Structure Design and Dynamic Model Analysis of Multi-degree-of-freedom Exoskeleton

Yang Wang
School of Engineering and Technology
China University of Geosciences (Beijing)
Beijing , China
e-mail: cugbwangyang@126.com

Rencheng Wang
Dept. of Mechanical Engineering
Tsinghua University
Beijing , China
e-mail:rc.wang@qq.com

Yiyong Yang
School of Engineering and Technology
China University of Geosciences (Beijing)
Beijing, China
e-mail: yangyy@cugb.edu.cn

Weifeng Liu
School of Engineering and Technology
China University of Geosciences (Beijing)
Beijing , China
e-mail: lwf900@163.com

Abstract— 1.Objective: This study aims to propose the changing of the joint force during walking cycle based on the multi-degree-of-freedom exoskeleton. 2.Methods: The dynamic model of the joint structure is built up and the force situation is gotten when it is working. Then the electric currents are obtained by DSPACE semi-physical simulation system during walking cycle which are divided into three groups. Group 1 is the exoskeleton robot walking with nothing; group 2 is the exoskeleton robot walking with 10kg loads which 5kg loads are on the thigh and another 5kg are on the shank; group 3 is that it was dressed by patient. 3. Results: The vale of motors electric current is within the limitation range and has a little bit huge wave. 4. Conclusion: The motor force can drive the exoskeleton robot and the driven scheme, which is used in rehabilitation treatment, is achievable and available.

Keywords-lower limb exoskeleton; rehabilitation; structure; current; experiment

I. INTRODUCTION

With more and more people have cerebral apoplexy and accidents in recent years, it leads to patients pay more attention to paraplegia and rehabilitation which is a recovery of walking function treatment approaches for patients[1-4]. Rehabilitation training can reduce the occurrence of diseases such as muscular dystrophy and bedsore which are caused by long-term laying in bed[5-6] .

Through combining the exoskeletons robot technology with rehabilitation medicine theory, paraplegia patients could go on training in standing and walking under the help of using exoskeleton rehabilitation robot which is driven by hips and knees motors. The exoskeleton robot keeps its balance by the patient's "intelligence" and provides its "manual" to drive the patients recovery[7].

II. STRUCTURE DESIGN OF EXOSKELETON ROBOT

The exoskeleton robot which is similar to Rewalk[8-10] and eLegs[11-13] in the degree of freedom (all of them are four DOFs) is driven by motors and kept balance by hand crutch or walking frame. Transmission scheme adopts four-bar linkage which is driven by motor through the screw and nut pair, and the length changing of the four-bar linkage leads to the joint angle changing which makes the joint rotating. The joint model is shown in Fig .1, and the exoskeleton robot is shown in Fig .2.

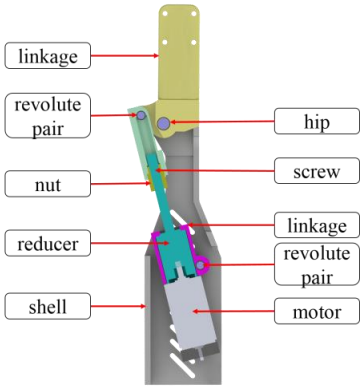


Figure 1.Joint model

Figure 2. Exoskeleton robot.

III. DYNAMICS ANALYSIS

Assuming that joints only move in sagittal plane and the joints are simplified into revolute pair. The exoskeleton robot could be simplified into a dynamic model as shown in Fig .3.

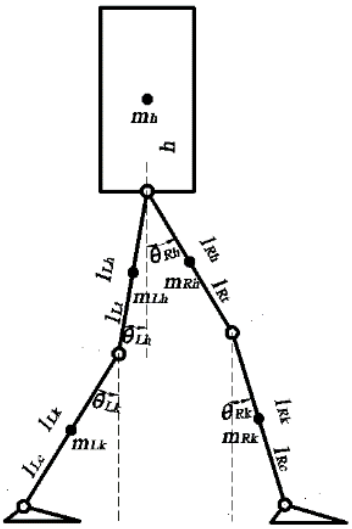


Figure 3. Dynamic model of the exoskeleton robot.

