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Model-Based Modeling and Simulation of Lower-Extremity Human-Robot System

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Abstract:
To assist in patients with lower-extremity disability, the work is devoted to developing the lower-extremity rehabilitation robot so as to replace the traditional training method, which mainly relies on therapist's one-by-one rehabilitation therapy. Firstly, the work designs an Exoskeleton Rehabilitation Robot (ERRobot). Because it is a human machine system, many considerations must be integrated. Next, we focus on the model construction of the Human-ERRobot system, in which the work adopts a model-based modeling methods, and some modeling tools such as Creo2.0, Matlab/Simmechanics, etc. Finally, the work designs two simulation experiments to validate constructed Muscle Tendon Complex (MTC) model and Human-ERRobot physical model, respectively. The results illustrate that the developed models are validness, which may lay a good foundation for further controller development.

Keywords:
Exoskeleton Rehabilitation Robot (ERRobot), Human Machine System, Muscle Tendon Complex (MTC), Model-based Method, Simulation Model

1. Introduction

1.1. Why Need Robot Assisting Rehabilitation Technology

With the increasing of physical movement disorder patients, high therapy cost and the demand for occupational therapists, the traditional rehabilitation has been unable to satisfy the needs, which mainly relies on therapist's one-by-one rehabilitation therapy. The shortage of occupational therapists has become a profound social problem. Therefore, Robot-assisted physical rehabilitation has become an active research area for the last few years [1], which is able to offer assistance to patients during rehabilitation of the locomotor system by guiding motions on correct trajectories to teach motion patterns, or give force support to be able to perform certain motions at all. The machines allow more effective training sessions, where patients can train up to 1000 steps within a typical training session of 15–20 min, whereas during manually assisted training only approx. 100 steps/session are performed [2], which now can reduce the labor intensity of PT ,time, and cost of the whole rehabilitation process. Its main goal is to reintegrate patients into social life and improve the patients' quality of life [3]. Besides, there are some other advantages by adopting the technology: Experimental data can be simultaneously recorded [4], which can be used in many other fields by simple analysis, such as the study on insight into the metabolic cost of locomotion [5] in the sports-medicine research; (2) the clinical medicine such as objective quantitative assessment(or diagnosis) outcomes [6,7]; better developing muscle rehabilitation training program by studying on which exercises are most useful in activating specific muscles, and Delp etc. [8] developed a graphical interface to allows the user to analyzing surgical procedures, etc.

1.2. Structure Types

Nowadays, many documents confirm that the robot rehabilitation training is able to improve most of the patients' mobility [9]. The lokomat exoskeleton is an example of the early gait trainer [10, 11], and evidence based data shows that lokomat therapy can improve gait symmetry, walking ability, increases muscle strength and so on compared to conventional physical therapy in stroke patients [12,13]. Therefore, there have been a number of attempts to develop automated and semi-automated robotic systems described in literature for the motor function rehabilitation of lower extremities in recent years. The paper classifies the developed devices into two groups: Single-Joint Training Robot (SJTRobot) and Multi-Joint Training Robot (MJTRobot).

SJTRobot is mainly to complete single joint function recovery, such as the hip joint, knee joint or ankle joint. The main objective of recovery training is to increase tension-generating capability flexibility, and endurance of muscles. In the article [14] the authors proposed a single Degree of Freedom(DOF) powered ankle foot orthosis. The powered lower limb orthosis developed at the University of Michigan aims at rehabilitation of patients with neurological injuries, whose detailed description of design and construction can be found in references [15,16]. Paper [17] proposed a knee joint exoskeleton controlled through the wearer's intention estimation. Ferris [16] and his group have designed a pneumatically powered, myoelectrically controlled ankle-foot orthosis as a tool for rehabilitation. Of course, there exist many other devices such as HME (Human Muscle Enhancer) [18], NeXOS [19], Multi-Iso [20], RoboKnee [21] and so on.

