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A Design of Lower Limb Rehabilitation Robot and its Control for Passive Training

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***Abstract*—Artificial intelligence-based rehabilitation robots can be applied for peoples with lower limb motor dysfunction usually caused by accident, war, sports, spinal cord injury, paralysis, and vascular diseases to enhance the motion ability of their lower limbs. A design of lower limb rehabilitation robot as well as its trajectory tracking which is suitable for passive training of patient with paralyzed or weak limbs have been presented in this paper. The contents were well organized and presented. Also, the experimental procedural setup of the lower limb rehabilitation robot is well described and conducted. Initially, AC servo motor was chosen as the actuator for controlling the robot due to good stability, fast response, low noise, wide speed range, low cost, high efficiency, and low maintenance. The corresponding simulation analysis of the actuator shows that it is good and can meet the design requirements. Secondly, the motion control of the robot was investigated using the kinematics model of the hip and knee transmission subsystem, the human hip and knee trajectory curves, the motion control data generation process, the planning target track, and the required servo motor drive pulse control instruction. Finally, the control experiments were conducted such that the pulse signal of the servo shaft rotational angle is received by the servo drive for pitch control in position control mode. By default, a complete rotation of 0.072 degrees corresponds to 500 pulses of the motor rotation time control. The experimental results show that by using PID controller, the actual trajectory is closer to the desired trajectory closely follows the actual trajectory and hence, demonstrated a promising patient's recovery.**

Keywords—lower limb rehabilitation robot, motion control card, motion control data generation process, Servo moto.

I. Introduction

In recent years, the number of people with lower limb motor dysfunction usually caused by accident, war, sports, spinal cord injury, paralysis, and vascular diseases is ever-increasing. In China alone, the number of patients with lower limb motor dysfunction surpassed 85 million [1-2]. This affects the livelihood of the people and incurs huge burden to the society. For that reason, gait training approach after stroke or spinal cord injury would be helpful in this regards.

Based on the literature, many studies have been done, but most of them still rely on traditional methods of rehabilitation, weight loss gait training is an important tool for the treatment of central nervous system injury rehabilitation as it shown in the Fig.1. However, this method still has many deficiencies: patients with physical training-based, while the secondary is often more time-consuming, cost is relatively high. Since the training process cannot be measured and feedback related to the treatment of information, the lack of objective data to evaluate the effect of rehabilitation is difficult to the team training to optimize the parameters in order to develop the best treatment. .Also the development of lower limb rehabilitation robot in traditional methods meet with many design difficulties, such as mechanical structure, control system design and human-computer interaction. Therefore, the proposed lower limb rehabilitation robot must be interacted with the patient's limb and should provide appropriate control strategies guarantor[3-5]. Hence, the proposed lower limb rehabilitation robot trajectory tracking training is a good means of recovery.

Additionally, some research status are presented here, the robot device system, composed by four main parts: power unity, lower extremity exoskeleton, actuation system and multi-sensor perception system. A joint force sensor and foot are communicated in order to give information to the control signal, by adjusting the display unit imaginary elastic and damping. A prediction of human motion intention is achieve by the control of exercises to provide the impetus to help extend of lower extremity wearer ability [6].

However, some key points are still big challenge in this field, to study how to optimize rehabilitation device design, which should provide accurately motor transmission action, and optimized control interaction to the patients [7]. Therefore, to provide this solution, a new approach was proposed in this research where, exoskeletal rehabilitation robots can be driven by volitional commands to control movement of paralyzed or weak limbs. In this study also, the improvement of lower limb rehabilitation robot training than a traditional method was investigated by using a passive rehabilitation training mode. The validity and applicability of the control system were investigated with experiments test, as well as the accuracy verification which promised excellent efficient and reliability. Passive training control strategy is to achieve the mechanical leg motion on the expected trajectory. Hence, the proportion integration differentiation (PID) control algorithm was designed in this study in order to obtain desired trajectory by adjusting and minimizing errors. AC servo motor was chosen as the actuator for controlling the robot due to good characteristics. The corresponding simulation analysis of the actuator shows that it is good and can meet the design requirements.

