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A Simple Control Method for Exoskeleton for Rehabilitation

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Abstract

The paper proposes an easy-to-implement training system for lower limb rehabilitation operated by impedance controllers. The proposed robotic leg exoskeleton consists of hip, knee and ankle joints driven by DC motors. Inverse kinematics with geometric strategy is applied to calculate joint angles from Clinical Gait Analysis (CGA) data. Then, the measured data undergoes a filtering process before being sent to the controllers to improve control quality. 3-DOF dynamic model of the exoskeleton is built by using MATLAB. Finally, performances of the proposed system are validated by simulation results.

Keywords *—Impedance control, exoskeleton, SimMechanics simulation.*

I. INTRODUCTION

Research on exoskeletons has become an interesting topicfor several decades. Starting with brief and unsuccessful attempts these years, advances in sensing, actuation and computing technologies have renewed the confidence in the viability of developing an autonomous exoskeleton system for human performance augmentation. Not only do these advances permit the realization of more compact, lightweight and robust robotic hardware design, but they also permit the development of increasingly sophisticated control laws in terms of both real-time processing capability and design and analysis computer aided tools [1-5].

The proposed robotic leg exoskeleton is configured with either a powered treadmills or a mobile platform to provide various rehabilitation purposes. The exoskeleton is comprised of two anthropomorphic legs and spine that provides a versatile loading interface. The device is to be designed and controlled in such a way that the human can conduct a wide spectrum of activities without feeling the device. The future possible applications of exoskeletons are endless and include construction workers, earthquake rescue personnel, space exploration, and physical rehabilitation. Currently, the demand of health care is the strongest need in the modern society.

The paper is organized into several sections. Section II introduces the structure of the proposed exoskeleton, mathematical model and inverse kinematics calculations of the proposed exoskeleton. Control method is presented in Section III. Section IV illustrates input signal processing, SimMechanicsmodel and simulation results of the system. Conclusions and future work are discussed in Section V.

II. EXOSKELETON SYSTEM

A. *Structure of the proposed exoskeleton system*

The proposed exoskeleton system consists of two legs, one treadmill, and one suspension bar as shown in Fig 1. Legs of the exoskeleton are designed with ability to adjust the length of thigh and shin to fit every patient (Fig. 2). The hip, knee and ankle jointsare driven by DC motors. Angulardisplacements and velocities of joints are obtained by encoders embedded in the motors.

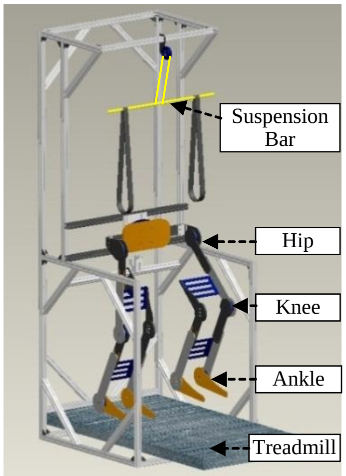

Fig.1. Structure of the Exoskeleton

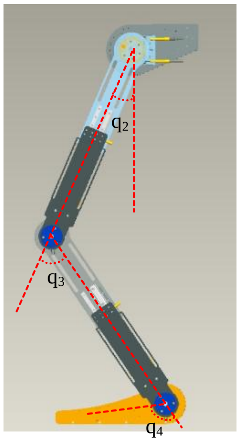

Fig.2. One leg of the proposed exoskeleton

Table I. Dimensions of the Exoskeleton

Segments	Length	Mass
Hip connection		254 g
Thigh (l_1)	$41 \pm 4.5\ cm$	465 g
Calf (l_2)	$41 \pm 4.5\ cm$	462 g
Foot		273 g
Human load		80 kg