MJTRobot can simultaneously perform rehabilitation training for multiple joints, including muscles function recovery training and coordinated action training among multi-joint muscles. Here, we classify them into two kinds, fixation and portability, according to whether or not they are lightweight and can move over-ground. For the "fixation" type, there are two working patterns: serial and parallel. (1)The serial work device is mounted to the user's legs or feet when working, and engages the ground instead of the user's own feet with a varying length that adds to the extension of his own legs [22], such as NEUROBike [23], LokoHelp [24] (LokoHelp Group, Germany),and HapticWalker [2]; (2) Devices in parallel with users' legs are mainly exoskeleton robot, and treadmill gait trainer is a main part among of them, such as LOKOMAT [25] (Hocoma AG, Volketswill Switzerland), ALEX(Active Leg Exoskeleton) [26], LOPES[27,28] and so on. For the "portability" training machines, it is over-ground gait trainers and it has been, and are being developed, such as HAL(Hybrid Assistive Limb) [29] from University of Tsukuba, BLEEX (Berkeley Lower Extremity Exoskeleton) [30] ,EXPOS from Sogang University [31,32] , Vanderbilt exoskeleton [33], REX Bionics [34], MINDWALKER exoskeleton [35], Ekso [36], Motion Maker [37].

In the paper, we design our rehabilitation robot as a wearable exoskeleton rehabilitation robot (i.e., ERRobot), and we pay our attention on the model development of the whole Human-ERRobot system based on a model-based method, which may lay a good foundation for further controller development.

2. Materials and Methods

2.1. ERROBOT Mechanism Design

As introduced above, the ERRobot is an exoskeleton robot. It braces the foot, wraps around the lower and upper leg, and map on to the anatomy of the human limb. To provide support and control of the lower limb, it is used to aid the partial weight-bearing gait [6] to restore lost or weak functions of lower extremity to their natural levels.

The ERRobot system designed in the work, so far, includes solely lower extremity exoskeleton and an upper extremity exoskeleton will be considered to add in future work. A convenient elements in the design phase is modularity and flexibility regarding the ability to make changes to the robot configuration during the experimental process. The complete robot consists of 2 identical left-right parts. It is a kind of wearable exoskeleton robot parallel to the people's lower limbs [38], which adopts an anthropomorphic architecture with similar kinematics to a human. The following paragraphs summarize the design of the ERRobot in terms of its mechanism, actuation and sensor characteristics.

2.1.1. Whole Mechanical Design

Mechanical composition of my design can be grouped into 3 parts: a back-mounted frame attached to the upper body, right and left lower limb mechanics which are mounted on that frame mechanics. In this work the Aluminum alloy is selected as the main material for these structures so that it would be lightweight and have sufficient rigidity to support the strains. We also design some necessary attachment devices where the ERRobot can be attached to the wearer at five main locations: footplate (no showing in model), shank, thigh, pelvis, and torso. The back-mounted frame is a rigid spine that serves as a payload attachment point and an exoskeleton-to-human attachment point through a compliant backrest. The control PC, battery for electronics and some other load are located in the frame.

In order to be adapted to different operators in terms of physical characteristics, increase level of comfort and also enable a quick donning and doffing capability, the mechanism is adjustable for different body and limb lengths, and cushioned interface is adopted.

2.1.2. Degree of Freedom (DOF)

The core driving part is actually a three links' mechanics (for single leg mechanics), including thigh part, thank part and foot part, all of which hold the subject's leg in a defined position. Based on human anatomy and joint ROM (Range of Motion), the desired DOFs for the ERRobot is specified to allow sitting, standing, and walking. The ERRobot is designed to include three joints and five DOFs per leg (the joint of Hip: 2DOFs, Knee: 1DOF, Ankle: 1 DOF, and toe: 1 DOF, respectively). For joints' driving methods, if every of DOFs is actuated, it will lead to unnecessarily high power consumption and control complexity. So only those joint DOFs that require substantial power when implementing specific motion should be actuated[30],that is, they are treated as active DOFs. At first step, because it is designed for the rehabilitation of lower limbs, and gait recovery training is viewed as a primary task, the CGA (Clinical Gait Analysis) data is used to facilitate the design by providing information such as joint velocity, torque and power. Based on gait analyzing, flexion/extension at the ankle, knee, and hip are designed as active joint DOFs, and the other DOFs are equipped with passive impedances.