In the remainder of the paper, The control method for passive training was achieved in this study, and was presented in Section 3 . Finally, experimental procedures were set-up with a good performance as presented in Section 4. In addition, Control hardware platform structure was designed as presented in Section 4 too. Discussion of results and conclusion were discussed in Section 4 and 5, respectively.

Fig.1. Traditional weight training walk

II. SYSTEM DESIGN

A. Overall mechanical schematic structure of lower limb rehabilitation exoskeleton robot

In general, rehabilitation of lower extremity exoskeleton robot system was designed in this paper, which consists of four major parts namely, walker exoskeleton legs, pelvis-supporting weight loss systems, mobile racks and medical treadmill as shown in Fig.2. Before rehabilitation, patients lose weight through the pelvis-supporting system, to support weight loss; patients are connected by straps and lower limb rehabilitation robot leg walker. The leg walker gait trajectory is set in advance, in accordance to drive patients on the normal walking machine and passive rehabilitation state [8]. Lower limb rehabilitation robot walker legs are humanoid leg design, with institutions and dynamic performance similar to human leg. Therefore, the design of an appropriate control system should enables lower extremity exoskeleton legs of the walker's gait, which can track a predetermined trajectory [9].

Lower limb rehabilitation robot control system provides the robot in charge mode (passive training mode) and patients in charge mode (active training mode) .When the patient is in the starting stage of rehabilitation, the choice of leading machine-style training mode. The power unit driven by lower extremity exoskeleton simulates natural movement of the patient's gait based on a fixed track. The training status of the patient is completely passive. With the rehabilitation process depth and lower limb muscle tone improved, patients were asked to actively participate in rehabilitation training. You need to select the patient dominant style training mode, where the power plant outside the proactive role of bone is reduced, but assist patients walk, play a role of assistance. Therefore, the exoskeleton power unit must be able to quickly detect the patient conscious active movement, and then adjust the action follows the movement of the legs of the patient. At the moment of rehabilitation training process, to control a stable weight force, so that the patient load support legs stable, the design of lower exoskeletons rehabilitation robots active loss system in force to maintain weight loss stable, played main key role. It is one of the key technologies of mechanical design.

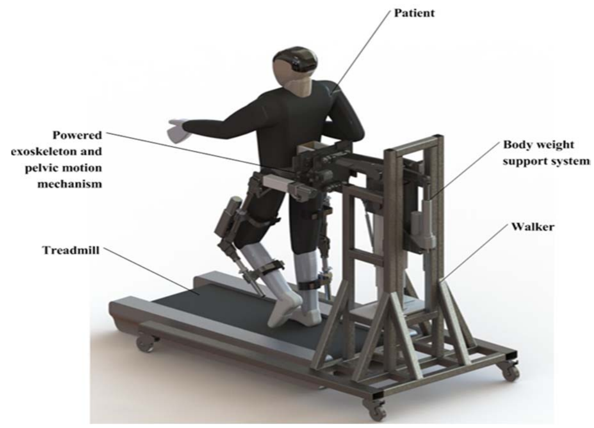

Fig.2. Overall mechanical schematic structure of lower limb rehabilitation exoskeleton robot

Generally, the design of Man- Machine coupling system is shown in Fig.3. Mechanical design is the basis of robot-assisted rehabilitation system, and should follow a basic principle of keeping its structure simple, lightweight, and easy to control. In order to select AC servomotor, you must first worked on kinetic analysis of patients with lower limb rehabilitation exoskeleton robot. It is composed by Man-machine coupling system which is a mainly part of the work. We used motion solid works conducted under.

