AECXXX (this number will be assigned after full manuscript is accepted)

Design and Development of a Robotic System for Lower Limb Rehabilitation

Trinnachoke Eiammanussakul[1], and Viboon Sangveraphunsiri[1,*]

[1] Department of Mechanical Engineering, Faculty of Engineering, Chulalongkorn University
Phaya Thai Road, Khwaeng Wangmai, Khet Pathumwan, Bangkok, 10330, Thailand
[*] Corresponding Author: Viboon.S@eng.chula.ac.th, Tel: 0-2218-6610-1, Fax: 0-2252-8889

Abstract

This paper presents a robotic system for lower limb rehabilitation of patients who suffered from muscle weakness. The system is a stationary based type which aims to provide various kinds of exercises in sitting position. The rehabilitation is done by an exoskeleton robot with three degrees of freedom: hip, knee, and ankle joints. To operate the wearable robot safely, the joint actuation is carefully designed and passive control algorithm is developed. The balance mechanism is also included in the system to reduce actuator size and transmission ratio. The control interface is developed for ease of use and flexibility of operation. Some preliminary experiments are conducted to study the feasibility of the robotic system for the rehabilitation tasks.

Keywords*:* Robotic system, Lower limb rehabilitation, Muscle weakness

1. Introduction

Stroke patients usually suffer from muscle weakness. Even though it can be recovered naturally. Many research has shown that proper rehabilitation exercise is beneficial. Different kinds of exercise are used as a physical therapy to restore mobility, strengthen muscles, proprioception, and functional activities [1-2]. For example, passive exercises may be applied to restore range of motion of the patients whereas exercise devices which creates assistive and/or resistive force can be used to increase muscle strength and endurance.

Rehabilitation robots for lower limb exercises have been developed in many research. MotionMaker [3-4] has two robotic orthoses for attachment to each legs. Each of them is able to move hip and knee flexion/extension direction and ankle dorsiflexion/ plantar flexion direction. The robot is also equipped with electrostimulator to deliver electric shock to patient’s muscles in order to induce motion of the leg in addition to his/her voluntary effort. However, the maximum induced torque is limited by the saturation of the stimulation current for safe operation. Physiotherabot [2] is another stationary based rehabilitation robot which can move in direction of hip abduction/adduction and hip and knee flexion/ extension. This robot implemented several control algorithms depending on types of exercises required by a patient. Position control algorithm is selected when undergoing passive exercises while impedance control algorithm along with obtained information from force sensors are able to generate proper assistance and resistance for the patient. The horizontal lower limbs rehabilitative robot developed by Guo et al. [5] has four degrees of freedom, namely, hip and knee flexion/extension, ankle dorsiflexion/plantar flexion and abduction/adduction. The control algorithm of this robot is PID control with velocity and acceleration feedforward with gravity compensation. However, this robot can only operate passive rehabilitation.

This rehabilitation exoskeleton is aimed to be used by stroke patients to strengthen their lower limbs. In section 2, mechanism design of the robot is described. The controller implemented on the robot is mentioned in section 3. The experimental result is shown and discussed in section 4 and 5. Finally, the conclusion summarizes the overall works of this research.

2. Mechanism Design

The robotic system for lower limb rehabilitation in Fig. 1 includes a powered exoskeleton, a balance mechanism, a control unit, and a computer screen. The system can operate on either right or left leg at a time.

The exoskeleton has of 3 degrees of freedom: hip flexion/extension, knee flexion/extension, and ankle dorsiflexion/plantar flexion. These degrees of freedom are chosen because they are the main movement during overground walking (as the preparation for gait training in the future). The general posture of the robot is in sitting position because stroke patients usually suffer from muscle weakness which makes standing or walking too difficult for them. The exoskeleton is actuated at each joints by AC servo motors via cable transmission. The cable transmission is chosen rather than gears because of inherent compliance, and no backlash. A 400W motor drives the hip joint and 200W motors drive the knee and ankle joints. The cable transmission has two stages with transmission ratio of 3:1 and 5:1. The total transmission ratio of 15:1 is considered not too high for the robot to be backdrivable.