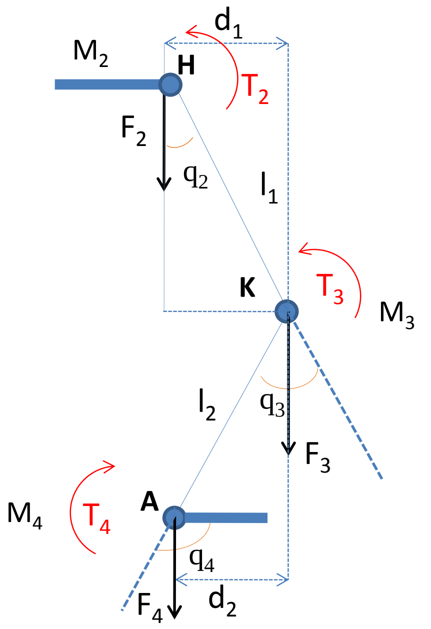

Fig.3. Estimated torques for exoskeleton design

The exoskeleton parameters and load capability are shown in Table 1. Embedded encoders are able to measure positions of joints. In order to design the mechanical system, maximum required torques (T_2, T_3, T_4) need to be estimated according to physical calculations as shown in equations (1-3). These equations aim at preparing for equipment selection and design but not for control design. More accurate model will be presented in part B of this section. Selected DC motors embedded in joints need to produce appropriate electric torques to drive the exoskeleton and user. F_2, F_3, F_4 are forces applying on joints in terms of masses M_2, M_3, M_4as depicted in Fig. 3.These weights are estimated on each joint consisting of the links' mass and human load.

$$T_2 = M_3 g d_1 \tag{1}$$

$$T_3 = M_2 g d_1 + M_4 g d_2 \tag{2}$$

$$T_4 = M_3 g d_2 \tag{3}$$

where g is the gravity acceleration constant, d_1 and d_2 are distances from hip to knee and from knee to ankle respectively.

B. *Mathematical model of the system*

Calculations of the kinetic energy and potential energy in cooperation with Lagrangian functionlead tothe mathematical model of the system as expressed in equation (4).

$$\vec{T}_a + \vec{T}_h = A_{sw}(\vec{q})\ddot{\vec{q}} + \vec{b}_{sw}(\vec{q},\dot{\vec{q}}) + \vec{p}_{sw}(\vec{q}) \tag{4}$$

where$T_a = [T_2 T_3 T_4]^T$is the joint input torque vector. $T_h = [T_{h2} T_{h3} T_{h4}]^T$ is the human-machine joint torque vector. $q = [q_2 q_3 q_4]^T$is the joint angle vector.$A_{sw}$is the kinetic energy matrix.$\vec{b}_{sw}$is the vector comprising of the centrifugal and Coriolis acceleration terms. $\vec{p}_{sw}$ is the joint torque vector induced by gravity. And the dynamics model of exoskeleton can be expressed as shown in equation (5).

$$\vec{T}_h = A_{sw}(\vec{q})\ddot{\vec{q}} + \vec{b}_{sw}(\vec{q},\dot{\vec{q}}) + \vec{p}_{sw}(\vec{q}) - \vec{T}_a \tag{5}$$

C. *Inverse kinematics*

In this research, the collected data contains information about positions of joints provided by an experimental measurement from human walking (Clinical Gait Analysis CGA). The author proposes the geometric method to solve inverse kinematics problemas illustrated in Fig. 4. It is assumed that $H(x_H,y_H,z_H)$, $K(x_K,y_K,z_K)$ and $A(x_A,y_A,z_A)$ are three marked points of hip, knee and ankle joints with coordinate data.G is a point that makes the line from H to G vertical to the ground then$G=(x_H,y_H,0)$and the pedal of the exoskeleton is always parallel to the ground. Solutions of joints angles (q_2,q_3,q_4) are determined in equations (6-9).

$$q_3' = \cos^{-1}((HK^2 + KA^2 - HA^2)/(2HK.KA)) \tag{6}$$

$$q_3 = \pi - q_3' \tag{7}$$

$$q_2 = \cos^{-1}\left(\frac{\overrightarrow{HK}.\overrightarrow{HG}}{HK.HG}\right) \tag{8}$$