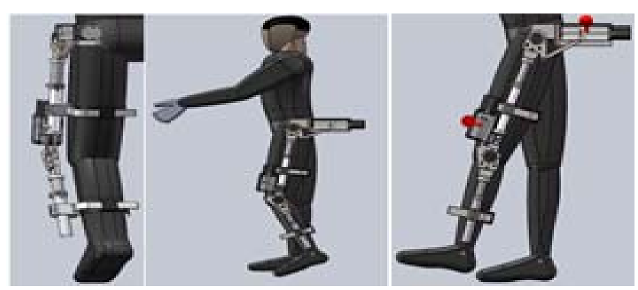

Fig.3. Man- machine coupling system in motion

Some key words of this work were careful considered. Which is include Adjust exoskeleton thigh, calf length to fit CAE model size (height 180cm) in order to ensure the hip and knee axis coincide and Mannequin exoskeleton model through leggings institutions connected and power transfer as shown in the fig.3. In general, the exoskeleton is used to describe a device that augments the performance of enable-bodied wearer.

B. The determination of actuator for the robot

- *Comparison between actuation approaches for lower limb rehabilitation robot*

During the utilization of linear motion of the drive way there are three approaches namely, hydraulic, pneumatic and servomotor drive actuators. Firstly, Consider hydraulic actuator provide good hydraulic power density, smooth transmission process and easy to control. However, the use of the process there will be a certain degree of oil leakage.

This device does not lead to rehabilitation robot, in line with the requirements of cleanliness are not convenience for use in the rehabilitation equipment. Secondly, pneumatic actuator, power is transmitted using air, clean pollution, fast response speed and easy maintenance, but because air is compressible characteristics, resulting in lower transmission accuracy, poor stability velocity, it is not easy to control. Finally, consider the motor drive mode, the drive motor has an easy control, high movement precision, fast response, low cost, easy to use, high driving efficiency, no noise pollution and other significance. Hence, it widely used in medical equipment.

Motor parameters are the followings: rated output torque of the hip motor is 1.3N * m (maximum limit torque 3.8N * m), rated output torque of the knee motor is 0.64N * m (maximum limit torque 1.91N * m).

- *Motor simulation analysis*

From the simulation results, you can get active lower limb rehabilitation exoskeleton robots, as we can see the behaviours of driving speed, angular rotation, torque and power as shown from the Fig. 4 to the Fig. 5. From these figures, rehabilitation robot hip, knee drive motor, maximum speed is less than 4000r / min, but the knee driving motor acceleration was significantly greater than the hip motor acceleration. Especially in the swinging leg phase, this feature is also in line with the natural gait characteristics. The motor output torque and motor power connection, the drive motor output torque of the hip and the knee was significantly greater than the required power. The cause of this feature is that the former need to drive the thigh and calf, and a large mass inertia load torque, while the latter simply drive leg, requiring a smaller output torque and power.

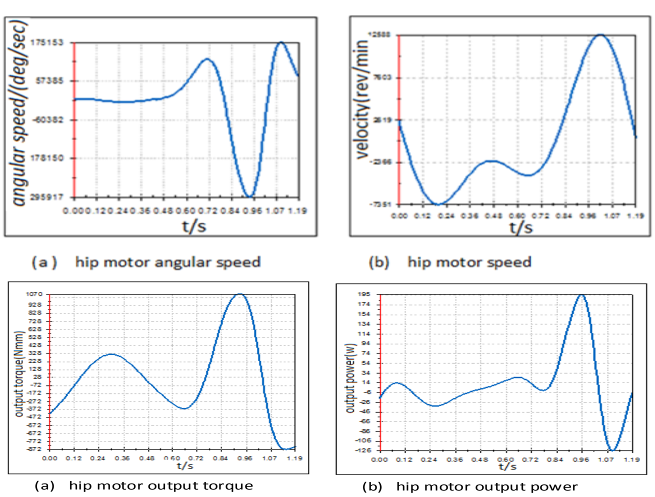

Fig. 4. Hip motor acceleration, hip motor speed and hip motor output torque and hip motor output power.

