as shown in Figure 6. Based on the model of Figure 2, a crank-link mechanism is added, the crank is fixed at 355° to the upper arm. The crank length is 8 mm, and the connecting rod length is 20 mm. The friction of each rotating joint is ignored. When the size of the exoskeleton element is clear, the joint driving force effect is mainly related to the spring stiffness and the pre-compression force.

The effect of the pre-compression force on the joint driving force is shown in Figure 7. When the spring stiffness is 136 N/mm and the pre-compression force is 750 N to 950 N, The additional required force moment for the shoulder joint to rotate with the upper arm is shown in Figure 7.

From Figure 7, it is concluded that after wearing the exoskeleton, the maximum torque required for the shoulder joint drops below 2500 N·mm, which greatly relieve the fatigue of the shoulder. At the same time, under this setting condition, as the pre-compression force increases, the effect of the exoskeleton is better, and the initial additional required force moment of the shoulder joint is reduced.
However, when the pre-compression force reaches 950 N, a negative initial additional required force moment appears which indicates that the arm has a tendency to rotate in the direction of anti-gravity, and the design should avoid this state.

The effect of the spring stiffness on the joint driving force is shown in Figure 8. When the pre-compression force is 800 N and the spring stiffness is 100 N/mm to 140 N/mm, the additional required force moment for the shoulder joint to rotate with the upper arm is shown in Figure 8.

![Figure 8. The effect of the spring stiffness on joint driving force.](image)

5.2. Optimization of joint driving force effect
Pre-compression force and spring stiffness have a great influence on the driving effect. To derive the most appropriate design variables, an objective function needs to be established for this boosting effect. When the upper arm rotation angle is set to $\phi$, the additional required force moment of the shoulder joint should be $f(\phi)$. According to the actual spring stiffness $K$ and the pre-tightening force $F_0$, the work of the additional required force moment is set as the objective function and the constraint conditions are as follows.

$$
\begin{align*}
\min \left( \int_{\phi_{min}}^{\phi_{max}} |f(\phi)| \, d\phi \right) \\
100 \leq K \leq 153 \\
0 \leq F_0 \leq 900
\end{align*}
$$

(1)

Under the condition of setting the above objective function and design variable on Adams, the optimization result is shown in Figure 9. The maximum torque is only 912 N·mm. The optimization results show that the spring stiffness $K$ is 153 N/mm, the pre-compression force $F_0$ is 900 N, and the work of the additional required force moment is 769.5 J. However, in the absence of exoskeleton assistance, the work should be 9503.3 J. The exoskeleton can save about 90% of energy consumption.

![Figure 9. The optimization of the additional required force moment.](image)

6. Conclusion
A wearable upper limb exoskeleton for factory assembly positions was designed. The trajectory and dynamics of the worker's arm during assembly was analyzed. According to the power demand, the corresponding torque drive scheme at the shoulder joint was designed. The effect on joint drive force was simulated on Adams. As shown by the result, pre-compression force and spring stiffness have a
great influence on the driving effect. Finally, with the work of additional required force moment for the shoulder joint as the objective function, the two parameters of spring stiffness and pre-compression force were optimized. Compared to not wearing the exoskeleton, the energy consumption of the exoskeleton was reduced by 90%.

The research in this paper suggests that the use of the wearable upper limb exoskeleton seems to be effective in helping workers save energy consumption during long hours of work, which is consistent with the conclusions of many scholars on upper extremity exoskeleton studies[11, 12]. Since occupational injuries of the upper limbs involved in the assembly process cannot be completely eliminated in the workplace [13], it is of great practical significance to study auxiliary equipment such as upper limb exoskeleton. We need further research and improvement of the design of the upper limb exoskeleton in the future, and evaluate the long-term effects of using upper limb exoskeleton, the effects on different populations and the potential benefits in actual workplaces (eg cars, aircraft assembly lines).

7. References
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