The counterweight mechanism is also a part of the system. It is designed to reduce load of the robot’s hip joint actuator so lower torque requirement and transmission ratio can be achieved [6]. This also

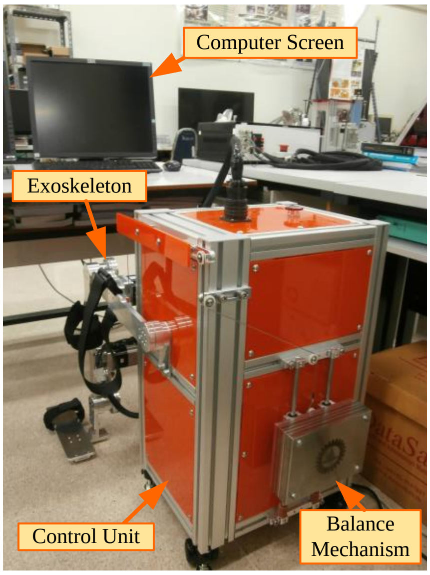


Fig. 1 The robotic system for lower limb rehabilitation

implies better open-loop backdrivability and safety of the system interacting with human [7].

The control unit contains a power supply, a computer, a data acquisition card, and motor amplifiers. The unit is also the base for mounting the exoskeleton's hip joint actuator and cable transmission and the counterweight mechanism. It also has casters to make the robotic system portable.

The computer screen is also considered as a part of the robotic rehabilitation system. It displays the software interface to operate the system and also shows the desired leg posture and actual leg posture for the training session. This visual feedback makes the training task easier to understand. Torque exerted by the robot in real time is shown on the screen so the therapist can assess the performance and progress of the treatment.

3. Control Algorithm

The exoskeleton is controlled at each joints by an impedance controller cascaded with inner torque and velocity control loops similarly to previous literature [8-11]. Stability and passivity of the controller have been proven [12] to ensure safety of the interaction between human and robot.

In Fig. 2, error between predefined desired joint angle $(\theta_{j,d})$ and actual joint angle (θ_j) is used as an input of an impedance controller. Desired torque $(\tau_{j,d})$ is computed with the following control law

$$\tau_d = K \cdot (\exp(|\theta_{j,d} - \theta_j|) - 1) \cdot \mathrm{sgn}(\theta_{j,d} - \theta_j) \quad (1)$$

where K is a stiffness gain. Next, joint torque (τ) and motor velocity $(\dot{\theta}_m)$ are controlled with PI controllers. Joint torque is estimated from motor current multiply with motor torque constant (K_t) and cable transmission ratio (N) whereas motor velocity is obtained by differentiation of motor angle (θ_m) measured by an encoder.

4. Experiment

To wear the exoskeleton, it is recommended the user to sit on a chair whose height is adjustable so that the hip joint axes of human and the robot can be aligned. Next, the length of the robot's shank and foot links must be adjusted to fit with the user's leg. Then, robot's and human's links are fastened together with Velcro straps.

Before a training session, the user has to define desired joint angle trajectory manually by moving the exoskeleton to desired consecutive postures and recording corresponding joint angles. The desired trajectories of each joints will be generated from this database. Also, the stiffness gain of the impedance controller and speed of the trajectory must be selected to desired value.

During the session, the previously recorded desired leg posture and actual leg posture are displayed on the computer screen as shown in Fig. 3(a). The objective of the training is that the user should try to move his/her leg to follow the reference leg as much as possible in order to achieve good tracking along desired trajectory. If the user can perfectly track along the desired trajectory, the exoskeleton will not exert any force on the user's limbs. On the other hand, if the joint angle error increases, the exoskeleton will generate assistive or resistive force as shown in Fig. 3(b) to ensure that the actual leg posture is still closed

