

Model-Based Active Impedance Controller Development of the Exoskeleton Rehabilitation Robot (ERRobot) For Lower-Extremity

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Abstract—This paper presents a hierarchy and hybrid control architecture for a wearable exoskeleton lower-limb rehabilitation robot. The highest level is to calculate muscle-tendon net moment around joint based on muscle-model and skeleton rigid mechanical system, do a lower-limb recovery assessment, and finally select a proper rehabilitation exercise (passive, active-assistive, active or resistive exercise). By using the information of exercise type, the middle-level controller make decision to implement which type of controller (impedance or torque controller) that creates the torque command to feed low-level controller. The low-level controller is the realization of torque controller for PMSM (Permanent Magnet Synchronous Motor). The paper focus on the design of active impedance control belonging to the middle-level control module. Active impedance control regulates the transfer of energy between the exoskeleton and the user, and its goal is to improve the dynamic response of the human limbs without sacrificing the user's control authority. The performance of the controller is demonstrated through simulation.

Keywords- active impedance controller, mode-based controller development, sEMG, musculoskeletal model, hierarchical control frame, FOC, wearable exoskeleton lower-limb rehabilitation robot,

I. INTRODUCTION

At present, welfare robot has become an active research area in order to make life easier for the caregivers and elderly, disabled people. The work will focus on the function rehabilitation of lower-extremity, so as to return patients to society, reintegrate them into social life. ¹

The rehabilitation robot for lower-extremity rehabilitation can be divided into two classes based on working and coupling pattern with users, that is, serial and parallel work devices. The type of serial device acts in series with the action of user's own legs to enhance their capability, such as NEUROBike[1]. The work has developed a parallel and wearable Exoskeleton Rehabilitation Robot (ERRobot) for lower-limb shown in Fig1, whose motion directly

corresponds with the motions of the operator's joints and it moves in parallel to the skeleton of the operator so that no additional DOF (Degree of Freedom) or motion ranges are needed to follow patient motions. This type of structure is relatively easy to implement mechanical safety limits to motion. The lokomat exoskeleton is an example of the early gait trainer[2][3], and evidence based data shows that lokomat therapy can improve gait symmetry, walking ability, increases muscle strength compared to conventional physical therapy in stroke patients [4][5].

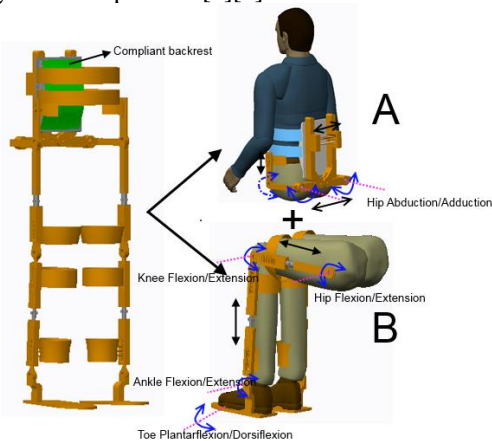


Fig.1. Overall mechanical structure of the developed Wearable Exoskeleton Rehabilitation Robot(ERRobot) for Lower-Limb

The control system accomplishment is one of the major difficulties in rehabilitation robot design. Different approaches were developed to control movement of robot-aided therapy attached to human limbs. They can be classified into three categories: force control [6][7], position control[8], position and force control [9]. Unlike industrial robots, rehabilitation-aided robots must be configured for stable, safe and compliant motion in contact with humans. The impedance control, developed by Hogan[10], can be used to implement the position and force control by adjusting the mechanical impedance, and it is viewed as the most effective control method in interactive human robot systems and in rehabilitation robots[11].Therefore, the work designs

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an active impedance controller in joint space for the Human-Robot system.

The main contribution of this work is to integrate the active impedance control method into proposed hierarchical control frame for an exoskeleton rehabilitation robot that is called ‘ERRobot’ in the work. The proposed hierarchical control framework can be easily extended and is also suitable for parallel computing. The active impedance and torque control scheme are implemented in intermediate control level, which is the focus of the paper, but we also give a simple description for the adopted lower-level torque controller in which the FOC (Field Oriented Control) method and motor model-based technology is used.

The rest of the paper is organized as follows. Section II introduces the control system structure. Section III models the dynamics model for the integrated human-robot system to prepare for the model-based controller development. Section 4 is the core of the paper, which introduces the realization of active impedance controller and low-level torque controller. Simulation results of the flexion/extension movement in the sagittal plane are given in Section V to illustrate the performances of this control law while section VI addresses the conclusions.

