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Lower Limbs Exoskeleton Control Strategy Based On Optimized Compliance Algorithm

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***Abstract* - Aiming at achieving the compliance control of lower limbs exoskeleton, a compliant control strategy basing on optimized compliance algorithm was proposed. The motion trajectory of human body was collected by using inertial sensors and electromyography sensors, and the information is taken as the reference information to the exoskeleton robot. By introducing muscle activation degree as the feedforward loop to offset the hysteresis phenomenon which is shown in the process of movement, the following movement achieved compliant. The feasibility of this control method is both verified on the simulation software platform and physical prototype. The experimental results show that this control method is effective and feasible in the lower limbs exoskeleton system.**

Index Terms - exoskeleton robot; optimized compliance control; muscle activation degree; lower limbs exoskeleton.

I. INTRODUCTION

Exoskeleton robot is a man-machine doubling system which could enhance users' exercising ability and improve patients' health during the rehabilitation, and many research institutes have focused on the design and control algorithm of the exoskeleton[1-8]. As the human is an important part of the control feedback loop, different research institutions adopt different control strategies on software and hardware to ensure the comfort of wearers and the structural stability of the exoskeleton, such as adopting model adaptive filtering algorithm of upper limb rehabilitation exoskeleton robot [9];Multi-mode elastic driver is used to realize the knee joint compliance control [10].Multiple sensor signal fusion technology is used to realize correlation control of exoskeleton [11][12].A hypothesis is proposed for verifying the role of center of mass vibration in gait transition and its behavior prediction in exoskeletons [13].A motor-cable driven flexible skeleton suit was proposed, which could optimize the energy expenditure by adopting the parameters self-tuning control algorithm [14]. A feedforward dynamic load-torque compensating method was proposed to improve the performance of the exoskeleton joint [15].

In order to achieving the flexibility of lower limb exoskeleton robots, an optimized control algorithm is proposed. By using the multiple source signals to enhance the compliance of the exoskeleton robot, the control algorithm was verified effectively on the simulation software and physical prototype platform.

II. COMPLIANCE CONTROL STRATEGY

A. Exoskeleton Design

Considering the structural strength and response speed, the aerometal material and motor actuator are adopted. As for realizing the human – robot soft and compliance control, the exoskeleton motion information should be easy to apply and collect, and the motor actuator could change the joint movement in a high reaction speed under the control of the computer. And the mass and power of the actuator, the motor driver could be more convenient than the hydraulic driver to realize the control method. Different sensors are used to collect the motion information to analyze the flexibility and motion condition. The exoskeleton prototype is in Fig. 1.

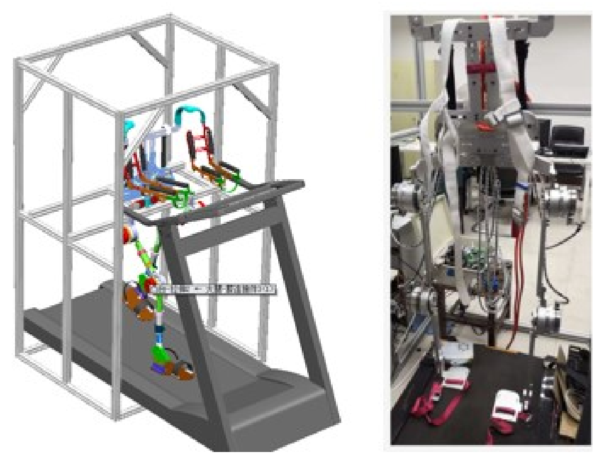

Fig. 1 Exoskeleton Prototpype

B. Optimization of sEMG signals

Surface electromyogram signals have been proved to be helpful to understand the motion of human. However, previous studies have focus primarily on motion classification of upper limb discrete gestures[16][17]. As the muscle movement shows the difference of surface electromyogram signals, the sEMG signals could be selected to predict the intends of the human lower limb motion. For the exoskeleton robot, the feedforward control loop should adopt effective signals to realize the control algorithm and analyzing.

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Considering the high levels of muscle recruitments[18], the lower limb muscle inertial sensors and sEMG sensors are used to collect different signals. As in Fig. 2, number 1, 4, 9 are the inertial sensors to collect the joint angle information, while the rest sensors are used to collect the sEMG signals.

Fig. 2 location and number of sensors

The impedance control is used to realize the compliance of exoskeleton, and desired trajectory could be converted into force by analyzing inverse dynamics. Using the plantar sensor as the trigger of desired trajectory, a noticeable force would be required to drive the exoskeleton, which could decrease the compliance. In order to improve the situation, surface electromyographic signals (sEMG) are used in the feedforward compensation to optimize control loop.