According to the Jacobi matrix, it can be obtained that the total kinetic energy T of the lower limb joints is:

$$\begin{aligned} T = {} & 1/2\, m_{Lc} l_{Lc}{}^2 \dot{\theta}_{Lk}^2 + 1/2\, m_{Lt} (l_{Lk}^2 \dot{\theta}_{Lk}^2 + l_{Lt}^2 \dot{\theta}_{Lh}^2) \\ & + 1/2\, m_h (l_{Lk}^2 \dot{\theta}_{Lk}^2 + l_{Lh}^2 \dot{\theta}_{Lh}^2) + 1/2\, m_{Rt} (l_{Lk}^2 \dot{\theta}_{Lk}^2 \\ & + l_{Lh}^2 \dot{\theta}_{Lh}^2 + (l_{Rh} - l_{Rt})^2 \dot{\theta}_{Lh}^2) + 1/2\, m_{Rc} (l_{Lk}^2 \dot{\theta}_{Lk}^2 \\ & + l_{Lh}^2 \dot{\theta}_{Lh}^2 + l_{Rh}^2 \dot{\theta}_{Rh}^2 + (l_{Rk} - l_{Rc})^2 \dot{\theta}_{Lk}^2) \end{aligned} \tag{1}$$

Assuming the potential energy of the ground is 0, the total potential energy V of the model can be calculated as follow:

$$\begin{aligned} V = {} & m_{Lc} g l_{Lc} \cos\theta_{Lk} + m_{Lt} g (l_{Lk} \cos\theta_{Lk} + l_{Lt} \cos\theta_{Lh}) \\ & + m_h g (l_{Lk} \cos\theta_{Lk} + l_{Lh} \cos\theta_{Lh} + h) + m_{Rt} g (l_{Lk} \cos\theta_{Lk} \\ & + l_{Lh} \cos\theta_{Lh} - (l_{Rh} - l_{Rt}) \cos\theta_{Rh}) + m_{Rc} g (l_{Lk} \cos\theta_{Lk} \\ & + l_{Lh} \cos\theta_{Lh} - l_{Rh} \cos\theta_{Rh} - (l_{Rk} - l_{Rc}) \cos\theta_{Rk}) \end{aligned} \tag{2}$$

According to Lagrange function $L=T-V$, it is easy to solve the torque on the joints. Therefore the dynamic equation of the simplified model is obtained like this:

$$Q_j = \frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_j}\right) - \frac{\partial L}{\partial q_j},\ j = 1, 2 \tag{3}$$

The equivalent moment of the joints is:

$$\begin{bmatrix} M_1 \\ M_2 \end{bmatrix} = \left(J_0'\right)^{-1} \left(\begin{bmatrix} Q_1 \\ Q_2 \end{bmatrix} - J \begin{bmatrix} F_x \\ F_y \end{bmatrix} \right) \tag{4}$$

IV. CONTRAST LOAD WITH DRESSED BY PEOPLE ABOUT THE DATE

This experiment is conducted based on DSPACE semi-physical simulation system which just gathers the unilateral leg's data, because the tracks of left and right leg are symmetry when people walk. During the walking cycle, the motor currents changing with the joint force, through which the performance of the exoskeleton robot could be obtained.

A. *Unilateral Experiment With No Load*

This unilateral no-load swing experiment requires the exoskeleton to be hung up, so that current changes and sudden changes of current of each joint motor of the exoskeleton could be observed in a motion period. Furthermore, that can be a contrast to the subsequent loaded experiment.