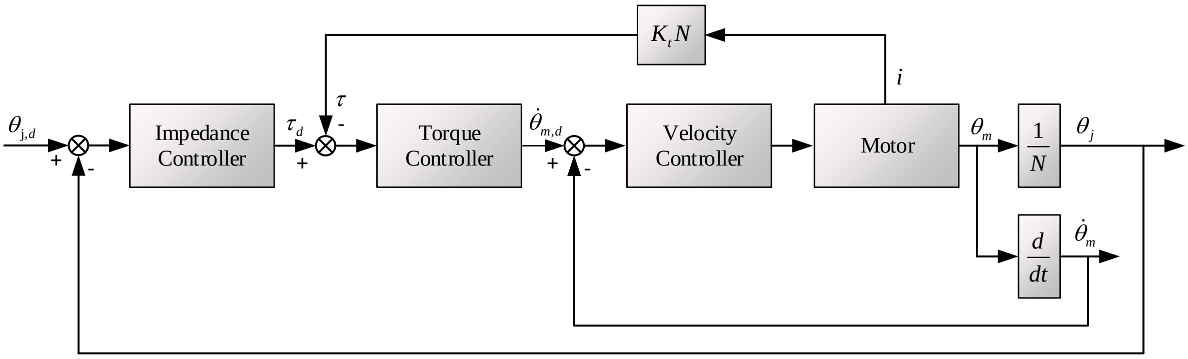
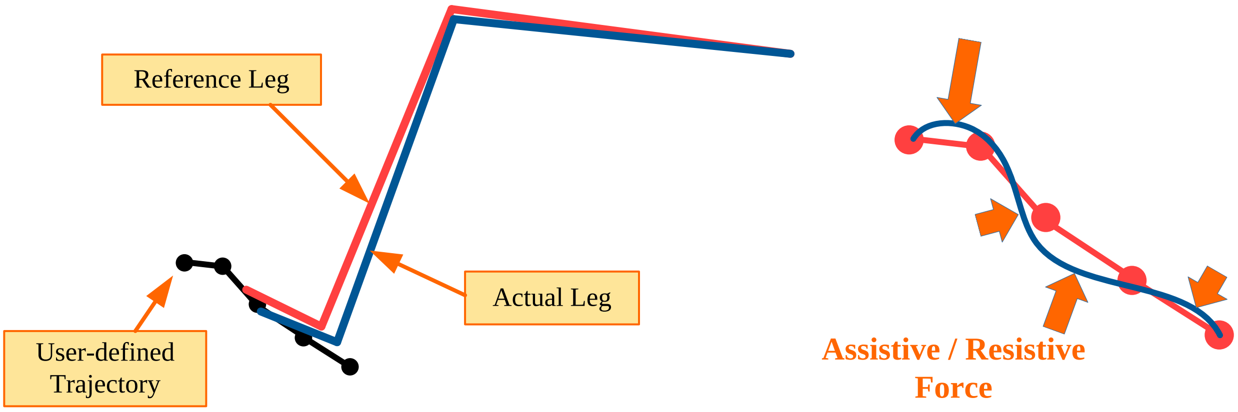


Fig. 2 Block diagram of the impedance controller with torque and velocity inner control loops



(a) (b)

Fig. 3 Trajectory tracking in the training session
(a) Illustration of the reference and actual leg
(b) Magnitude and direction of assistive force generated by the exoskeleton

to the desired leg posture. The amount of this force depends on the selected stiffness gain of the impedance controller according to the control law (1).

In this paper, a preliminary experiment is conducted on a healthy subject to investigate the behavior of the impedance controller applied in a lower limb rehabilitation task. The desired trajectory as shown in Fig. 3 is defined such that the training includes the combination of hip, knee and ankle joint movement. The training is completed in six cycles of movement. In the first three cycles, the subject relaxes his leg. In the last three cycles, the subject tries to track along the defined trajectory.

4. Result

As seen in Fig. 4 – 5 before 80 seconds (the subject relaxes his leg), the actual hip joint largely deviates from the desired hip joint whereas hip joint torque is very high. On the contrary, after 80 seconds (the subject tries to move his leg along desired trajectory) the angle error is lower and the hip joint torque also decreases. Similarly, as shown in Fig. 6 – 7, the angle error and torque of the knee joint in the first 80 seconds is very large compared to those after 80 seconds. As well as the ankle joint in Fig. 8 – 9, high angle error and torque are noticed during the first 80 seconds.

The relationship between angle error and torque is resulted from the control law of the impedance controller proposed in (1). If there is no angle error $(\theta_{j,d} - \theta_j = 0)$, the desired torque will be zero. When the angle error is higher, the desired torque increases exponentially. The magnitude of the desired torque can also be adjusted from the stiffness gain (K). For the same angle error, if the stiffness gain is increased, the desired torque will be higher too.