C. *Muscle Activation Degree*

The muscle activation model can describe the relationship between muscle activation intensity and sEMG. Due to the non-linearity of human physiological signals, the relationship can be described by the following equation:

$$a(t) = \frac{e^{\lambda u_i} - 1}{e^{\lambda} - 1}, -3 < \lambda < 0 \tag{1}$$

u_i is the processed sEMG signal, and the muscle activation degree can be calculated and the results are shown in Fig. 3. It can be seen form the below curve that the activation degree can be used to evaluate the human muscle activation degree before the moment of lower limbs, which could work as a feedforward compensation to reduce the hysteresis of the control loop in the exoskeleton system.

D. *Compliance Control algorithm*

The optimized compliance control loop is shown in Fig. 4. Motion information is collected by inertia sensors, and it could provide desired trajectory which could be triggered by plantar pressure sensors. X_d 、$\dot{X}_d$ 、$\ddot{X}_d$ are the specific desired motion information, and the output force could be calculated . The compliance control model is as follow:

$$F = M(\ddot{X}_d - \ddot{X}) + B(\dot{X}_d - \dot{X}) + K(X_d - X) \tag{2}$$

X、$\dot{X}$、$\ddot{X}$ are the actual position, velocity and acceleration of the exoskeleton; The flexibility of the system could be realized by adjusting the three independent parameter M, B and K..