II. CONTROL SYSTEM STRUCTURE

Fig.2 shows the proposed control system architecture of the Human-Robot rehabilitation system. From the hierarchy point of view, the proposed control system can be grouped into three levels, which are master upper-level control module, intermediate control module, and a low-level control module. Communication among the three level modules is made via CAN-bus, and Ethernet is adopted between screen and master upper-level control layer.

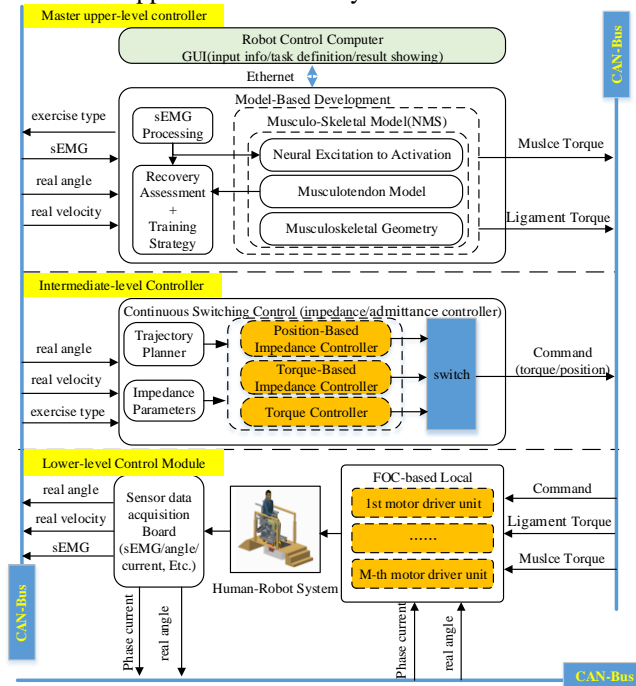


Fig.2. The hierarchical control architecture of the Human-Robot system

① Master upper-level controller

This control module is the highest level controller. It mainly consists of Graphical User Interface (GUI), Motion Intent Parse (MIP), Rehabilitation Assessment Module (RAM), and Training Strategy Decision (TSD). GUI is used to enter the data of the patient, and some necessary parameters by physiotherapist or operator, then the controller executes some logic and arithmetic calculation based on the inputs. These modules have been published in my previous paper[12][13][14][15].The following only give them a simple description.

● MIP

Combing with the NMS (Neural-Musculo-Skeletal) model, the sEMG signal is used as the human-machine interface to directly get subjects’ action intention, calculate desired muscle-tendon force. The usage of sEMG can improve the real-time performance of system because it can predict human movement previous muscle actually moving.

● RAM

Recovery assessment is necessary to select a proper training exercise in full-autonomously rehabilitation system. In [12], the scores of HAI (Health Assessment Index) is used to scale the healthy state of lower limb with seven different levels from 0 to 6, pulsing a middle stage of 0.5. Zero level represents the total health, whereas level six represents the paralysis. The type of the applied training exercises changes according to this scale.

● TSD

There are 4 types of therapeutic exercises: passive, active-assistive, active and resistive exercises. Active exercise is furtherly divided into 3 groups: isometric, isokinetic, and isotonic[16][17].

② Intermediate-level module

The instruction that is created by upper-level controller to represent the exercise type is used as the inputs to activate a needed controller like impedance control law or torque controller. They have the corresponding relation: (a) passive exercise: position control; (b) active-assist exercise: torque and position control; (c) active exercise: torque control; (d) resistive exercise: torque control.

③ Lower-level Control Module

Main task of the low level controller is to implement the torque control of PMSM motor. Each active DOF has its own low-level micro-controller board hardware to perform the local control loop.

The low level controller is coded in STM32F407 with on board clock 168MHz, which is in charge of the following major functionality: 1) Calculate angular velocity by the single-ended incremental quadrature encoders attached to every rotor; 2) Torque control on motor level by using the FOC method; 3) Execute hardware protection logic when any joint is trying to go beyond its working space, which is done by resetting torque command to zero.

III. HUMAN-ROBOT SYSTEM DYNAMIC MODELING

Fig3 shows a simplified seven-segment human model (two feet, two shanks, two thighs, and an HAT segment). It includes three joints and four DOFs per leg (the joint of Hip:

2DOFs, Knee: 1DOF, and Ankle: 1 DOF, respectively). The generalized coordinate \mathbf{q} is defined as Equation (1)

$$\mathbf{q} = [q_1, q_2, \dots, q_m]^T \quad (1)$$

Where, m is the number of generalized coordinates.