The ERRobot kinematics are close to human kinematics, so the ROM of the ERRobot joint is determined by examining human joint ROM, and it is designed to be equal to or larger than human joint ROM in walking, and less than the maximum ROM of operator's joint for safety [22].These data can be found by examining CGA data and other study [39,40].

2.1.3. Selection of Actuators and Sensors

Specifying the actuation is a key step in the design process of the ERRobot. It must provide the necessary assistance if the subject is not capable of correctly performing the movement. For the considerations of actuators' selection, these include power or force density, efficiency, size and weight, and cost. In addition, since the ability of walking is the primary rehabilitation task in the thesis, many parameters can be determined by gait analysis. Human joint angles for a typical walking cycle are collected via human video motion capture. The torque and power requirements are estimated based on the given motion, which are completed to perform the same motion by a similarly sized human. Figure 1 shows the information of kinematics and kinetics of human gait from a normal, healthy individual (70 kg, 0.90 m leg-length) walking at 1 m/s, including joint angle, torque, and power for hip, knee, and ankle flexion/extension motions during level-ground walking. They are plotted through some modifications for the original data that can be found in reference [39]. The data of y-axis is relative to body weight.

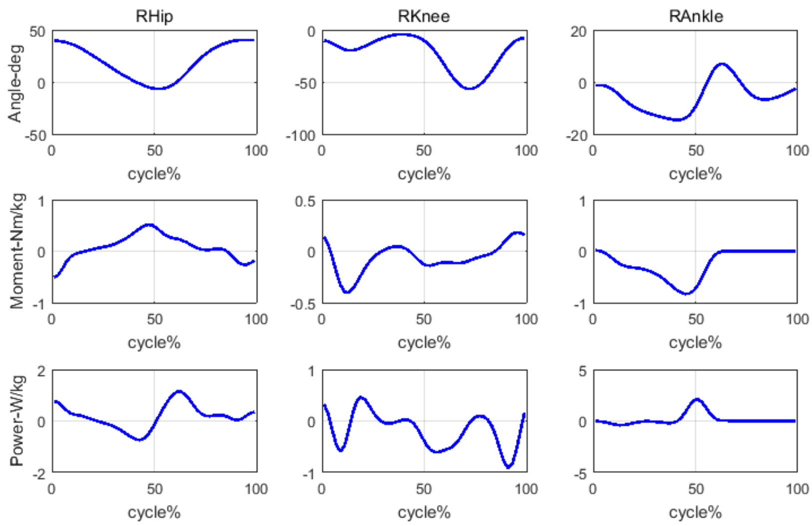


Figure 1. *Kinematics and kinetics of human gait from a normal gait (walking speed 1m/s).*

Through data processing for original data, the max torques of three joints can be obtained easily. Take a user with a weight of 80 kg for an example, these joint torque values are listed in Table 1 and the table also lists the corresponding positions in gait cycle, which located in the parentheses. From the table, we can see that the torque of ankle joint is maximum of three joints and the torque value increases with the increase of the walking speed for same person. For instance, the torque of ankle joint is around 70 N m during plantar flexion for push-off (around 47 % of gait cycle) for the same wearer. However, other work also present a bigger torque. According to these reference data described above, the appropriate motor and reducer can be determined. The reference [41] indicates that the permanent magnetic brushless DC motors generally have relatively higher torque density and efficiency. In the work, six brushless DC motors with the gear reducers are used in the work due to its excellent controllability, ease of supplying power, and so on compared with other actuators such as hydraulic and pneumatic actuators [42]. It imposes sagittal plane torques at hip, knee and ankle joints. ERRobot contains seven segments, which are: two shank segments, two thigh segments, two foot segments and one pelvis segment. These motors are used to drive the hip, knee and ankle articulations through a speed-reduction transmission. As a safety measure, both knee joints include normally locked brakes.