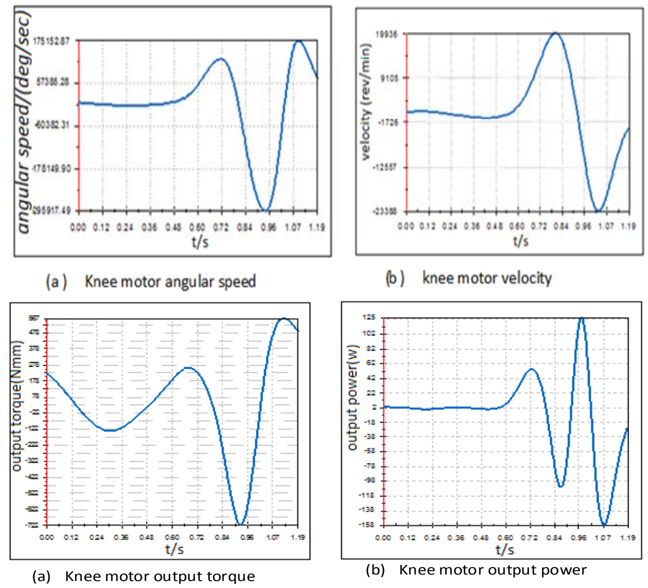

Fig.5. Knee motor acceleration, knee motor velocity and knee motor output torque and knee motor output power

As shown in the figures above Hip motor speed curves and angular rotation curve, the maximum motor speed value is 2098r /min and maximum negative motor speed is -1225r/min. Hip motor output torque is bi-directional, range from -872Nmm ~1070Nmm. Hip motor output power has two-way, ranging from -126W ~ 196W while Knee motor output torque is bi-directional, range from (-722Nmm ~ 567Nmm) and Knee motor output power for two-way, ranging from (-158W ~ 125W).

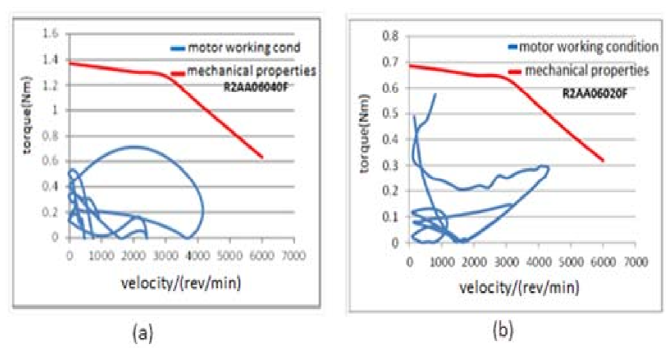

Fig.6. Hip and Knee motor mechanical properties and working conditions

Fig.6 (a) presenting hip motor characteristic curve and Fig.6 (b) presenting knee motor characteristic curve. As can be seen from the Fig.6, operating curve of hip and knee drive motor are all located below the corresponding motor mechanical properties curve and thus, it concluded that, the performance of selected AC servo motor can meet the design requirements.

III. CONTROL METHOD

A. Basic structure of control system

Passive training mode is the process in which the robot helps the patients to track the predetermined trajectory through repeated tracking control for passive training. Additionally, Exoskeleton leg walker boot in accordance with a pre-set lower limb movement gait trajectory. The key of this control method is to study the system dynamic model of the exoskeleton robot as shown in the Fig. 7. The more details are explained in the next parts.

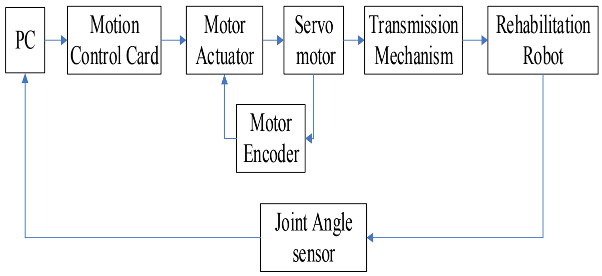

Fig .7. Basic structure of control system

- Control principle

As shown in Fig.2, Fig.3and Fig.7. The control principal of lower limb rehabilitation exoskeleton robot is following: the planned target trajectory walker leg mathematical model input IPC was explained, data generated by the motion control software convert it into a set of joint angle of the trajectory to the discrete data, and calculate the set of discrete joint angle data corresponding to a group motor motion control commands, and then sent it to the motion controller. The motion controller converts the received command into several pulses and frequency and sent to the servo motor driver. Motor drives received pulse signal and then converted into voltage and a certain amount of current supplied to the servo motor to drive the servo motor in accordance with a predetermined angle and speed of movement. Encoder built -in servo motor will rotate the motor shaft angle, information is feedback to the motor drive to achieve semi-closed loop control of the walker leg joints corner. Motor rotation by ball screw rotary motion into linear motion and then drives the articulation of the walker legs by slider-crank mechanism. Walker leg angle sensor mounted to the joint shaft angle; information is feedback to the host computer motion control program within the closed-loop control of the walker leg joints corner.