These coordinates are the relative angles of each link, and are measured with respect to the coordinate frame fixed with proximal segments.

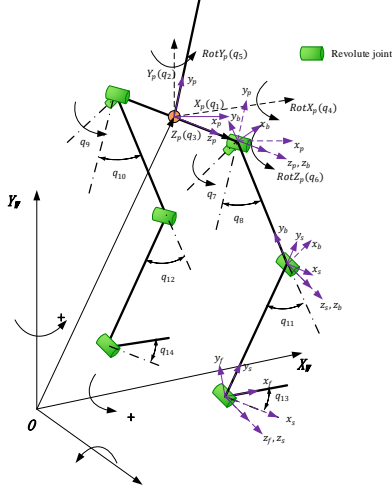


Fig.3. Simplified 7-segment Human-Robot model: (1) Generalized coordinates q_i ($i=1,2,\dots,m$); (2) global and local reference frames fixed on links. Only the part of right leg is shown in the figure

As the first step of kinetic analysis and model-based controller development, the work formulated the equations of motion (kinetics equation) by Lagrange approach.

- ERRobot dynamics model:

$$\mathbf{M}^R \ddot{\mathbf{q}}^R + \mathbf{D}^R \dot{\mathbf{q}}^R + \mathbf{K}^R \mathbf{q}^R = \boldsymbol{\tau}_{mt2r} + \boldsymbol{\tau}_{h2r} + \boldsymbol{\tau}_d + \mathbf{J}^T \mathbf{F}_r \quad (2)$$

$$\boldsymbol{\tau}_{mt2r} = \mathbf{n} \cdot \boldsymbol{\tau}_{motor}$$

Where, $\mathbf{q}^R, \dot{\mathbf{q}}^R, \ddot{\mathbf{q}}^R$ represents the positions, velocity, and accelerate vector of robot link from the equilibrium position of $\boldsymbol{\tau}_{mt2r} = \boldsymbol{\tau}_{h2r} = \boldsymbol{\tau}_d = \mathbf{J}^T \mathbf{F}_r = \mathbf{0}$, $\mathbf{M}^R, \mathbf{D}^R$ and \mathbf{K}^R are the inertia, damping, and stiffness coefficient matrix, respectively. $\boldsymbol{\tau}_{mt2r}$ is the torque vector exerted on robot joint from motor, $\boldsymbol{\tau}_{h2r}$ is the torque from human leg and $\mathbf{J}^T \mathbf{F}_r$ represents the environment constraint moment (\mathbf{J}^T is the transpose of Jacobian matrix \mathbf{J} (related with \mathbf{q})). We also introduce another item $\boldsymbol{\tau}_d$ to represent other disturbance factors, and if other non-conservation generalized forces are existed, they are also added here.

- Human rigid link dynamics model

$$\mathbf{M}^H \ddot{\mathbf{q}}^H + \mathbf{D}^H \dot{\mathbf{q}}^H + \mathbf{K}^H \mathbf{q}^H = \boldsymbol{\tau}_{r2h} + \boldsymbol{\tau}_{muscle} + \boldsymbol{\tau}_{lig} \quad (3)$$

Where, $\mathbf{q}^H, \dot{\mathbf{q}}^H, \ddot{\mathbf{q}}^H$ represents the positions, velocity, and accelerate vector of leg segment from the equilibrium position of $\boldsymbol{\tau}_{r2h} = \boldsymbol{\tau}_{muscle} = \boldsymbol{\tau}_{lig} = \mathbf{0}$, $\mathbf{M}^H, \mathbf{D}^H$ and \mathbf{K}^H are the inertia, damping, and stiffness coefficient matrix for human leg link system, respectively. $\boldsymbol{\tau}_{r2h}$ is the torque from robot, $\boldsymbol{\tau}_{muscle}$ is the joint muscle torque (related with $\mathbf{q}, \dot{\mathbf{q}}$),

and $\boldsymbol{\tau}_{lig}$ represents the passive tissue torque from ligament(related with $\mathbf{q}, \dot{\mathbf{q}}$).