$$q_4 = 2\pi - q_2 - q_3' \tag{9}$$

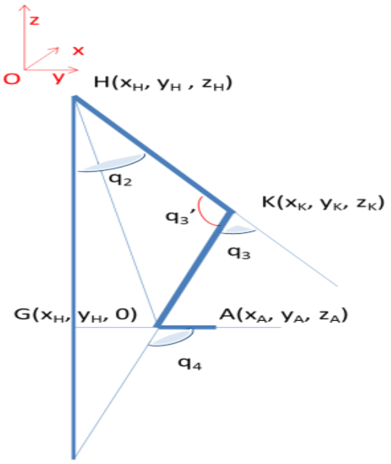

Fig.4. Geometric Method for Inverse Kinematics Calculations

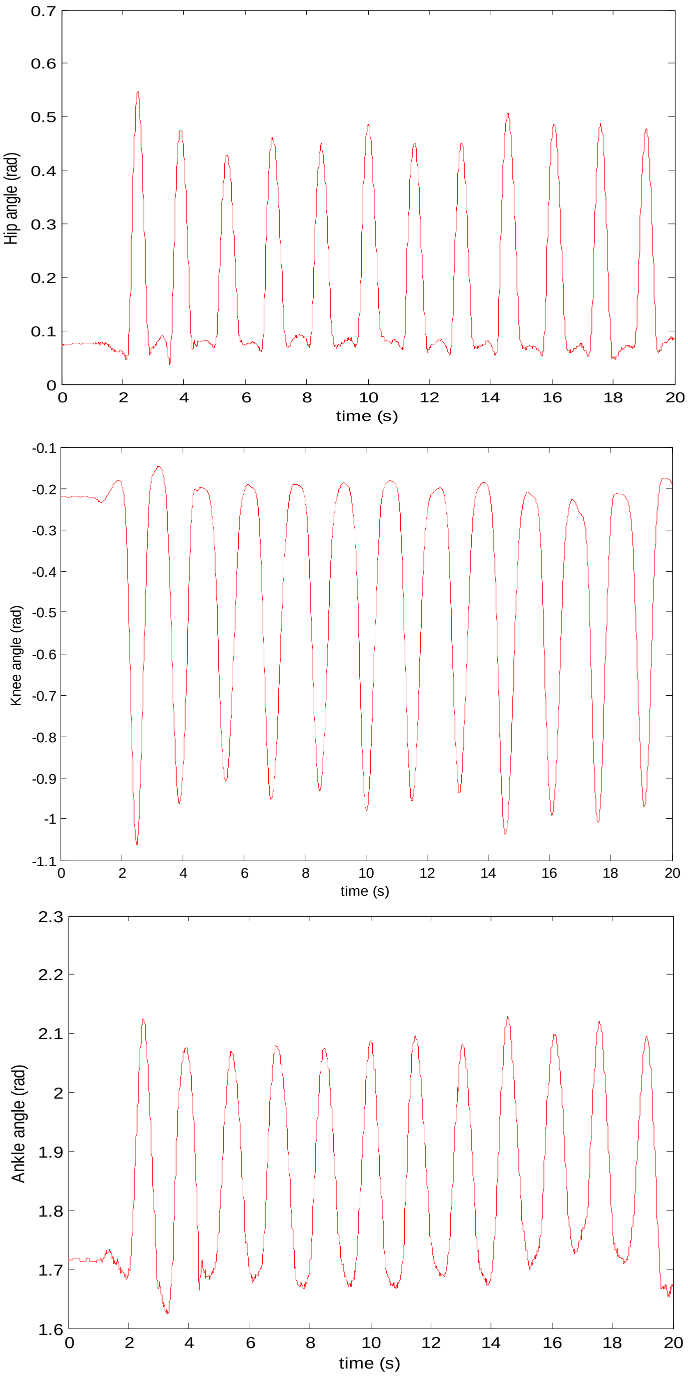

Fig.5. Angular Data Determined from CGA Data Byinverse Kinematics Calculation.

Reference angles for the proposed exoskeleton joints calculated from CGA data and inverse kinematics are shown in Fig. 5 with radian unit.