The control system of lower limb rehabilitation robot can be divided in two parts namely, hardware and software. These two main parts of the system are closely linked together in this study. Finally Control strategy also deeply explained, here trajectory tracking controller, tracks the desired trajectory using a feedback linearized PID controller by comparing the desired inputs signals with output actual signals as it shown in the Fig.8.

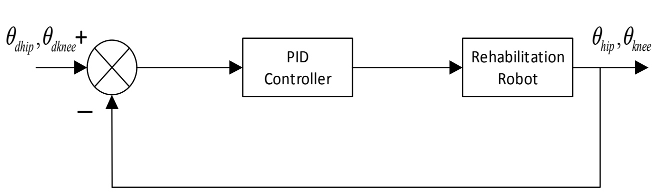

Fig.8. Control algorithm of hip and knee joints angles

B. Motion control card

We have been chosen motion control card as a motion controller, ADT-8949 multi-axis motion control card is based on a high-performance and four-axis motion control card PCI bus computer. The robot control to take the position control mode, each axis moves independently in accordance with the target set position, speed or stop the independence movement, the movement can be changed in real time driving speed. Through specific number and frequency transmit pulse to achieve good performance as shown in the Fig. 9.

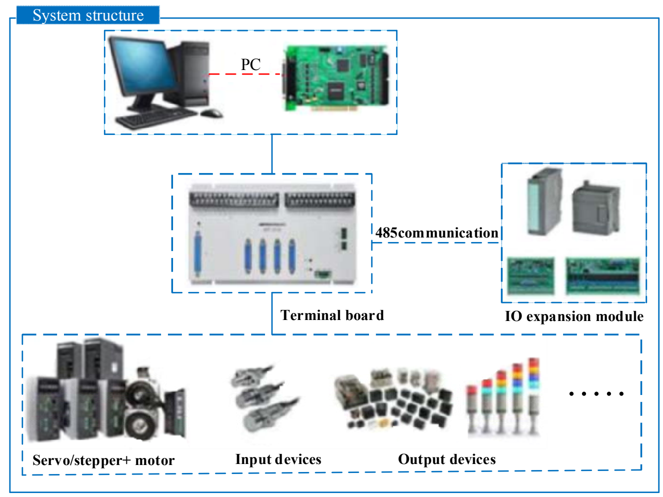

Fig.9. Exoskeleton rehabilitation robot control system hardware

- TRAJECTORY TRACKING CONTROL OF THE LOWER LIMB REHABILITATION EXOSKELETON ROBOT

Trajectory tracking control of the lower limb rehabilitation exoskeleton robot should answer the following questions: how to make the exoskeleton mechanical means to move? And how the patient gait training exercise to achieve recovering stage? Therefore, the following specific requirements should be considered in order to achieve the targeting purpose: (1) Walking training rehabilitation robot driven by the patient's gait is best to get natural gait (trajectory and speed), when he or she is walking. Because each patient's physical condition and physical rehabilitation are essential for gait recovery. Also, the condition is different, walking gait training should have a variety of models to choose from, such as the synchronization speed, unsynchronized long gait patterns to meet the needs of different patients at different stages of rehabilitation. (2) Information gathering normal gait when disease is free from people. Storage backup is a good defensive methods.

In the study of novel robot walking rehabilitation training, it is best to establish normal gait standby database information, in order to provide power. About the Control Strategy, Position control mode; the angle of rotation and the rotational speed of the servo motor shaft should have a great accuracy requirement, which is severe way to follow the walker leg trajectory planning movement during exercise.