When we assume that the coupling between leg and robot link is rigid, and neglect the deformation of robot links, segments of lower limb, active DOF joint connection between actuator and link, then there exist the following relationships.

$$\mathbf{q} = \mathbf{q}^R = \mathbf{q}^H \quad \dot{\mathbf{q}} = \dot{\mathbf{q}}^R = \dot{\mathbf{q}}^H \quad \ddot{\mathbf{q}} = \ddot{\mathbf{q}}^R = \ddot{\mathbf{q}}^H \quad (4)$$

Based on Equation (2)(3), and clarifying the relationship between $\mathbf{M}, \mathbf{D}, \mathbf{K}$ and $\mathbf{q}, \dot{\mathbf{q}}$, the dynamics of the integrated Human-Robot system can be written as Equation エラー! 参照元が見つかりません. .

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{D}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{K}(\mathbf{q})\mathbf{q} = \boldsymbol{\tau}_{mt2r} + \boldsymbol{\tau}_o \quad (5)$$

Where,

$$\left. \begin{aligned} \boldsymbol{\tau}_o &= \boldsymbol{\tau}_{muscle} + \boldsymbol{\tau}_{lig} + \boldsymbol{\tau}_d + \mathbf{J}^T \mathbf{F}_r \\ \mathbf{M} &= \mathbf{M}^R + \mathbf{M}^H \\ \mathbf{D} &= \mathbf{D}^R + \mathbf{D}^H \\ \mathbf{K} &= \mathbf{K}^R + \mathbf{K}^H \end{aligned} \right\} \quad (6)$$

From Equation (6), we know that the net moments actuating on a joint of integrated system include internally generated torques ($\boldsymbol{\tau}_{muscle}, \boldsymbol{\tau}_{lig}$) and externally added torques ($\boldsymbol{\tau}_{mt2r}, \boldsymbol{\tau}_d$ and environment constraint moment $\mathbf{J}^T \mathbf{F}_r$).

IV. ACTIVE IMPEDANCE AND TORQUE CONTROLLED

In order to be applied to various tasks, this work adopts the active-impedance method meaning that the mechanical impedance is (actively) adjustable by controlling actuator. When in passive exercise mode, the work adopts the torque-based impedance controller to implement position control, which uses feedback position, velocity signal as the input to calculate the desired torque. While active training mode is selected, the torque controller is used to implement zero torque control, that is, control motor torque so as to keep the torque between human and robot zero always. If the active-assistive exercise is selected, both of this two control methods are switched to be implemented according to the interactive force direction from patient to robot.

Considering the torque controller is commonly used in each training exercise implementation, so we first introduce the designed torque controller briefly, and then the design process of impedance controller is given.

A. Model-Based Torque Feedback Controller

The work adopts the PMSM to drive active joint. This type of motor has the advantage of high speed driving because it uses an electronic inverter instead of the brush and commutator, which is needed for the active-impedance control. Moreover, in order to be able to reduce the motor volume, the transmission comprising of a gearbox and belt drive subsystem is used for assistance of the motor to increase the motor torque.

We accomplish the torque control by using the following FOC based framework shown in Fig 4. We use the motor mathematical model in d-q axis to design the control system, so as to the gains of all PI controller used in d-q axis current control and torque control can be automatically adjusted when motor parameters are changed. As shown in Fig4, the feedback torque controller, and non-interference controller are designed to construct this system. For the torque feedback control, we don't measure the value by using torque sensor, but calculate it by the measured current value.

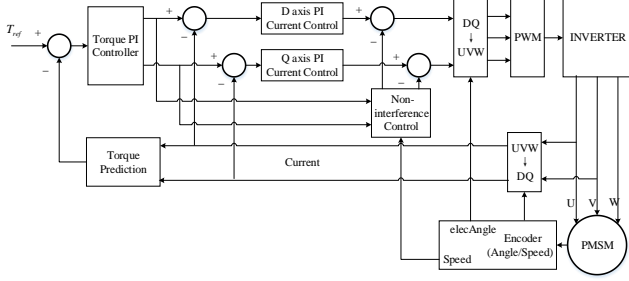


Fig. 4. FOC-based torque control block diagram

B. Force-Based Impedance Control

We assume that the desired impedance of the human-robot system to resultant torque τ_o in joint space is expressed by Equation (7).

$$\mathbf{M}_d \ddot{\mathbf{q}}_d + \mathbf{D}_d (\dot{\mathbf{q}} - \dot{\mathbf{q}}_d) + \mathbf{K}_d (\mathbf{q} - \mathbf{q}_d) = \tau_o \quad (7)$$