III. CONTROL METHOD

Impedance controllers are consideredto control the proposed exoskeleton system. The purpose is to make the exoskeleton walk autonomously as a human. The impedance controllers are used to control the hip, knee and ankle joint angles separately. It is thanks To MATLAB/Simulink/Simmechanicsthat the model is designed toverify impedance controllers. The block diagram of the virtual torque control law is shown in Fig.6. *G* represents the system transfer function, which is difficult to obtain the accuracy model. Therefore, $G^{'}$ is an estimate of the machine forward dynamics.T_h denotes the torque exerted on the exoskeleton by human. T_a denotes the torque exerted by actuator. The human-machine torque can be modeled as:

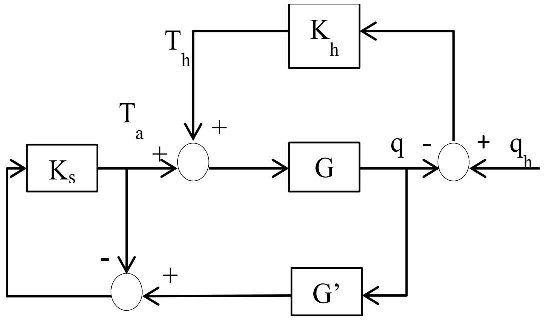

Fig.6. Block diagram of the virtual torque controller

$$T_h = K_h(q_h - q) \qquad (3)$$

where$K_h$is the impedance between the human and the machine, q_h is the human's position (the reference angle signal), and q is the machine's position (the feedback signal)[6].

The reference signal q_h could be either sinusoidal in a simplified case or the exoskeleton reference angles stored in a look-up table measured from a laboratory experimental system with a walking human. The machine's position q is determined by encoders embedded in each joint of the system.

If the system transfer function G is perfect, we haveGG'=1. Thus,$K_s$is chosen as a PD controller as shown in [7].

$$K_s=K_p+K_d s \qquad (4)$$

IV. SIMULATION RESULTS

In this section, SimMechanicsbased on the Simscape™ softwaremodelin MATLABis used to demonstrate the performance of the exoskeleton system.The SimMechanics block library provides the functional blocks to model the exoskeleton with dynamic characteristics.Unlike other Simulink blocks, which represent mathematical operations or operate on signals, Simscape blocks represent physical components or relationships directly. Figs. 7-8 present the structures of the models with 1-DOF and 3-DOF respectively. Normally, the model consists of leg model, controllers, input and output sections.

Table 1. Controller Parameters

Joint	K_P	K_d	K_h
Hip	10000	20	5
Knee	3000	20	1
Ankle	1000	1	10

Figs. 9-11 illustrate the angles of thehip, knee and ankle joints with respect to the sinusoidal reference input.In this figure, the sinusoidal signal is used to be the input position q_h and the hip joint position tracking is performed precisely.The minor errors can be obtained by the controllers with suitable values of K_p and K_d and K_h as shown in Table 2.Figs. 12-14 depictthe torques exerted in the hip joint, knee joint, and ankle joint.It is clear that the actuators provide much more torques than that of human. It means that the system is effective in scaling down the torque production from users.Figs. 15-17 show the performance of each joints with the human trajectories obtained from the experimental data (CGA).