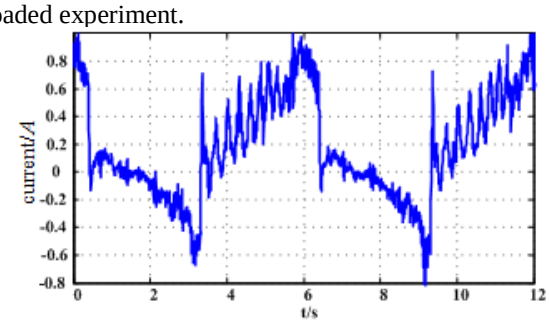


Figure 4.Current curve of hip joint

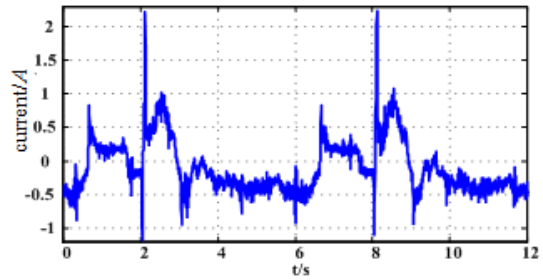


Figure 5.Current curve of knee joint

It's obvious in the current curve of Fig .4 that the current of hip joint is maintained between -1A to +1A , without huge wave, which demonstrates that there are no sudden change of the speed in hip joint, conforming to the control conditions. As illustrated by the current curve in Fig .5, the current of knee motor has a small saltation during a period of 6s, which also within the permissible range and satisfied the control conditions.

B. *Unilateral Experiment With 10kg Load*

According to the survey, the weight of one person's legs occupied 30%-40% in the total weight of one person. And the weight ratio of thigh, shank and feet is 21:13:7 for a normal person. The shank and feet can be regarded as a whole, both of which are actuated by knee joint motor, because the ankle joint of the exoskeleton is actuated with passive degrees of freedom. That is, the weight ratio of thigh and shank is almost 1:1.

Taking a 172cm-high and 60kg-weight adult as the case, the weight of one-side thigh is around 5kg, and the weight of shank is around 5kg. Therefore, 5kg weights are

loaded on thigh and shank respectively in the loaded experiment. The changes of current in one walking cycle period are shown in Fig .6 and Fig .7:

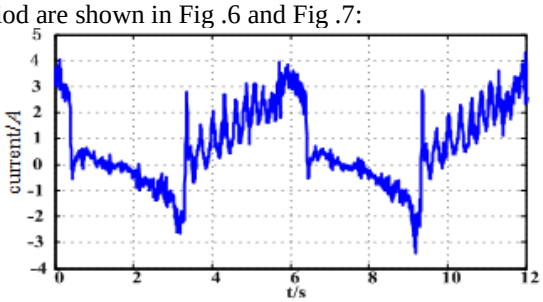


Figure 6.Current curve of loaded hip joint with 10kg

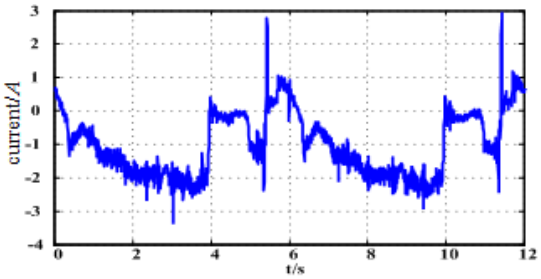
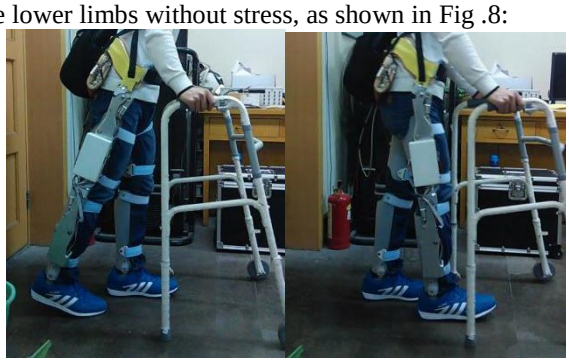


Figure 7.Current curve of loaded knee joint with 10kg

As shown in Fig .6 and Fig .7, it can be figured out by comparing with no-load current curves that the basic trends of current curves are the same. While, with the increase of load, current is increasing, and the driving moment force of motor is increasing, too. When both of the load weights on thigh and shank are 5kg, both of the motor current are maintained between-4A to +4A, which still under the rated current of the motor. It demonstrates that the weight of people can be actuated normally by the motors.