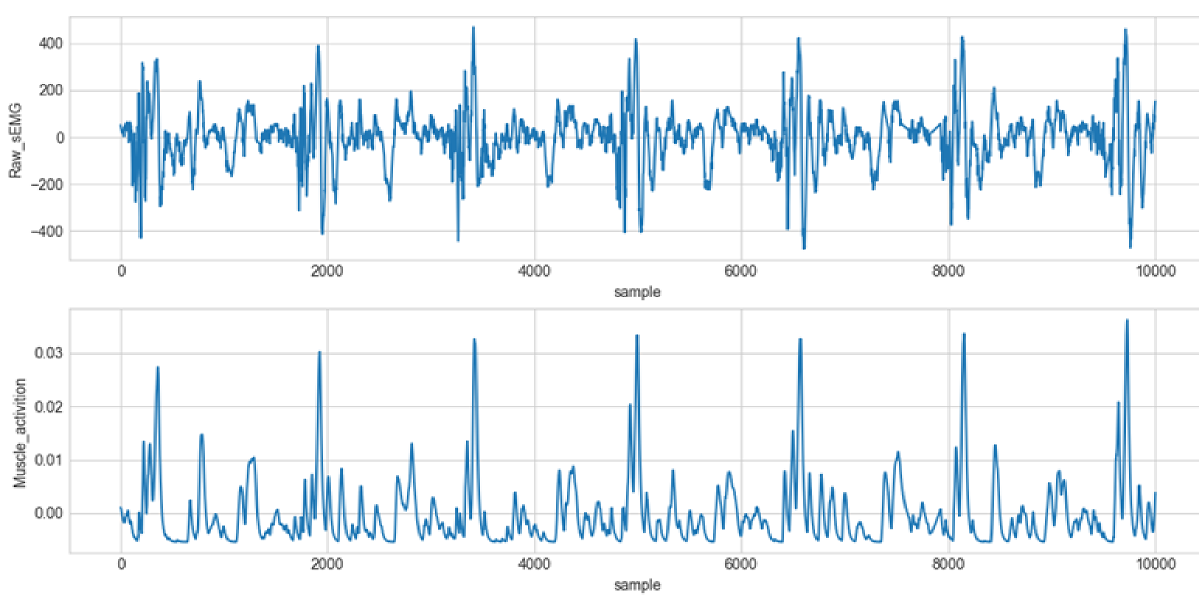


Fig. 3. Electromyography original signal and activation signal

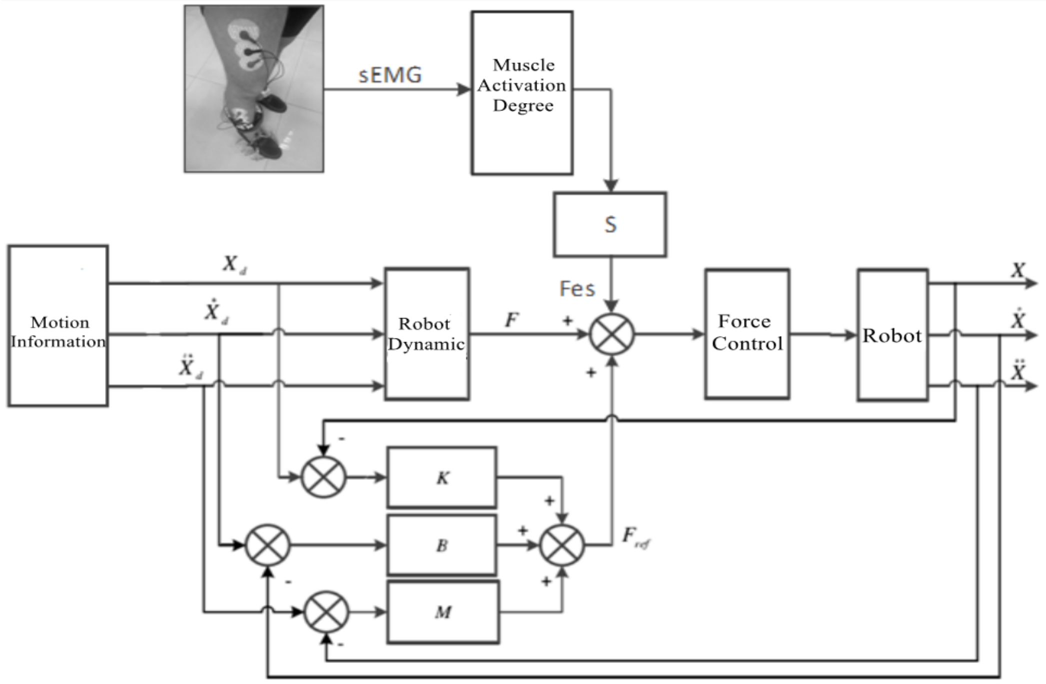


Fig. 4. Activation signal optimized impedance control

III. SIMULATION AND EXPERIMENT

In order to verify the motion following and compliance of this control method, simulation tests and physical experiments have been made as follow. Using inertial sensors to record the human body joint trajectory information, the torque output could be calculated by the lower limb's inner dynamic script. The simulation model in V-rep is showed in Fig. 5.

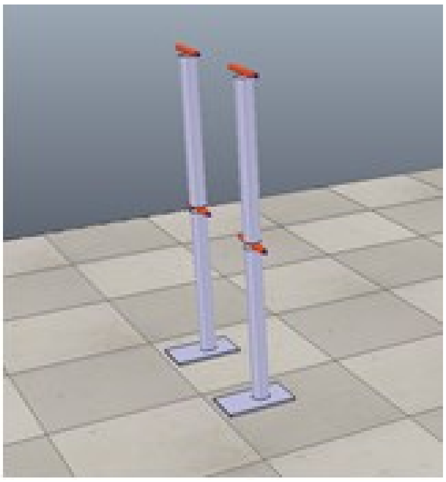
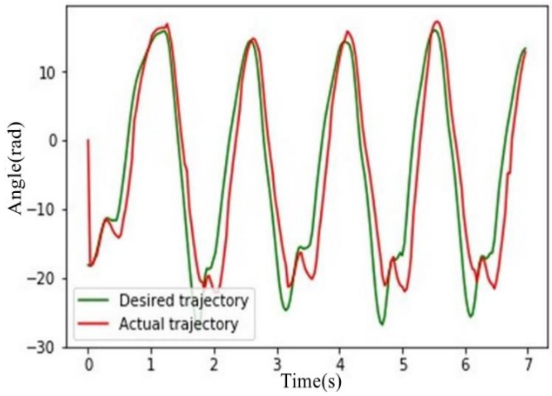


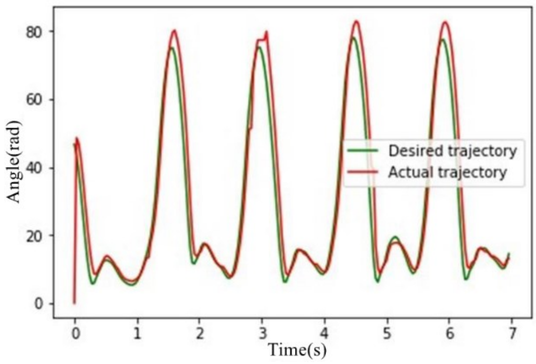
Fig. 5 Lower limbs exoskeleton simulation model

A. Simulation

Using inertial information and the script, simulation control feedback could be tested to verify the effectiveness. The following results are shown in Fig. 6.