- *Mathematical model between joint rotation angle and its motor rotation angle*

The relationship between hip motor rotation angle and hip rotation angle can be given by the following formula:

$$\phi_1 = \frac{360}{p} \times \left(s_{\theta_{1=0}} - s\right) \quad (1)$$

And the relationship between knee motor rotation angle and knee rotation angle given by the following formula too:

$$\phi_2 = \frac{360}{p} \times \left(s_{\theta_{2=0}} - s\right) \quad (2)$$

- *Motion control data generation process*

Motion control data generation software works is explained here. A target trajectory planning is based in accordance with the control process to the principles of motion transfer. The transfer function of each level is obtained between the motions passed, and finally calculate the required servomotor drive pulse control instruction as can be shown in the Fig.10.

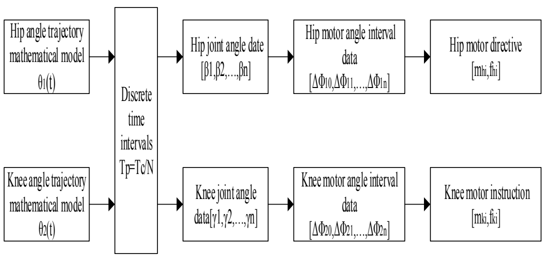

Fig. 10. Motion control data generation process

Changes generates joint angle trajectory data, when the discrete data taken is N data sampling time interval:

$$T_p = T_C/N. \quad (3)$$

From the starting point of the period since the beginning step to step of the cycle is completed, a gait cycle to obtain $N+1$ set of discrete data, each discrete data sequence respectively corresponding to the times: 0, , 2 , ⋯, N . Then after they obtained a discrete group of hip and knee data angle which is$[\beta_i, \gamma_i]^T (i = 0,1 \ldots, N)$.

Corresponding equations stated below,

$$\beta_i = \theta_1(i * T_P) \quad (4)$$

$$\gamma_i = \theta_2(i * T_P) \quad (5)$$

Generating a servo motor rotational angle interval of the command data is detailed below.

In the position control mode, the rotation angle of the servo motor shaft pulse signal is received by the servo drive to control the spacing needs to be converted to the motor rotation angle, data pulses corresponding to the data. Each set of data pulses has two data items, sending a number of pulses m, a transmission frequency of the pulse is f.

By default, a complete rotation of 0.072 degrees corresponds to 500 pulses of the motor rotation time control to move a ball screw nut lead 5mm. Therefore, the motor rotation angle interval ΔΦ and control relationship between the numbers of pulses m command is donated as following equation

$$m = \left[\frac{5000}{360} \Delta\phi\right] \quad (6)$$

M is an integer number of pulses only when m is positive, then motor forward, otherwise reverse.

Pulse frequency f is the number of pulses transmitted per unit time, the pulse frequency is higher, the number of pulses per unit time of the transmission, it determines the speed of the servo motor. Hip angle track data changes in an angle is rotated to the next angle adjacent to the elapsed time for corresponding to the number of pulses from m. Then, the process pulse frequency of the motor command signal is computed by the following formula:

$$f = \frac{|m|}{T_P} = \frac{|m|N}{T_C} \quad (7)$$

According to the previous formula hip trajectory data angle $\beta_i (i = o, 1 \ldots, N-1)$ is rotated to a next adjacent angle $\beta_i + 1$, is also converted to the corresponding interval angle command motor data $[m_i, f_i]$. Similarly, the knee can be obtaining data.

IV. Experimental and Result Analysis

A. Experimental procedures

The Figure 11. Shows experiment procedure block diagram which is mainly include host computer, motion control card amplifier and motors.