Where \mathbf{M}_d (Nm · rad/s²), \mathbf{D}_d (Nm · rad/s) and \mathbf{K}_d (Nm/rad) are the desired virtual rotational inertia, damping, and spring stiffness coefficient matrix, respectively, and \mathbf{q}_d is the desired joint angle trajectory. When \mathbf{q} , $\dot{\mathbf{q}}$ and $\ddot{\mathbf{q}}$ are measurable, we can use the control law as shown Equation (8)

$$\begin{aligned} \tau_{mt2r} = & (\mathbf{M} - \mathbf{M}_d) \ddot{\mathbf{q}} + (\mathbf{D} - \mathbf{D}_d) \dot{\mathbf{q}} + (\mathbf{K} - \mathbf{K}_d) \mathbf{q} \\ & + \mathbf{D}_d \dot{\mathbf{q}}_d + \mathbf{K}_d \mathbf{q}_d \end{aligned} \quad (8)$$

When substituting Equation (8) into Equation (5), we can get Equation (7), which shows the closed-loop system has the desired impedance. In addition, if the torque τ_o is also measurable, we can furtherly remove the acceleration item. Here, we use another method to reduce Equation (8) to a simple position and velocity feedback law shown Equation (9), that is, we make the desired \mathbf{M}_d equal to the original inertia \mathbf{M} .

$$\begin{aligned} \tau_{mt2r} = & (\mathbf{D} - \mathbf{D}_d) \dot{\mathbf{q}} + (\mathbf{K} - \mathbf{K}_d) \mathbf{q} + \mathbf{D}_d \dot{\mathbf{q}}_d + \mathbf{K}_d \mathbf{q}_d \\ = & \mathbf{D}_d (\dot{\mathbf{q}}_d - \dot{\mathbf{q}}) + \mathbf{K}_d (\mathbf{q}_d - \mathbf{q}) + \mathbf{D} \dot{\mathbf{q}} + \mathbf{K} \mathbf{q} \end{aligned} \quad (9)$$

Based on Equation (9), we design a PD controller and a feed-forward (FF) controller to calculate the torque τ_{mt2r} . Because feedback signal exist noise, we replace \mathbf{q} , $\dot{\mathbf{q}}$ with \mathbf{q}_d , $\dot{\mathbf{q}}_d$ to design a FF controller as depicted in Fig.5. It includes an outer impedance position control loop, a FF

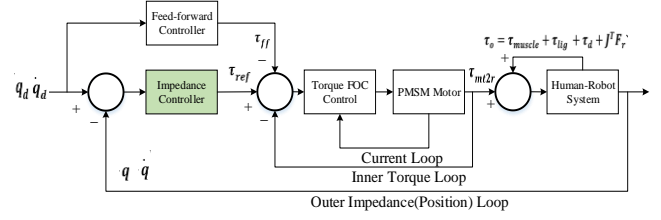


Fig. 5. Block diagram of impedance control architecture

controller, an inner torque control loop, current control loop and a nonlinear compensator that fully compensates the nonlinearities of the dynamic model.

V. EXPERIMENT

In the paper, only the verification experiment of impedance controller in passive exercise is implemented. For this purpose, we simplify the Human-Robot rehabilitation system to a 3-link robot-human mechanical system for simplicity as depicted in Fig6. In order to show the parameters and interactive torque clearly, the coupling system is separately shown, that is, human skeleton model (left) and robot link model (right) with same joint axis.

A. 3-Link Human-Robot System Model

The Lagrange's equation as Equation (9) is adopted to derive the dynamic model of the system.

$$\frac{d}{dt} \left(\frac{\partial L}{\partial \dot{q}_k} \right) - \frac{\partial L}{\partial q_k} = \tau_k, k = 1, 2 \quad (9)$$

Where, L is the Lagrangian and is defined as the difference between system kinetic energy terms KE and system potential energy PE throughout the moving body(s), that is, $L = KE - PE$.