C. *Human-machine Experiment*

Human-machine experiment tests are conducted with normal person wearing exoskeleton under the condition of the lower limbs without stress, as shown in Fig .8:



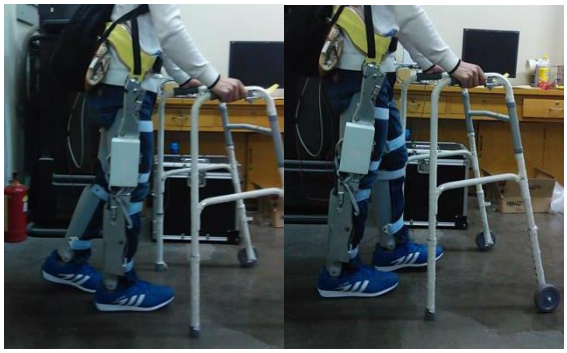


Figure 8. Exoskeleton human-machine experiment

In the experiment, motor pulse number changes over time as shown in Fig .9 and Fig .10, motor current changes as shown in Fig .11 and Fig .12.

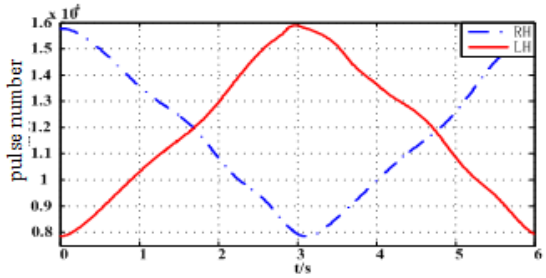


Figure 9.Curves of hip position in walking cycle

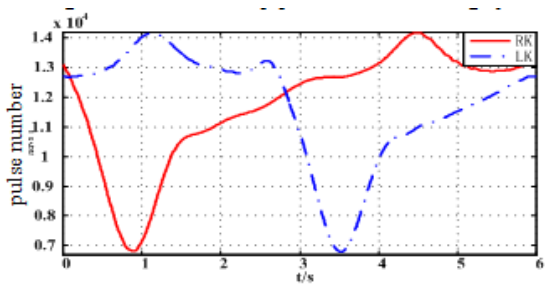


Figure 10.Curves of knee position in walking cycle

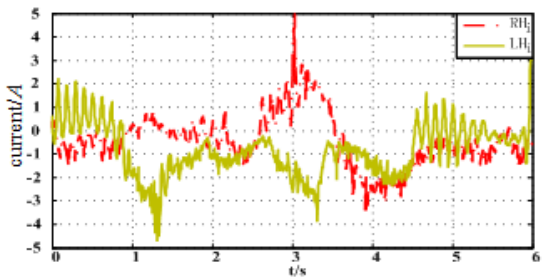


Figure 11.Curves of hip electric current in walking cycle

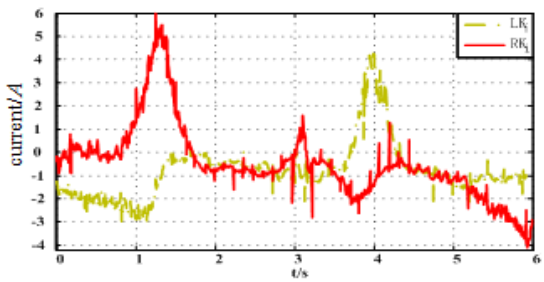


Figure 12.Curves of knee electric current in walking cycle

Contrasting the human-machine experiment and load current curve, Some conclusions can be drew that hip current curves are basically consistent within each other during a walk cycle while there is a little bit difference in a small range, which may be because of the small displacement between body and exoskeletons in the process of experiment or of the change of the motor driving force induced by the involuntarily controlling leg movement of tester.