(a)

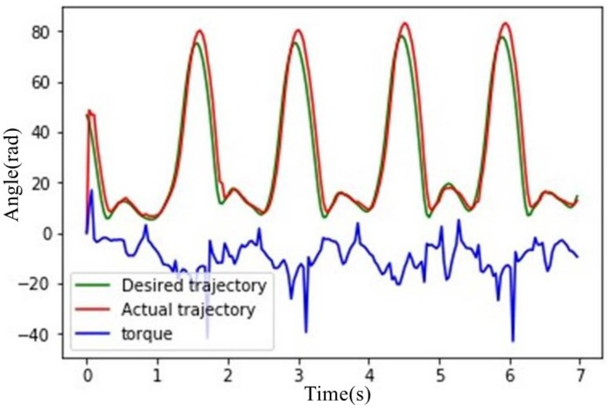


(b)

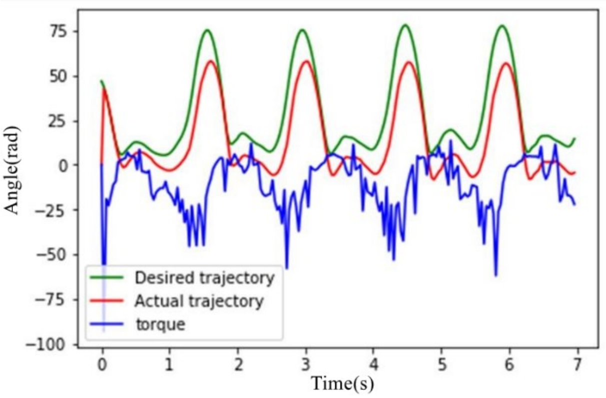
Fig. 6 knee joint (a) and hip joint (b) trajectory simulation result

The red curve is the desired trajectory and the green curve is the actual trajectory. The maximum error at the turning point of the track is about 5 rad, while the following error in the monotonous track interval is less than 0.5 rad, which indicates that it has a good following ability during the continuous motion.

To verify that the turning point of error is safe for the wearer, compliance tests are designed for lower limbs: An obstacle is added on the exoskeleton trajectory as being an external interference. When the lower limb touch the obstacle, the motors' torque would be influenced. If the motor torque increases suddenly when touching the obstacles, it means the motor try to get to the right position without considering the force value, which means that the users may suffer the potential harm if they want to change their movement. ,and this situation equals to no compliance situation. Simulation tests are put under two circumstances: Having an obstacle or not, and the result are shown in Fig. 7.



(a)



(b)

Fig. 7 The compliance test of lower limb exoskeleton (without obstacles (a) or not (b))

The red curve is the desired trajectory, the green curve is the actual trajectory and the yellow curve is the motor output torque. While exoskeleton touches the obstacle, its' motor torque shows a small fluctuation and a small location error happens, which indicates the compliance of exoskeleton. The error between the desired cure and actual cure shows the tolerance for the motor actuator and the fluctuation torque shows the compliance control method made the robot try to narrow the trajectory error with considering a reasonable torque to not hurt the wearers.

B. *Physical Experiments*

Considering the symmetry of lower limb exoskeleton, physical verification experiments are carried out with the right lower limb to test the exoskeleton motion control function, which is shown in Fig. 8.

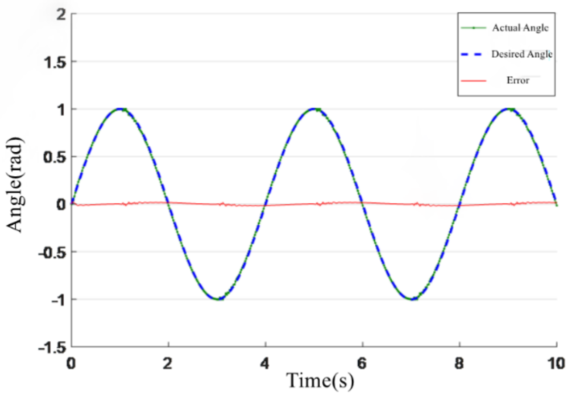
Fig. 8 Human body wearing exoskeleton verification

Considering to the safety during the experiment, different expected trajectories were set respectively:

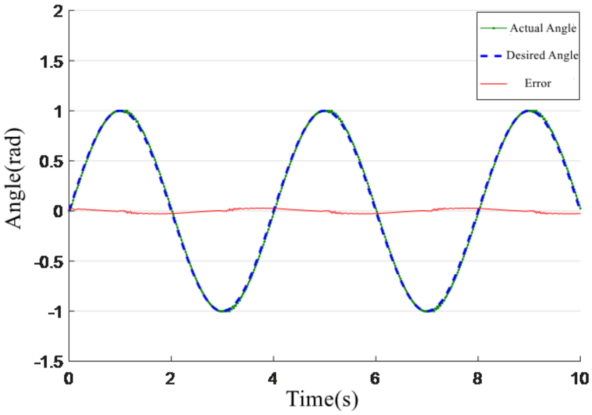
1) *Desired hip Angle and desired knee angle are respectively:*

$$\theta_{dhip} = \sin(\frac{\pi}{2}t) \quad \theta_{dknee} = \sin(\frac{\pi}{2}t)$$