In Fig. 5, 7, and 9, the actual torque of hip, knee and ankle joints can track their desired torque very fast so we will not notice difference between them. This implies that PI controller can be used for accurate torque control.

5. Discussion

It can be seen that when the subject could not track along the trajectory reference (which generate high angle error) the exoskeleton generates high assistive torque. On the contrary, if the subject can track the reference trajectory by himself/herself, the exoskeleton will decrease the magnitude of assistive force applied to the subject. Therefore, it can be implied that proposed impedance controller acts corresponding to the subject's strength and participation in the training session and the robotic system has a potential to be applied to lower limb rehabilitation of stroke patients. The assist-as-needed control algorithm would be beneficial for the stroke rehabilitation. Furthermore, the function to monitor strength and participation of the patients facilitates therapists to evaluate the development of the patients.

6. Conclusion

This paper presents the development of a robotic system for lower limb rehabilitation. This system is designed for stroke patients to perform physical therapy in sitting position. Impedance control with inner torque and velocity control loops is chosen to implement on the system. The experiment result shows that the control law can be used to generate proper assistive force for rehabilitation tasks.

7. Acknowledgement

This research is supported by The 100th Anniversary Chulalongkorn University Fund for Doctoral Scholarship.

8. References

[1] Yoon, J., Ryu, J. and Lim, K.-B. (2006). Reconfigurable ankle rehabilitation robot for various

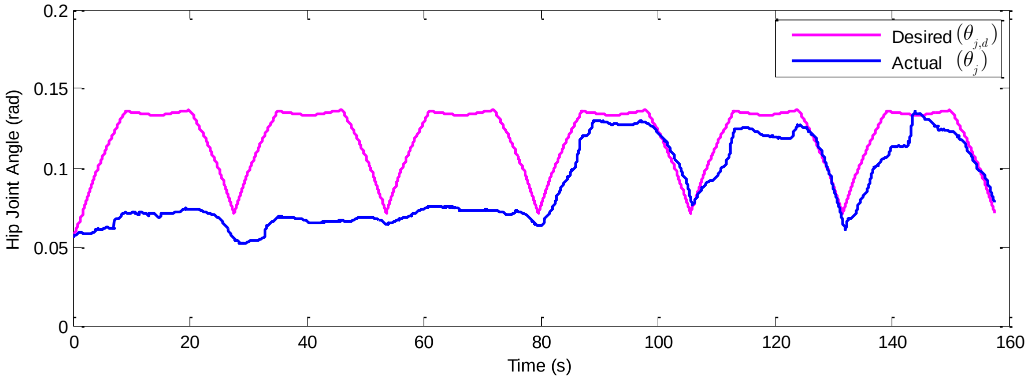


Fig. 4 Comparison of desired and actual hip joint angle during the training session

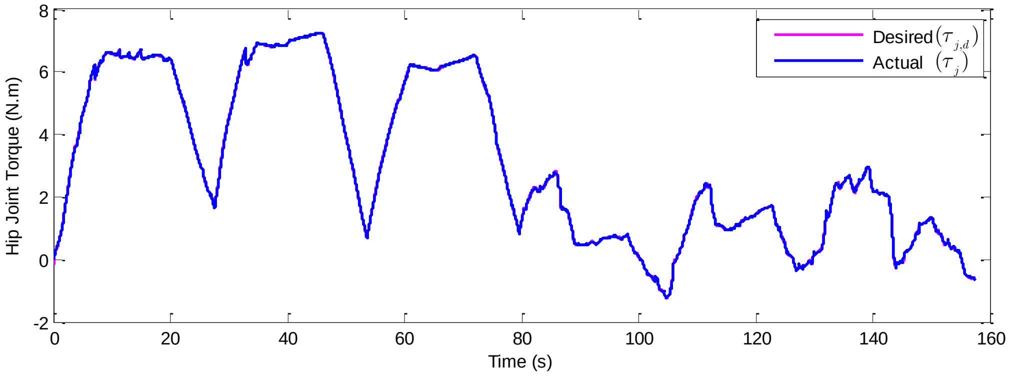


Fig. 5 Comparison of desired and actual hip joint torque during the training session