V. RESULTS

The whole trend of the knee motor electric current curves also under a same direction contrast to a little difference partly. In the human-machine experiment, the current changing curves of the two legs have a half of the gait cycle difference, which according with human body normal walking patterns. The maximum currents of the motors are no more than limited current, which meets the control condition.

VI. CONCLUSION

By analyzing the experimental data, we can draw a conclusion that the heavier of the load, the larger of the motor current and the bigger of the motor output torque, which matches the actual situation very well. After deduction, analysis and comparisons of the experiments, it can be obtained that the exoskeleton designed in this paper can provide the power for lower limb walking normally. The motor force can drive the exoskeleton. And the driven scheme, which is used in multi-degree-of-freedom exoskeleton, is achievable and available. Moreover, the exoskeleton mechanism is suitable for walking recovery treatment of paraplegia patients in hospitals and it also can help people ,whose lower limb are disability, walking normally in their daily life. Furthermore, this multi-degree-of-freedom exoskeleton could burden load for soldiers or normal people ,especially in their journey.

ACKNOWLEDGMENT

This work is financially supported by National Science and Technology Major Project(2011ZX02403-4-3)

REFERENCES

[1] Harkema S, Gerasimenko Y, Hodes J, et al. Effect of epidural stimulation of the lumbosacral spinal cord on voluntary movement, standing, and assisted stepping after motor complete paraplegia: a case study [J]. Lancet, Vol. 377: 1938–47, 2011.

[2] Stopforth R. Customizable Rehabilitation Lower Limb Exoskeleton System [J]. Int J Adv Robotic Sy, 2012, 9(152).

[3] Behrman AL, Bowden MG, Nair PM. Neuroplasticity After Spinal Cord Injury and Training: An Emerging Paradigm Shift in Rehabilitation and Walking Recovery [J]. Physical Therapy. 2006, 68(10): 1406-1425.

[4] Herr H. Exoskeletons and orthoses: classification, design challenges and future directions [J]. Journal of NeuroEngineering and Rehabilitation, 2009, 6: 21.

[5] Hubli M, Dietz V. The physiological basis of neurorehabilitation - locomotor training after spinal cord injury [J]. J Neuroeng Rehabil. 2013, 10(5).

[6] Behrman AL., Harkema SJ. Locomotor Training After Human Spinal Cord Injury: A Series of Case Studies. Physical Therapy. 2000, 80(7): 688-700.

[7] Lingjun Rao. The research of Lower limb exoskeleton walking rehabilitation robot [D]. Shanghai Jiao Tong University, 2012.

[8] Talaty M, Esquenazi A, Briceno J E. Differentiating ability in users of the ReWalkTM powered exoskeleton:

An analysis of walking kinematics[C]//Rehabilitation Robotics (ICORR), 2013 IEEE International Conference on. IEEE, 2013: 1-5.

[9] Esquenazi A, Talaty M, Packel A, et al. The ReWalk powered exoskeleton to restore ambulatory function to individuals with thoracic-level motor-complete spinal cord injury [J]. American Journal of Physical Medicine & Rehabilitation, 2012, 91(11): 911-921.

[10] Zeilig G, Weingarden H, Zwecker M, et al. Safety and tolerance of the ReWalk™ exoskeleton suit for ambulation by people with complete spinal cord injury: A pilot study [J]. The journal of spinal cord medicine, 2012, 35(2): 101-96.

[11] Neuhaus P D, Noorden J H, Craig T J, et al. Design and evaluation of mina: A robotic orthosis for paraplegics[C]//Rehabilitation Robotics (ICORR), 2011 IEEE International Conference on. IEEE, 2011: 1-8.

[12] Tanabe S, Saitoh E, Hirano S, et al. Design of the Wearable Power-Assist Locomotor (WPAL) for paraplegic gait reconstruction [J]. Disability and Rehabilitation: Assistive Technology, 2013, 8(1): 84-91.

[13] Kim J H, Han J W, Kim D Y, et al. Design of a walking assistance lower limb exoskeleton for paraplegic patients and hardware validation using CoP [J]. Int J Adv Robotic Sy, 2013, 10(113).