Research on Human Machine Interaction of Exoskeleton

Xi Yang[1, a], Jichen Wang[1, b], Chong Gao[1, c], Jiangpeng Hou [2, d]

[1] Jiangmen power supply bureau, Guangdong, China

[2] Beijing Institute of Technology, Beijing, China

[a] 593802030@qq.com, [b] 3186559265@qq.com, [c] 759790321@qq.com, [d] 626881646@qq.com

Abstract. In the exoskeleton system, the interaction force between the exoskeleton and the human body is one of the important factors determining the efficiency of exoskeleton assistance, and the constraints generated by the positional deviation between the exoskeleton and the human body can affect the human-machine interaction force. Therefore, this article first focuses on the mechanical characteristics of the relative position deviation of the external skeleton binding point, and obtains the constraint characteristics in different directions through experiments. Secondly, different exoskeleton mechanical models are established in the support phase and swing phase, and the magnitude of human-machine interaction forces is calculated based on the constraints generated by weight bearing gravity, human-machine deviation, and the inertia force generated by exoskeleton motion at each joint. Then, we analysed the impact of driving torque on human-machine interaction forces during active assistance at the hip and knee joints of the exoskeleton. When 100% assistance is provided to the hip and knee joints of the exoskeleton, the human-machine interaction force is the smallest and the assistance effect is the most obvious. Finally, a human-machine coupled motion model was established in Adams, and the mechanical factors of the exoskeleton model were added through constraints and driving functions. Simulation experiments were conducted on the impact of active assistance at the exoskeleton joints on human-machine interaction forces. Verified the accuracy of theoretical research results on the impact of exoskeleton joint matching on the relative position deviation of the binding position and active joint assistance on human-machine interaction force.

Keywords: exoskeleton; human-computer interaction.

1. Introduction

Establishing a dynamic model that can describe the assist characteristics of exoskeletons is the key to achieving human-machine collaborative motion of exoskeletons and the foundation for researching control methods.

In 1987, J. Furusho from Japan first established a five-link motion model for bipedal robots[1-3]. In 1990, a seven-link dynamic model was established for the foot. The University of Berkeley in the United States established a seven-link dynamic model, which was divided into "single foot support", "double foot support", and "double foot support with one foot touching the ground"[4-8]. The system was modelled as a 3 degree of freedom parallel to a 4 degree of freedom connecting rod. The five-link model adopted by Zhejiang University exoskeleton[9-11], which ignored the wearer's foot and only analysed the two states of "single leg support" and "double leg support" in one gait cycle. Although the five-link model may be simpler in theoretical modelling and calculation, its feet were parallel to the ground and had a significant deviation from the lower limb movements of normal wearers[12-13].

The above models do not consider the interaction forces between humans and machines, which results in significant errors from the actual situation. Therefore, this article first conducted mechanical characteristics experiments on the relative position deviation of human-machine and analysed the constraints during a gait cycle. We established dynamic models of the assisted exoskeleton according to the support phase and swing phase to study the impact of joint active assistance on the interaction force between humans and machines. Finally, a simulation model of exoskeleton and human body was established in Adams, and the influence of joint active assistance on human-machine interaction force was verified.

2. Method

2.1 Experiment

During a gait cycle of the wearer's exoskeleton movement, the relative positions of the human-machine coupling binding points at the large and small legs generated slippage along the direction of the wearer's leg member and offset perpendicular to the direction of the leg member. So this article conducted mechanical characteristic tests on the relative position deviation between humans and machines, and explored the relationship between the relative position deviation and constraint force at the big and small legs between humans and machines. The Motion system can measure the relative displacement and slip between the exoskeleton and the wearer at the binding point, and the digital tension meter can detect the binding force between the exoskeleton and the wearer in real-time. Paste reference points on the exoskeleton leg member and the subject as shown in figure 1.

figure 1 The weight bearing gravity and human-machine interaction force of the supporting exoskeleton