Table 1. *Max torque of three joint in the sagittal plane at three different walking velocity.*

Walking velocity(m/s)	Hip(Nm)	Knee(Nm)	Ankle(Nm)
0.5	38.4(2%)	17.0(14%)	62.9(45%)
1.0	41.4(47%)	32.4(12%)	66.4(45%)
1.5	49.3(48%)	48.2(12%)	70.3(47%)

The selection of sensor depends heavily on the specifics of the target application when the system is developed. According to the control requirements, encoders are adopted to measure the rotational joint angles [43] and velocities at active joints. Inertia Measurement Units (IMUs) at the segments of thigh, shank and foot are also tested to measure the acceleration, velocity and orientation of the corresponding segments in the world frame. In order to record the force and torque applied by the human, ATI Gamma force/torque sensors are used at active joint. These sensors require careful design to securely fasten them to the human. To ensure safe, each major axis (joints 1, 2 and 3) is equipped with electromagnetic brake, which is activated when power is removed from the motors.

2.2. Development of Human-Robot Engineering Model

The ERRobot contacts directly with users, so it’s a Human -Machine (ERRobot) system. Control system design starts with an accurate Human-Robot model. To build the plant model, the paper firstly models the biomechanical model of human lower extremity, and then constructs the whole system engineering model, in which the ERRobot is processed as a force provider.

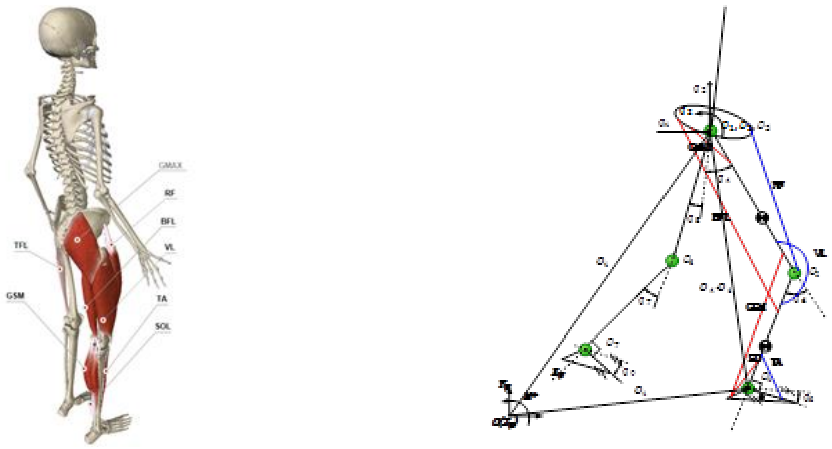
2.2.1. Lower Extremity Biomechanical Model

The biomechanical model here mainly refers to the musculoskeletal model comprised the skeleton model and the Muscle Tendon Complex (MTC) model.

(a) Muscular System

The muscles are the natural actuators of the skeletal system. Through muscle belly connecting to the bones or other muscles at points called origin and insertion by tendons, muscles is able to generate force between two end points either actively through contraction or passively through their resistance to stretch.

In this project the focus is on activating the lower leg muscle to generate a lower limb movement (for example, walking movement). It could be useful to model all the possible lower leg muscles [44], but with the main reason of simplification a choice of 8 lower leg muscle is selected. They are Gluteus Maximus (GMAX), Tensor Fasciae Latae (TFL), Rectus Femoris (RF), Biceps Femoris Long head (BFL),Vastus Lateralis (VL), Gastrocnemius Medial(GSM), Tibialis Anterior(TA), Soleus(SOL). In our analysis, because of the consideration that the TFL muscle is related with the muscle GMAX in function and structure, TFL is often eliminated. They are showed in Figure 2(a). Besides, all these muscles' models are built by using a type of Hill-type [45] muscle model in my work, which follows the work of paper [46] modified slightly. Muscle model is to find the relation between the neural input and mechanical output, i.e. a contraction force. We classify the muscle model to the activation and contraction dynamics, which are represented by two ordinary differential equations (ODEs): one ODE per muscle is used to describe the delay between muscle activation signals and muscle active states. A second ODE per muscle is used to describe the contractile dynamics. This work has been partially published in the IEEE international conference on DASC2014 [47].