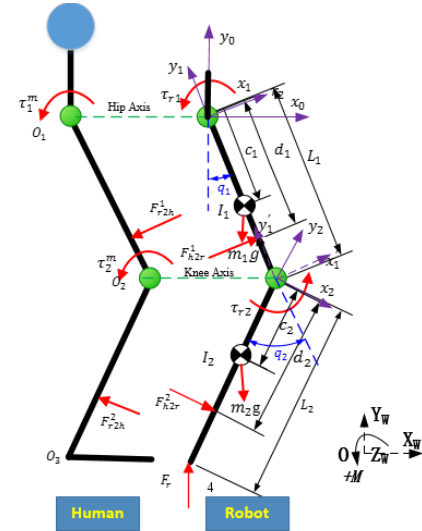


Fig. 6. 3 Links Model for dynamic analysis, which includes link lengths (L_1, L_2), the distance between the center of the mass of the limbs and the rotational point (c_1, c_2), mass moments of inertia of Human-Robot segments about its COM (I_1, I_2), net moments acting on a joint torques, and external torques

Finally the robot dynamic can be derived as following

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{D}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{K}(\mathbf{q}) = \boldsymbol{\tau} \quad (10)$$

Where,

$$\mathbf{q} = [q_1, q_2]^T \quad \dot{\mathbf{q}} = [\dot{q}_1, \dot{q}_2]^T \quad (11)$$

$$\mathbf{M} = \begin{bmatrix} \mathbf{M}_{11} & \mathbf{M}_{12} \\ \mathbf{M}_{21} & \mathbf{M}_{22} \end{bmatrix} \quad (12)$$

$$\mathbf{M}_{11} = I_1 + I_2 + m_2 L_1^2 + m_1 c_1^2 + m_2 c_2^2 - 2m_2 c_2 L_1 \cos q_2$$

$$\mathbf{M}_{12} = I_2 + m_2 c_2^2 - m_2 c_2 L_1 \cos q_2$$

$$\mathbf{M}_{21} = I_2 + m_2 c_2^2 - m_2 c_2 L_1 \cos q_2$$

$$\mathbf{M}_{22} = I_2 + m_2 c_2^2$$

$$\mathbf{D} = \begin{bmatrix} m_2 c_2 L_1 \dot{q}_2^2 \sin q_2 + 2m_2 c_2 L_1 \dot{q}_1 \dot{q}_2 \sin q_2 \\ -m_2 c_2 L_1 \dot{q}_1^2 \sin q_2 \end{bmatrix} \quad (13)$$

$$\mathbf{K} = \begin{bmatrix} m_2 g L_1 \sin q_1 - m_1 g c_1 \sin q_1 - m_2 g c_2 \sin(q_1 + q_2) \\ -m_2 g c_2 \sin(q_1 + q_2) \end{bmatrix} \quad (14)$$

- For lower-limb object

$$\boldsymbol{\tau} = \boldsymbol{\tau}_{r2h} + \boldsymbol{\tau}_{muscle} + \boldsymbol{\tau}_{lig} \quad (11)$$

Where, $\boldsymbol{\tau}_{r2h}$: robot assistive torque; $\boldsymbol{\tau}_{muscle}, \boldsymbol{\tau}_{lig}$: internally net moments generated by human muscle and ligament;

- For robot object :

$$\boldsymbol{\tau} = \boldsymbol{\tau}_{mt2r} + \boldsymbol{\tau}_{h2r} + \boldsymbol{\tau}_d + \mathbf{J}^T \mathbf{F}_r \quad (12)$$

Where, $\boldsymbol{\tau}_{mt2r}$ is the torque applied on robot joint by actuator (PMSM motor); $\boldsymbol{\tau}_{h2r}$ is the human limb resistive torque; $\boldsymbol{\tau}_d$ is external disturbance torques and $\mathbf{J}^T \mathbf{F}_r$ is environment constraint moment.

The interactive torque between human and robot can be calculated by Equation (13)

$$\boldsymbol{\tau}_{h2r} = -\boldsymbol{\tau}_{r2h} = \begin{bmatrix} F_{h2r}^1 d_1 \\ F_{h2r}^2 d_2 \end{bmatrix} \quad (13)$$

For the simulations we used the anthropometric data of a male of 65kg with 1.7 m height shown in Table, which is calculated according to [18] and list them in the Table 1.

TABLE I. BODY SEGMENT ANTHROPOMETRICAL DATA (HEIGHT=1.7M WEIGHT=65KG)

Segment	Notation	Value
Thigh	L_1 [m]	0.4165
	c_1 [m]	0.1803
	m_1 [kg]	8.0
	I_1 [kg · m ²]	0.1176
Shank	L_2 [m]	0.4182
	c_2 [m]	0.1811
	m_2 [kg]	3.72
	I_2 [kg · m ²]	0.0482

According to the Equation (10) and the given parameters' values, we obtain the lower-limb dynamic equation shown

in Equation (14).