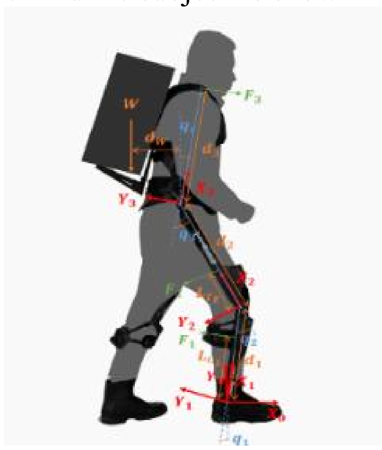

figure 2 Mechanical analysis of the weight-bearing gravity and human-machine interaction forces of the supporting exoskeleton

$\boldsymbol{v}_{ij}^{t}$ is the direction vector between any two points. For the sliding between humans and machines along the direction of the leg, α_h^t is the sliding angle between the wearer's reference point and the direction vector composed of P_1 and P_2. h_T^t is the sliding amount along the direction of the leg member. For the offset between the human machine and the human machine perpendicular to the leg member direction, α_p^t is the offset angle between the wearer's reference point and the direction vector composed of P_1 and P_2.h_p^t is the offset between the human and machine perpendicular to the direction of the leg member.

2.2 Human-machine mechanical model

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}}) + \boldsymbol{G}(\boldsymbol{q}) = \boldsymbol{\tau}_E + \boldsymbol{\tau}_W + \boldsymbol{\tau}_R + \boldsymbol{\tau}_H \quad (1)$$

Among them, $\boldsymbol{q}$ is the joint angle of exoskeleton motion, $\boldsymbol{M}(\boldsymbol{q})$ is the positive definite mass matrix, and $\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})$ The centrifugal force and Coriolis force vector depend on the position and velocity of the exoskeleton, where $\boldsymbol{G}(\boldsymbol{q})$ is the gravity vector. τ_E represents the driving torque of the exoskeleton joint driver, τ_W represents the applied torque of the load's gravity, τ_R is due to the binding force between the exoskeleton and the wearer due to relative positional deviation, τ_H represents the moment of interaction between humans and machines.

$$\begin{cases} \boldsymbol{F}_W^3 = \begin{bmatrix} -Wcosq_t \\ Wsinq_t \\ 0 \end{bmatrix} \\ \boldsymbol{N}_W^3 = \begin{bmatrix} 0 \\ 0 \\ Wd_w \end{bmatrix} \end{cases} \quad (2)$$

Equation (2) are the force and torque generated by the load at the hip joint. Let this portion of the weight-bearing gravity be W, and the distance between its center of gravity and the center of rotation of the exoskeleton hip joint on the sagittal axis is d_w. The forces and moments generated in the knee and ankle joints are the same.

$$\begin{cases} \tau_W^1 = \boldsymbol{N}_W^{1\,T} \hat{Z} \\ \tau_W^2 = \boldsymbol{N}_W^{2\,T} \hat{Z} \\ \tau_W^3 = \boldsymbol{N}_W^{3\,T} \hat{Z} \end{cases} \tag{3}$$

$$\tau_H^i = \sum_{j=i}^{3} (\boldsymbol{P}_{F_j}^i \times \boldsymbol{F}_J^I)^T \hat{Z} \tag{4}$$

Equation (3) and (4) are the torque generated by the weight bearing gravity assisted by the exoskeleton at each joint. τ_H^i is the total equivalent torque of human-machine interaction force on each joint. $\boldsymbol{P}_{F_j}^i$ is the position of the interaction force on each member in the i-th joint coordinate system. $\boldsymbol{F}_J^I$ is the position of the interaction force on each member in the i-th joint coordinate system. The calculation method for the equivalent torque of the relative position deviation of the big and small leg ties at each joint is the same as the human-machine interaction force. The dynamic modelling method for swing phase is the same as that for support phase.