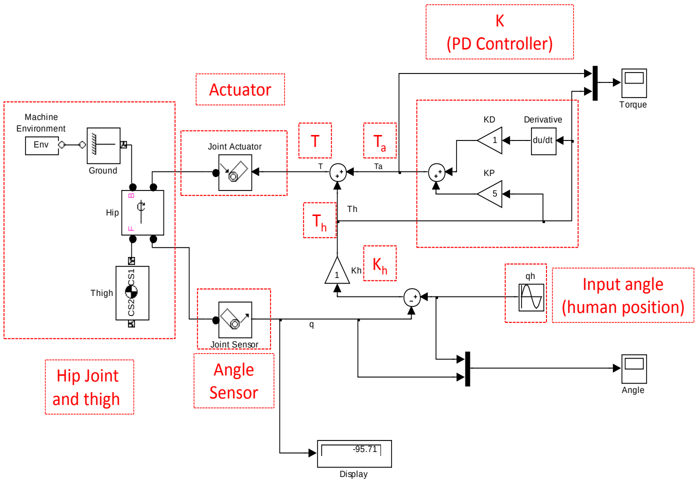

Fig.7. SimMechnics Model and Controller of Hip Joint

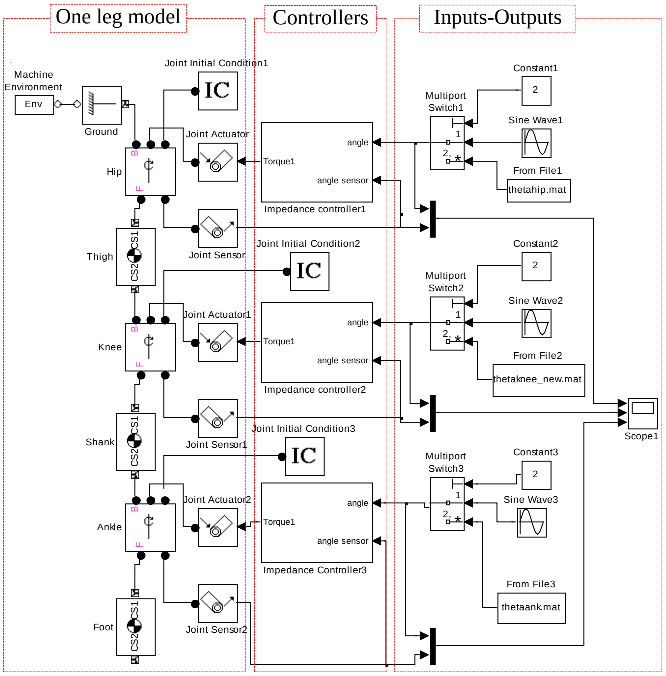

Fig.8. SimMechanics Model of 3-DOF Leg and Control System

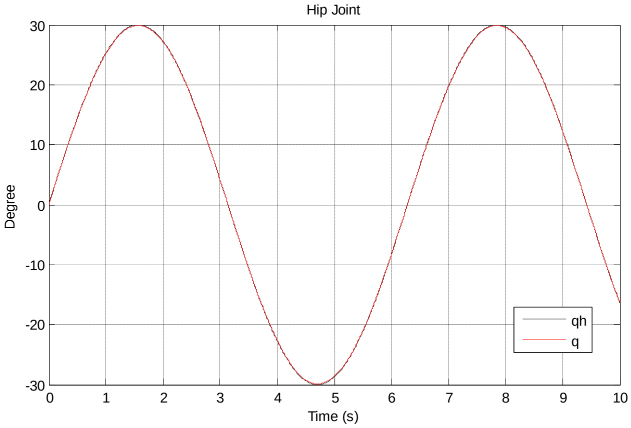

Fig.9. Curve of the Hip Joint Angle

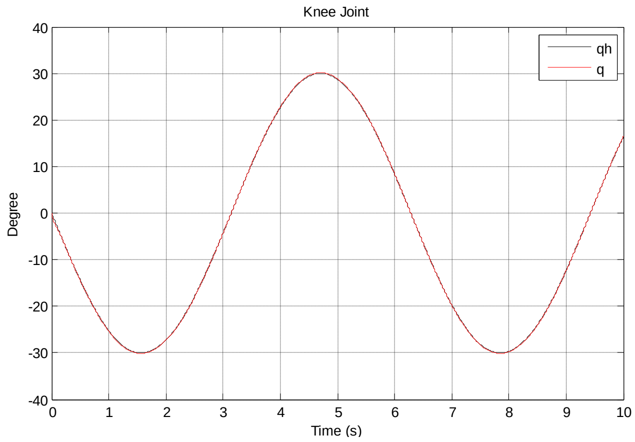

Fig.10. Curve of the knee joint angle

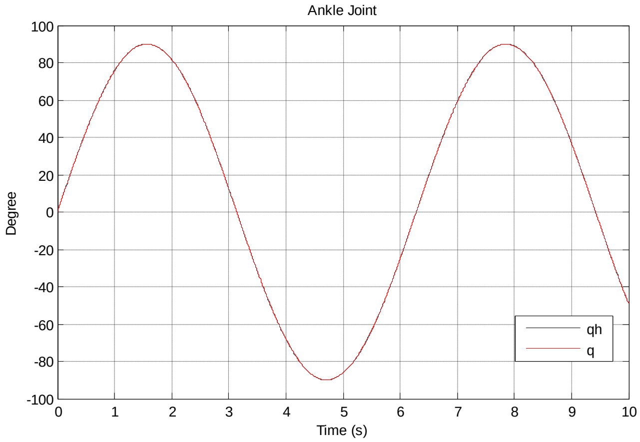

Fig.11. Curve of the ankle joint angle

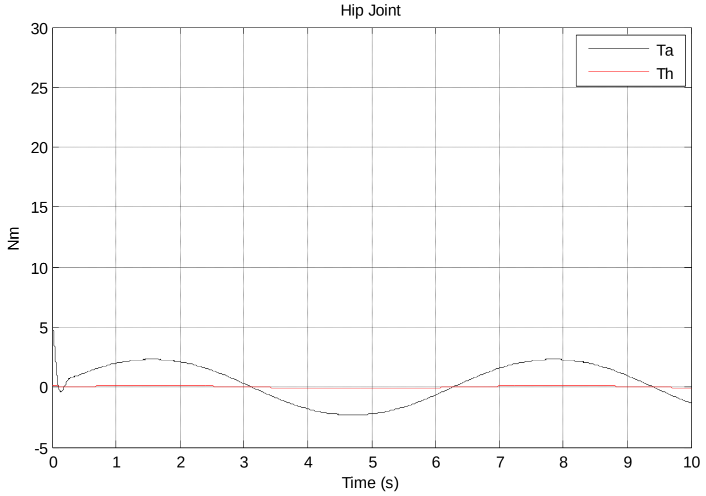

Fig.12. Curve of the torque exerted in the hip joint

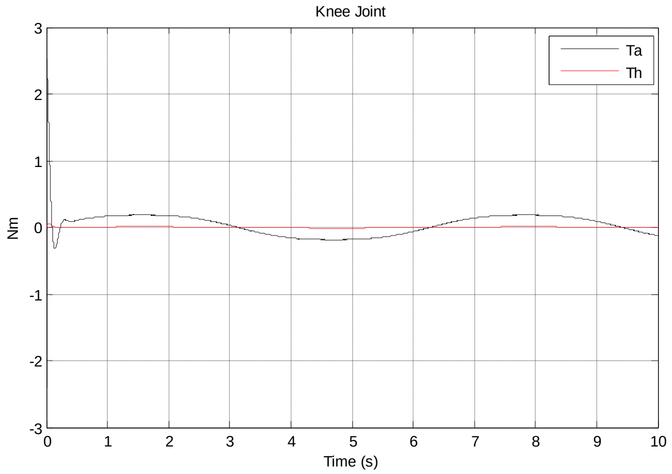

Fig.13. Curve of the torque exerted in the knee joint