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{D}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{K}(\mathbf{q}) = \boldsymbol{\tau} \quad (14)$$

$$\mathbf{M}(\mathbf{q}) = \begin{bmatrix} 0.561 \cos q_2 + 1.19 & 0.281 \cos q_2 + 0.170 \\ 0.281 \cos q_2 + 0.170 & 0.1702 \end{bmatrix}$$

$$\mathbf{D}(\mathbf{q}, \dot{\mathbf{q}}) = \begin{bmatrix} -0.281 \sin q_2 \dot{q}_2^2 - 0.561 \dot{q}_1 \sin q_2 \dot{q}_2 \\ 0.281 \dot{q}_1^2 \sin q_2 \end{bmatrix}$$

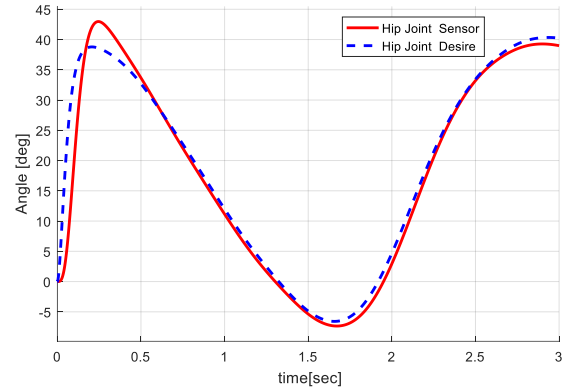
$$\mathbf{K}(\mathbf{q}) = \begin{bmatrix} 6.6 \sin(q_1 + q_2) + 29.3 \sin q_1 \\ 6.6 \sin(q_1 + q_2) \end{bmatrix}$$

B. Validation of Impedance Controller

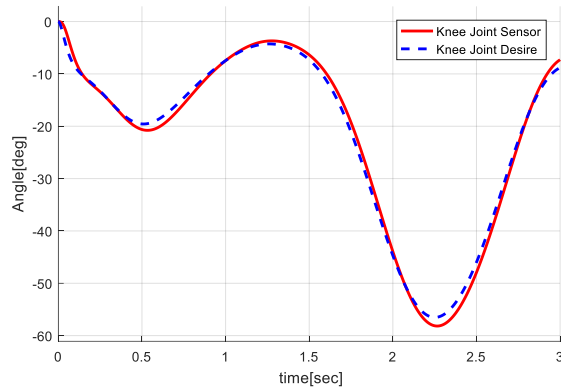
In passive exercise mode, position controller is needed to track the desired trajectory directly given by therapist or decided based on the recovery state of lower-limb. Two trajectory tracking experiments are implemented to validate the validness of the developed impedance controller using in position control.

The MATLAB/Simulink model is developed to implement the simulations experiment under the initial condition of no external torque interference and inner torque, and to simplify the model, we don't take into account the ground contact. We define two desired motion trajectory $q_d^1(t), q_d^2(t)$ for hip, knee joint respectively, and the desired stiff parameters $K_d^{\text{Hip}} = 1000, K_d^{\text{Knee}} = 800$, desired damping parameters $D_d^{\text{Hip}} = 200, D_d^{\text{Knee}} = 100$ are determined to feed to the impedance controller. In order to realize a precise motion tracking, a high impedance is given.

The output result is also shown in the same figure. It is obvious that the output angle (red line) follows the input quite fast.



(a) Hip joint angle trajectory in one gait cycle



(b) Knee joint angle trajectory in one gait cycle

Fig.7. Trajectory tracking result

Because the two given trajectories is the joint angle time sequence during one gait cycle, the simulation model can also estimate the demand torque characteristics as shown in Fig8. From the figure, we can know that a minimum of 198Nm hip joint moment and 49Nm knee joint moment are needed during a gait cycle, which can provide a reference for the selection of actuator and transmission.

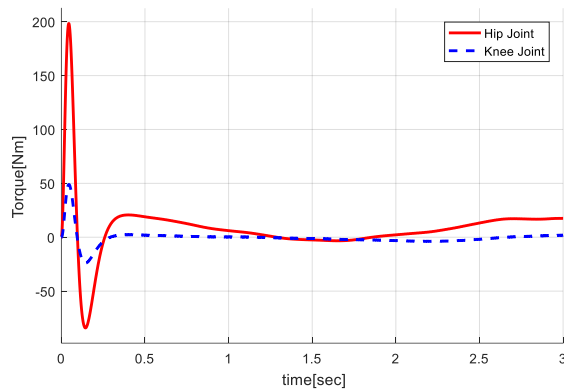


Fig.8. Joint torque characteristics in walking

VI. CONCLUSION AND FUTURE WORK

The paper presents a hierarchy and hybrid control architecture for a wearable exoskeleton lower-limb rehabilitation robot. The highest level is to calculate muscle-tendon net moment around joint based on muscle-model and skeleton rigid mechanical system. The intermediate-level controller make decision to implement which type of controller (impedance or torque controller) that creates the torque command to feed low-level controller. The paper mainly focus on the design of active impedance control belonging to the middle-level control module. The performance of the controller is demonstrated through simulation.