2.3 Research on human-machine interaction force

Based on the force curve characteristics of human-machine interaction force, the influence of joint driving torque on the human-machine interaction force at the large and small legs was explored at the hip and knee joints of the exoskeleton according to the sine function curve property of joint driving torque.

$$\tau_E^{knee}(t) = \begin{cases} 10sin\left(\frac{\pi}{40}t\right) & t \in [0 \quad 40] \\ 0 & t \notin [0 \quad 40] \end{cases} \tag{5}$$

$$\tau_E^{hip}(t) = \begin{cases} 10sin\left(\frac{\pi}{30}t - \pi\right) & t \in [0 \quad 30] \\ 5sin\left(\frac{\pi}{30}t - \pi\right) & t \in [30 \quad 60] \\ 0 & t \in [60 \quad 100] \end{cases} \tag{6}$$

3. Result

3.1 Research on the influence of hip joint assistance

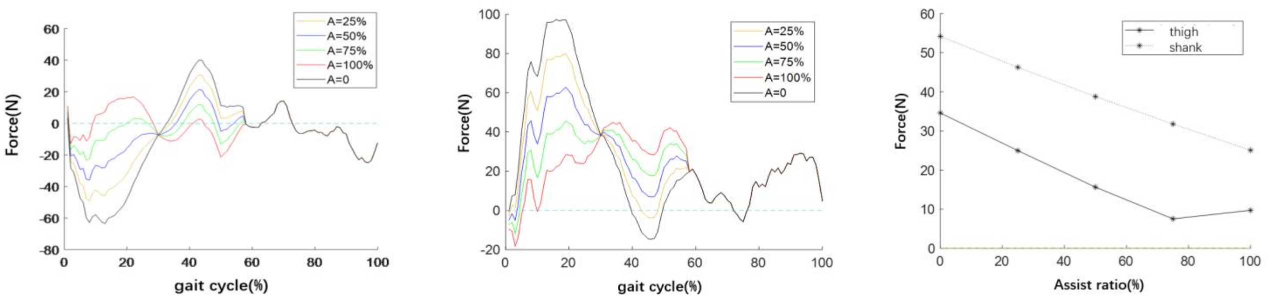

figure 3 Human machine interaction force under hip joint assistance
(a) Force at the thigh, (b) Force at the lower leg, (c) Average force

In the first half of the support phase, as the active extension torque of the hip joint increased, the forward interaction force on the exoskeleton thigh continuously decreased. When 100% assistance was provided at this stage, a backward interaction force generated, and the backward interaction force on the exoskeleton calf reduced. In the second half of the support phase, with the increase of the hip joint active assist flexion torque, the peak rearward interaction force on the exoskeleton thigh decreased, but the rearward interaction force at the calf increased. According to the average interaction force curve during the assistance phase, as the active assistance degree of the exoskeleton hip joint increased, the average interaction force at the lower leg continuously decreased, and the average interaction force at the thigh continuously decreased. When providing 75% assistance degree, the average interaction force in the front and back directions at the thigh reached the minimum value. If the active assistance degree of the hip joint continued to increase at this time, it will reduce the average interaction force value between the front and back of the lower leg. Therefore, according to the designed exoskeleton hip assist curve, active joint assistance can significantly reduce the peak human-machine interaction force at the exoskeleton thigh leg. When 100% assistance was performed, the assistance effect was most obvious.