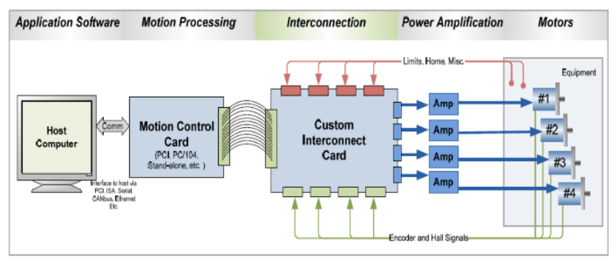

Fig .11. Experiment procedure block diagram

The User of interface program input ,output interfaces, interaction between the operator platform and motion control system, should help to achieve three functions: ① provide gait training and training command parameter input window; ② real-time graphical display of walk training the angular position of the joints in patients with lower limb, velocity and acceleration curve, value and other parameters; ③ patient information database operation, automatically read and store patient training data. The control hardware platform is shown the Fig. 12.

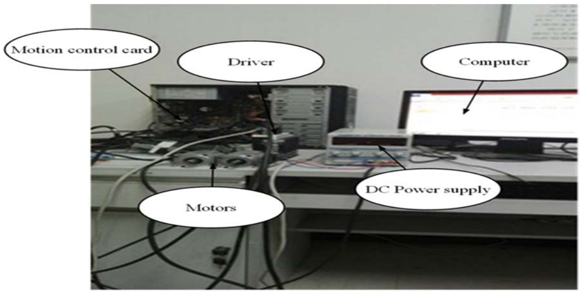

Fig .12. Control hardware platform structures

B. *Results and discussion*

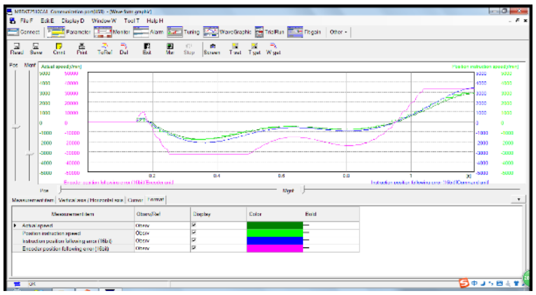

Fig.13. hip joint motor trajectory tracking signals

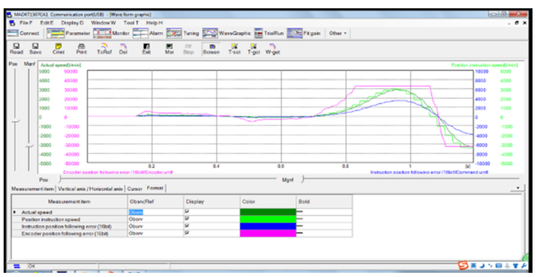

Fig 14. Knee joint motor trajectory tracking signals

The Fig.13 and Fig.14 both represents hip and knee motor trajectory tracking signals, as can be seen in both figures, the green color signal is representing actual speed, yellow color signal is the position instruction speed (desired signal or reference signal), the blue one is the instruction position following error (16 bit) and pink color signal is encoder position error. According to the results of the debugging load control map, you can see how the motor position control (positioning accuracy) and speed control to achieve the functional requirements. The motor can operate continuously and stably with the minimum errors.

The motor no-load commissioning and the motor stable operation, in order to meet the performance requirements, is necessary to carry out electromechanical device to determine load operation of the motor. The motor running to ensure that the mechanical properties meet the controlled object (stiffness) changing performance requirements. Therefore, as can be seen the motor have been fulfillment the description above according to the experiment results. Finally, result is excellent because the actual trajectory is closer to the desired trajectory signal.

V. Conclusion

In conclusion, a lower limb rehabilitation robot was designed and trajectory tracking control was achieved in order to enhance the recovery of patients with lower limb motor dysfunction. The experiments were set-up and conducted in detail by demonstrating the exchange information between different subsystems namely, the PC, control card, servo driver, servo motor and sensors.

Also, the motion control of the rehabilitation robot was investigated using the kinematics model of the hip and knee transmission subsystem while the motion control data generation process has been used to calculate the required servomotor drive pulse control instruction. Finally, the result shows that, by using PID Controller, the actual trajectory signal follows the reference trajectory signal with the minimum errors and thus, it demonstrated a promising rehabilitation recovery. In the further study, we will trial different control strategies in order to enhance the results as much as possible.

Acknowledgment

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