In the future, we'll first further study the method of impedance parameters estimation aiming to various task. Then the developed control method is test in a realistic

human-machine system so as to make it better meet the real system requirements.

REFERENCES

- [1] Monaco, V., et al., Design and evaluation of neurobike: a neurorehabilitative platform for bedridden post-stroke patients. *Neural Systems and Rehabilitation Engineering*, IEEE Transactions on, 2012. 20(6): p. 845-852 .
- [2] Jezernik, S., et al., Robotic orthosis lokomat: A rehabilitation and research tool. *Neuromodulation: Technology at the neural interface*, 2003. 6(2): p. 108-115.
- [3] Riener, R., *Technology of the Robotic Gait Orthosis Lokomat*, in *Neurorehabilitation Technology*. 2012, Springer. p. 221-232.
- [4] Husemann, B., et al., Effects of locomotion training with assistance of a robot-driven gait orthosis in hemiparetic patients after stroke randomized controlled pilot study. *Stroke*, 2007. 38(2): p. 349-354.
- [5] Westlake, K.P. and C. Patten, Pilot study of Lokomat versus manual-assisted treadmill training for locomotor recovery post-stroke. *Journal of neuroengineering and rehabilitation*, 2009. 6: p. 18.
- [6] Kazerooni, H. and M.-G. Her, The dynamics and control of a haptic interface device. *Robotics and Automation*, IEEE Transactions on, 1994. 10(4): p. 453-464.
- [7] Kazerooni, H., *The human power amplifier technology at the University of California, Berkeley*. *Robotics and autonomous systems*, 1996. 19(2): p. 179-187.
- [8] Rosen, J., et al., A myosignal-based powered exoskeleton system. *Systems, Man and Cybernetics, Part A: Systems and Humans*, IEEE Transactions on, 2001. 31(3): p. 210-222.
- [9] Bernhardt, M., et al. Hybrid force-position control yields cooperative behaviour of the rehabilitation robot LOKOMAT. in *Rehabilitation Robotics*, 2005. ICORR 2005. 9th International Conference on. 2005. IEEE.
- [10] Hogan, N. (1984, June). Impedance control: An approach to manipulation. In *American Control Conference*, 1984 (pp. 304-313). IEEE.
- [11] Akdoğan, E., & Adli, M. A. (2011). The design and control of a therapeutic exercise robot for lower limb rehabilitation: *Physiotherobot. Mechatronics*, 21(3), 509-522.
- [12] Lei, S., & Zhen, L. Study on Control System of Lower Extremity Exoskeleton Rehabilitation Robot Based on Neuromusculoskeletal Model.
- [13] Lei Shi, Kun Jiang, Qiang Wang, Zhen Liu, A New Method of Quantitative Rehabilitation Rating in Robot-Assisted Recovery System[J]. *Intelligent Networks and Intelligent Systems (ICINIS)*, 2012 Fifth International Conference on, Page(s):278 – 281.
- [14] Shi, L., Liu, Z., & Wang, Q. (2013, December). A Novel Method of sEMG Signal Segmentation. In *Mobile Ad-hoc and Sensor Networks (MSN)*, 2013 IEEE Ninth International Conference on (pp. 515-520). IEEE.
- [15] Shi, L., & Liu, Z. (2014, August). Design of soft human-robot interface based on neuro-muscular-skeletal model. In *Dependable, Autonomic and Secure Computing (DASC)*, 2014 IEEE 12th International Conference on (pp. 536-541). IEEE.
- [16] AKDOĞAN, E. (2016). Upper limb rehabilitation robot for physical therapy: design, control, and testing. *Turkish Journal of Electrical Engineering & Computer Sciences*, 24(3).
- [17] Kayhan O. *Physical Medicine and Rehabilitation*. Istanbul, Turkey: Marmara University Press, 1995.
- [18] Winter, D.A., *Biomechanics and motor control of human movement*. Fourth ed. 2009, Canada: John Wiley & Sons, Inc, Hoboken, New Jersey.