The actual angles of hip joint and knee joint were collected by the computer, and are shown in Fig. 9. The green curve represents the actual joint Angle, the blue curve represents the desired joint angle, and the red curve represents the error. It shows that the hip joint maximum is 0.0249 rad, and the maximum knee angle error is 0.0328 rad.



(a)



(b)

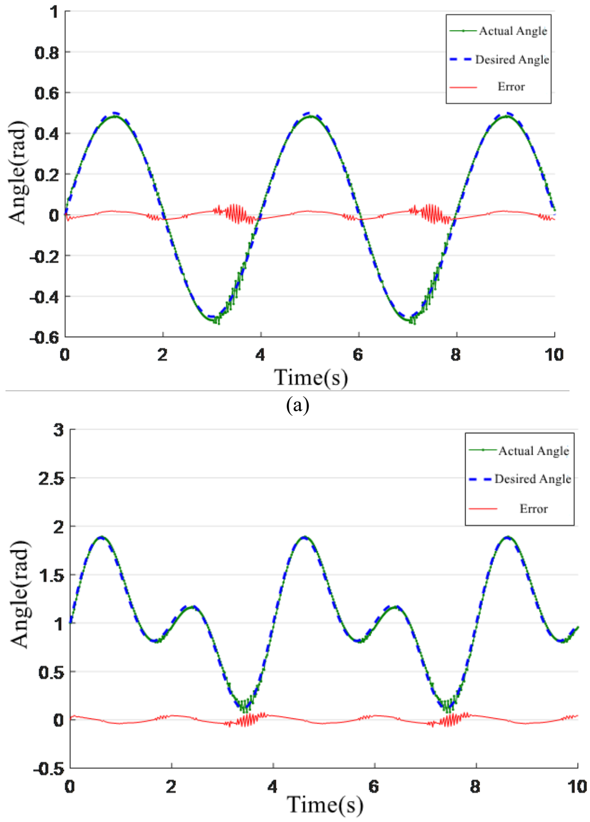
Fig. 9 Experimental results of hip joint（a）and knee joint（b）

2) Desired hip Angle and desired knee angle are respectively :

$$\theta_{dhip} = \frac{1}{2}\sin(\frac{\pi}{2}t) \quad 3) \; ,$$

$$\theta_{dknee} = \frac{1}{2}(\sin(\frac{\pi}{2}t)+\sin(\pi t))+1$$

The experimental results are shown in Fig. 10. A noticeable error can be seen when the joint angle increases from the minimum value to the maximum value, with a maximum error of 0.05267 rad for hip joint and 0.07622 rad for knee joint, which reflects a good following and compliance ability.



(b)

Fig. 10 Experimental results of hip joint (a) and knee joint (b)

IV. CONCLUSION

To achieve the effectiveness and efficient reaction of robot, a lower limbs exoskeleton was designed. Considering the experience of the formal experiments and references, the control algorithm was selected. As imposing the different sensors to collect signals, the algorithm was identified to be more reliable for using these information to optimize the feedforward control loop. The information of the sEMG sensor is processed into the muscle activation degree for predict the movement of the body, while the collection of the inertial information is used as the information of the exoskeleton trajectory. The experiments in simulation and physical platform are designed precisely and the results show the reasonability of the exoskeleton.

In this lower limb exoskeleton robot platform, this paper proposed a compliance control algorithm, which combine with the collected movement trajectory information and sEMG information. Using muscle activation degree as the feedforward compensation to optimize the compliance control algorithm and achieve the flexibility of the exoskeleton. Finally, by imposing trajectory and compliance experiments, the simulation tests and physical experiments verify the feasibility of the optimized control algorithm. These features shows the control algorithm could optimize the movement of the exoskeleton without designing a complex structure to fulfill the soft human – robot interaction.

To support the exoskeleton compliance control in the exoskeleton robot, multiple signals are used to optimize the control methods, and the results show that the hip and knee joints have no more than 0.06 rad and 0.08 rad errors respectively. The motion error shows a good interaction for robot to achieve the compliance control. Further experiments would be tested to verify the interaction between robot and human.

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