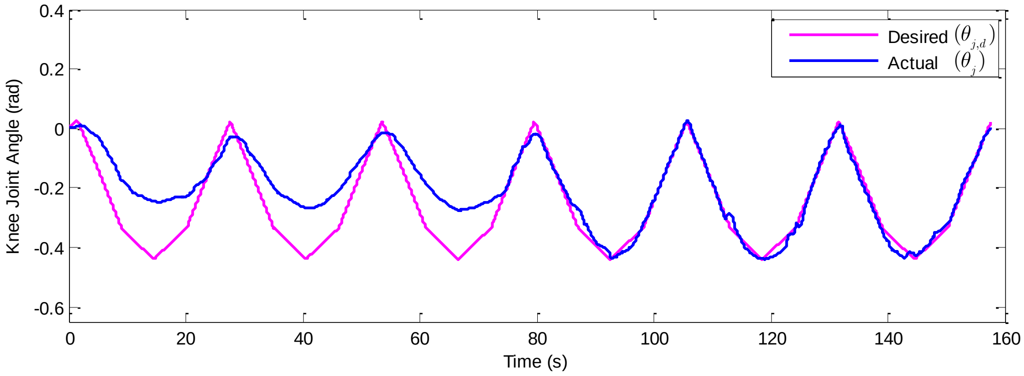


Fig. 6 Comparison of desired and actual knee joint angle during the training session

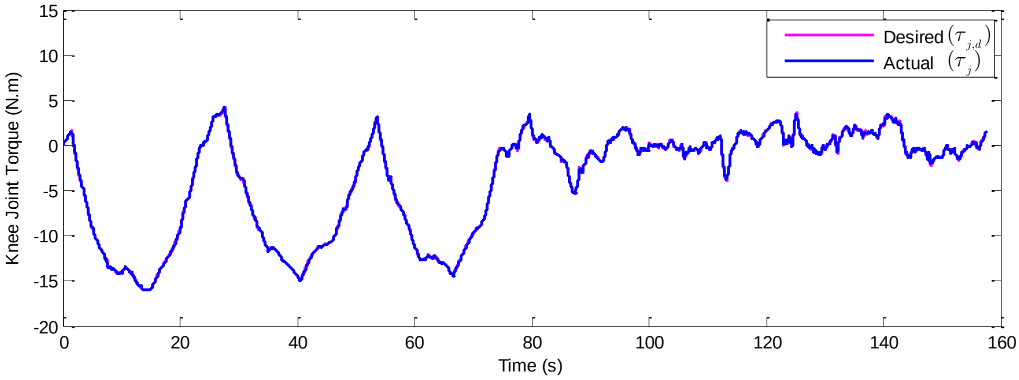


Fig. 7 Comparison of desired and actual knee joint torque during the training session

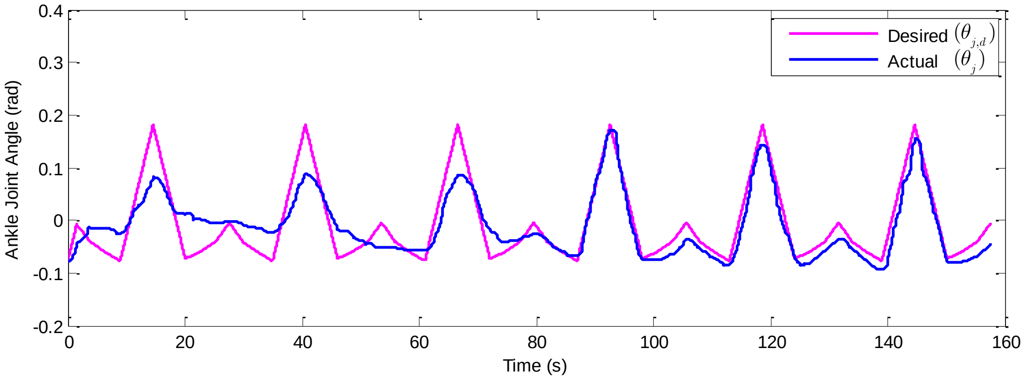


Fig. 8 Comparison of desired and actual ankle joint angle during the training session