(a) (b)

Figure 2. *Adopted muscles and lower-extremity Muscle-Skeleton model.*

(b) Skeleton System

In anatomy, each bone is a complex living organ that provides attachment points for muscles to allow movements at the joints. For human joints, according to predominant tissues that supports the articular elements together, joints typically have three major types, that is, fibrous, cartilaginous, or synovial [48] joints. Among of them, the synovial joint is the main joint type associated with lower limb movement. For different categories of joints, corresponding movements are permitted, e.g. flexion and extension, medial and lateral rotation and so on. The work simplifies the lower-extremity model as a seven-segment link model (two feet, two legs, two thighs, and a HAT segment). It is designed to include three joints and four DOFs per leg (the joint of Hip: 2DOFs, Knee: 1DOF, and Ankle: 1 DOF, respectively). The muscle-skeleton model in sagittal plane is displayed in Figure 2(b).

2.2.2. Human-ERRobot Model-Based Modeling

As stated previously, ERRobot is processed as a force provider in the work, therefore, we can get the whole system model by adding the created moment by muscles and ERRobot into skeleton model that is modeled as an articulated multibody system. For simplification, the ERRobot is supposed to be rigidly attached to the wearer's leg such that the whole system rotates synchronously about the three joints.

This modeling method is done using blocks provided by MATLAB/Simulink/SimMechanics. The tool supports each stage of the development process for control system design, from plant modeling to deployment through automatic code generation. In the process of model developing, to get the kinetic quantities (mass and moments of inertia, etc.) of each segment, we build the detailed Human-ERRobot model using the Creo2.0 (3D Computer Assisted Design (CAD) software, PTC Inc.) software package. Then, we import the developed model into the Matlab environment by way of the data interchanging interface between them, which can simultaneously import into the mass, inertial, properties of different components and coordinate configuration, therefore, the integrated Human-ERRobot simulation model is not only a mathematical model but a physical model to some extent.

3. Results and Discussion

3.1. Muscle Model

In the work, the developed muscle model is a MISO system of three inputs (neural excitation u, MTC length of L_{MTC}, MTC velocity of V_{MTC}) and one output (MTC unit force). Moreover, because the MTC velocity is the differential of its length, the muscle model is processed to be a system of two inputs and one output, that is, MTC velocity is directly calculated by its length differential. In order to start the simulations, first of all, the model must be provided with all required parameters. The simulation takes the parameters of muscle "Vastus Lateralis (VL)" as an example. For the module of activation dynamic, we let the minimum of the input u be 0.001 and set the initial output activation value of integration 0.001. And in addition, the time constants of ramping up and down of muscle activation are 0.01s and 0.04s, respectively.

Next, we import signals into the MTC dynamic system, and view the system response. For the selection of neuromotor inputs, there are two classic types [50]: (1) a 2 ms duration electric pulse that caused action potentials .The corresponding muscle response is called a twitch response by physiologists, or an impulse response by engineers; (2) a high stimulation frequency (e.g., 100 Hz) that resulted in a maximal (saturating) ability to generate muscle force. The corresponding muscle response is called tetanus by physiologists, or a maximal step response by engineers). According to the introduction above, the work can executes three tests of six classic muscle tests defined in literature [50], whose outputs are MTC force, that is,

(a) isometric twitch:$\mathrm{input\ a} = \mathrm{impulse},\ V_{MTC} = 0,$ and output F_{MTC} measured;

(b) isometric tetanus: $\mathrm{input\ a} = \mathrm{max\,step}\,, V_{MTC} = 0,$ output F_{MTC} measured;

(c) max isokinetic: $\mathrm{input\ a} = \mathrm{max}, V_{MTC} = \mathrm{const},$ output F_{MTC} measured.

The used Simulink models are constructed and implemented by manually changing the switches of the model shown in Figure 3.