3.2 Research on the influence of knee joint assistance

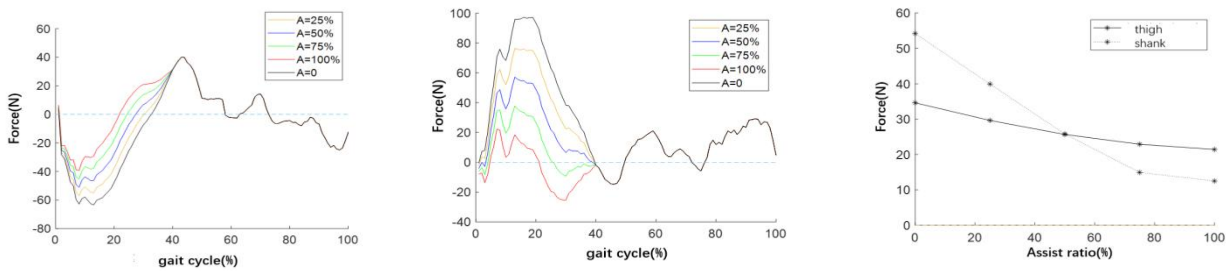

figure 4 Human machine interaction force under knee joint assistance
(a) Force at the thigh, (b) Force at the lower leg, (c) Average force

In the first half of the support phase, as the active extension torque of the hip joint increased, the forward interaction force on the exoskeleton thigh continuously decreased. When 100% assistance was provided at this stage, a backward interaction force generated, and the backward interaction force on the exoskeleton calf reduced. In the second half of the support phase, with the increase of the hip joint active assist flexion torque, the peak rearward interaction force on the exoskeleton thigh decreased, but the rearward interaction force at the calf increased. According to the average interaction force curve during the assistance phase, as the active assistance degree of the exoskeleton hip joint increased, the average interaction force at the lower leg continuously decreased, and the average interaction force at the thigh continuously decreased. When providing 75% assistance degree, the average interaction force in the front and back directions at the thigh reached the minimum value. If the active assistance degree of the hip joint continued to increase, it will reduce the average interaction force value between the front and back of the lower leg. Therefore, according to the designed exoskeleton hip assist curve, active joint assistance reduced the peak human-machine interaction force at the exoskeleton thigh leg. When 100% assistance was performed, the assistance effect was most obvious. The hip joint provided extension torque in the first half of the support phase, which reduced the human-machine interaction force at the large and small legs; Providing bending moment in the second half of the support phase can reduce the human-machine interaction force at the thigh, but it will also increase the human-machine interaction force at the thigh; Active assistance that provides flexion torque during the first 40% of the gait cycle at the knee joint can reduce the human-machine interaction force at the large and small legs. During the process of active assistance at the upper and lower legs according to the set joint torque curve, analysis showed that the assistance effect was better when providing 100% assistance.

3.3 Simulation

In Adams simulation, the human-machine collaborative system was simplified as a rigid body model.

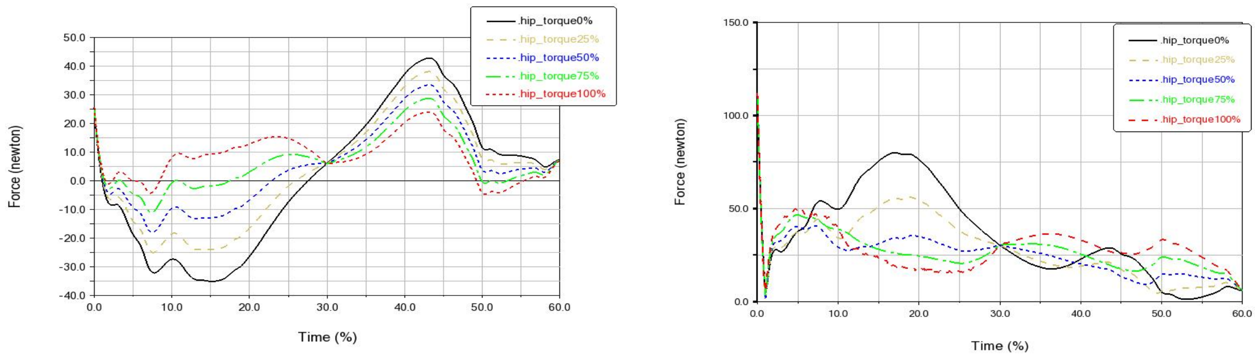

figure 5 Human machine interaction force in the case of active hip joint assistance
(a)Force at the thigh, (b) Force at the lower leg