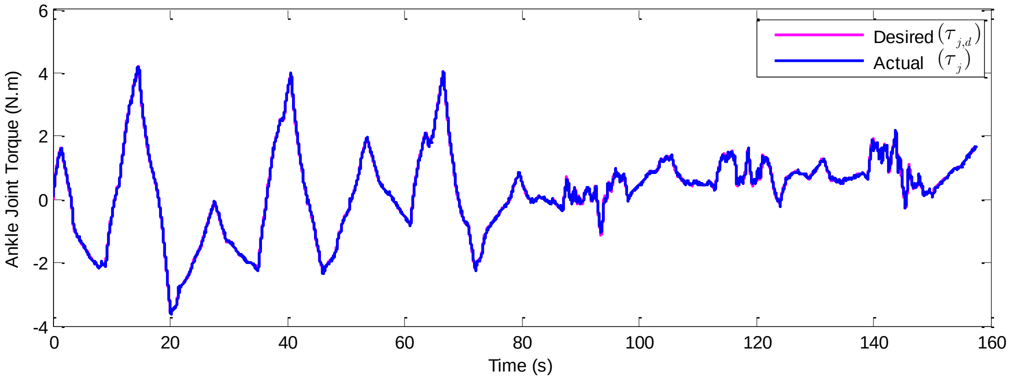


Fig. 9 Comparison of desired and actual ankle joint torque during the training session

exercises. *Journal of Robotic Systems*, vol.22 (S1), pp. S15 – S33.

[2] Akdogan, E. and Adli, M.A. (2011). The design and control of a therapeutic exercise robot for lower limb rehabilitation: Physiotherabot, *Mechatronics*, vol.21(3), April 2011, pp. 509 – 522.

[3] Schmitt, C., Métrailler, P., Al-Khodairy, A., Brodard, R., Fournier, J., Bouri, M. and Clavel,, R.(2004). The MotionMakerTM: A Rehabilitation System Combining an Orthosis with Closed-loop Electrical Muscle Stimulation, paper presented in *the 8th Vienna International Workshop on Functional Electrical Stimulation*, Vienna, Austria.

[4] Metrailler, P., Brodard, R., Stauffer, Y., Clavel, R. and Frischknecht, R. (2007). Cyberthosis: Rehabilitation Robotics with Controlled Electrical Muscle Stimulation, Rehabilitation Robotics, I-Tech Education and Publishing, Vienna, Austria.

[5] Guo, B., Han, J., Li, X., Fang, T. and You, A. (2016). Research and design of a new horizontal lower limb rehabilitation training robot, *International Journal of Advanced Robotic Systems*, vol.13(10), January 2016.

[6] Whitney, J.P. and Hodgins, J.K. (2014). A Passively Safe and Gravity-counterbalanced Anthropomorphic Robot Arm, paper presented in *2014 IEEE International Conference on Robotics & Automation (ICRA)*, Hong Kong, China.

[7] Rooks, B. (2006). The harmonious robot, *Industrial Robot: An International Journal*, vol.33(2), pp.125 – 130.

[8] Vallery, H., Veneman, J., van Asseldonk, E., Ekkelenkamp, R., Buss, M. and van der Kooij, H. (2008). Compliant actuation of rehabilitation robots, *IEEE Robotics & Automation Magazine*, vol.15(3), pp. 60 – 69.

[9] Kwa, H.K., Noorden, J.H., Missel, M., Craig, T., Pratt, J.E. and Neuhaus, P.D. (2009). Development of the IHMC Mobility Assist Exoskeleton, paper presented in IEEE International Conference on Robotics and Automation, Kobe, Japan.

[10] Lagoda, C., Schouten, A.C., Stienen, A.H.A., Hekman, E.E.G. and van der Kooij, H. (2010). Design of an Electric Series Elastic Actuated Joint for Robotic Gait Rehabilitation Training, paper presented in *the 3rd IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics*, Tokyo, Japan.

[11] Sergi, F., Accoto, D., Carpino, G., Tagliamonte, N.L. and Guglielmelli, E. (2012). Design and Characterization of a Compact Rotary Series Elastic Actuator for Knee Assistance during Overground Walking, paper presented in *The 4th IEEE RAS/EMBS International Conference on Biomedical Robotics and Biomechatronics*, Roma, Italy.

[12] Vallery, H., Ekkelenkamp, R., van der Kooij, H. and Buss, M. (2007). Passive and Accurate Torque Control of Series Elastic Actuators, paper presented in *the 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems*, San Diego, CA, USA.