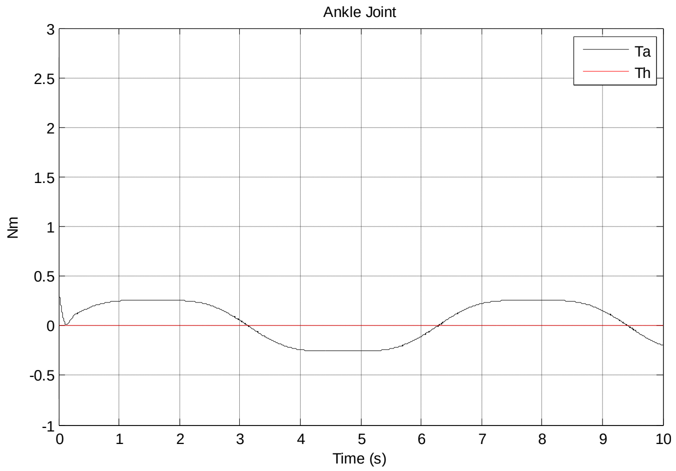

Fig.14. Curve of the torque exerted in the ankle joint

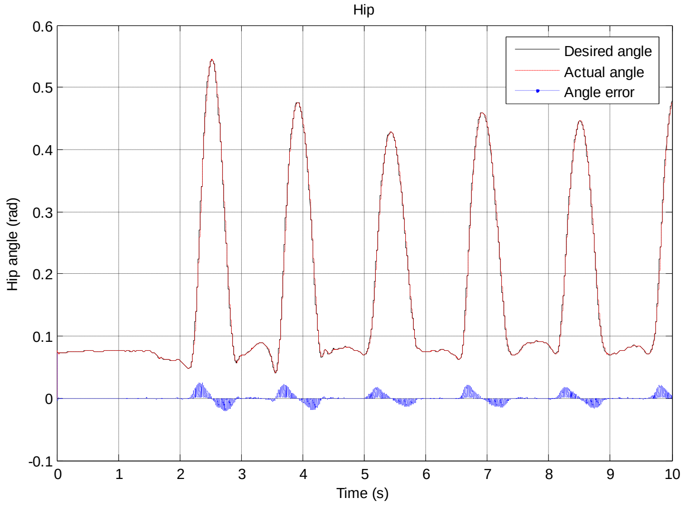

Fig.15. Hip angle with human trajectory from CGA

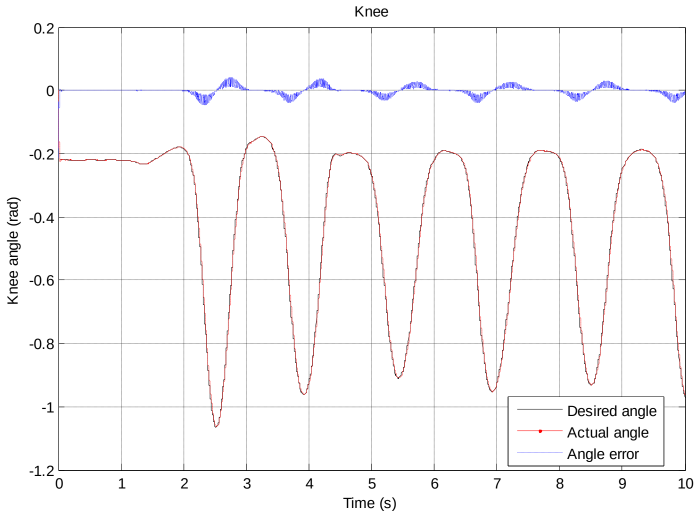

Fig.16. Knee angle with human trajectory from CGA

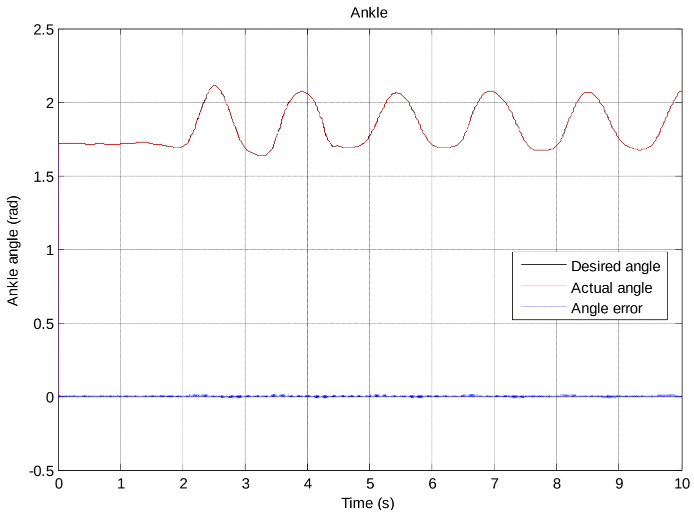

Fig.17. Ankle angle with human trajectory from CGA

V. CONCLUSION

In this paper, an easy to implementcontroller applied to the lower limbexoskeleton for rehabilitation purposeis proposed. The impedance controlleris used to generate control signals to DC motors embedded in joints of the exoskeleton system. Mathematical calculations are undertaken to design and design controllers while 3-DOF model built in SimMechanics facilitates workability of the controller. Finally, it should be re-emphasized that the intelligent lower extremity rehabilitation training system proposed in this paper can achieve a good performances and effectiveness.In the future, other controllers would be considered to adapt changes in the system parameters. Moreover,the system will provide a series of rehabilitation programs for the elderly and muscle disease patients with neural connection between the device and users.

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