As shown in figure 5, as the active extension torque of the hip joint increased, the forward interaction force on the exoskeleton thigh decreased. When 100% assistance was provided at this stage, a backward interaction force generated during the full foot contact stage. In the second half of the support phase, as the hip joint assisted flexion moment increased, the peak interaction force on the exoskeleton thigh towards the rear decreased. The interaction force behind the lower legs increased. Therefore, the results of simulation experiments on the human-machine interaction force of hip joint active assistance were basically consistent with the conclusions of theoretical analysis.

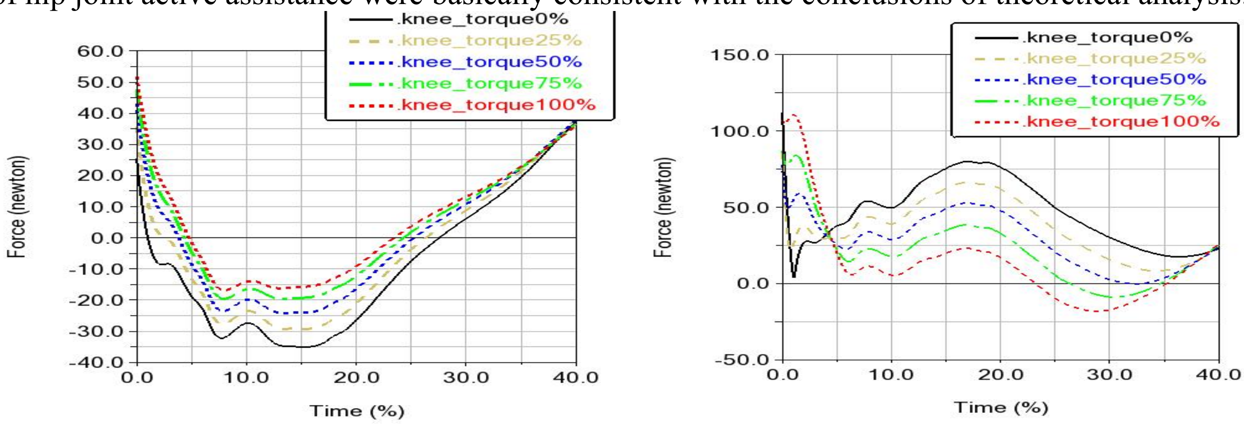

figure 6 Human machine interaction force in the case of active knee joint assistance
(a)Force at the thigh, (b) Force at the lower leg

As shown in figure 6, as the driving torque of knee joint flexion increases, the forward interaction force on the exoskeleton thigh during the full foot contact stage continuously decreased, and the backward interaction force gradually increased during the heel contact and mid support stage. The posterior interaction on the lower leg of the exoskeleton was more pronounced, and when the degree of assistance exceeded a certain range, a forward interaction force generated and gradually increased in the middle of the support. Therefore, the results of simulation experiments demonstrating the effect of active knee joint assistance on human-machine interaction force were basically consistent with the conclusions of theoretical analysis.

4. Conclusion

This article conducted a mechanical characteristic experiment on the relative position deviation of the exoskeleton binding point, and analysed the binding force generated by the relative position deviation between humans and the exoskeleton. We established dynamic models of each joint for the support phase and swing phase exoskeletons to study the impact of the torque characteristics of joint active assistance on human-machine interaction force. When 100% assistance is provided to the hip and knee joints of the exoskeleton, the human-machine interaction force is the smallest and the assistance effect is the most obvious. Furthermore, we established a load-bearing assistance simulation model for the human-machine coupling of exoskeleton robots. The accuracy of the exoskeleton dynamics model established by theoretical analysis was demonstrated, and the impact of joint active assistance on human-machine interaction force was verified. In the future, we will consider optimizing the model from the perspective of foot modelling and improving the assist control strategy.

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