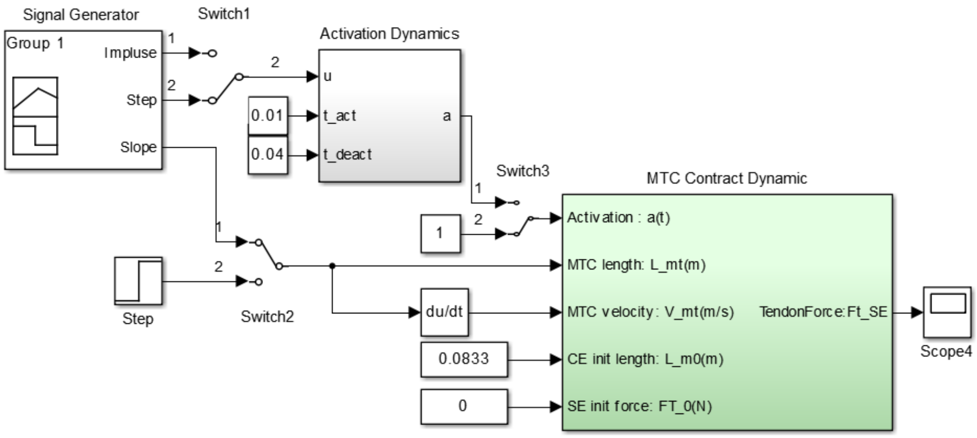


Figure 3. *MTC dynamic simulation model.*

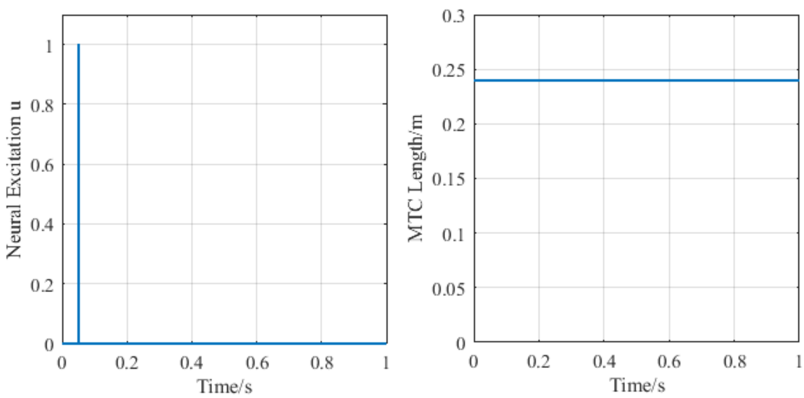
(1) Isometric twitch

Isometric is a special case of isokinetic [50], namely the prescribed velocity is zero. In the test, the input u is an impulse signal and L_MTC is a constant. In order to run the simulation, we change the switch position of the model shown in Figure 3 according to Table 2.

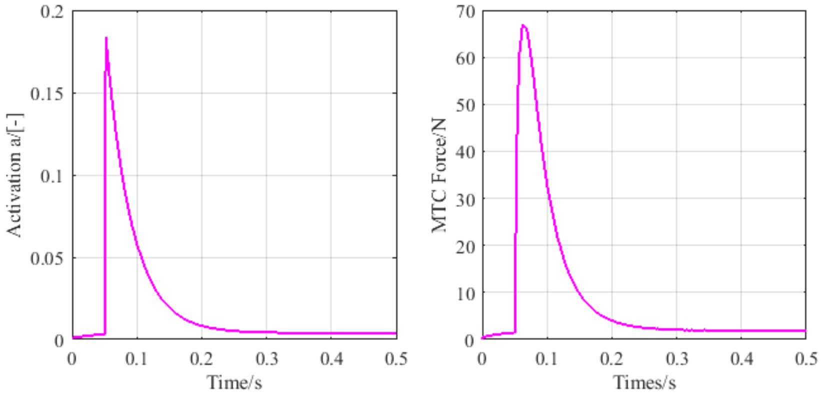
Table 1. *Switch position for every muscle test type.*

Test types	Switch position		
	Switch1	Switch2	Switch3
Isometric twitch	Up	Down	Up
Isometric tetanus	Down	Down	Up
Max isokinetic	Up/Down	Up	Down

As introduced above, the simulation adopts the muscle parameters of muscle "Vastus Lateralis (VL)". we know that its optimal muscle length is 0.084m and slack length is 0.157.Their sum is 0.241m.Therefore, the simulation set initially the length of MTC 0.24m, and make the length of tendon equal to slack length 0.157m so as to warrant the zero initial value for tendon force. For the other initial input, i.e., active muscle fiber CE length, its value is found by evaluating the muscle-tendon path length equation. Therefore, we assign the initial CE element value as 0.0833 and initial tendon force as 0 N. The inputs and the results for the muscle task are shown in Figure 4. The isometric twitch task represents the force response of the muscle to a single neural activation impulse.



(a) (b)

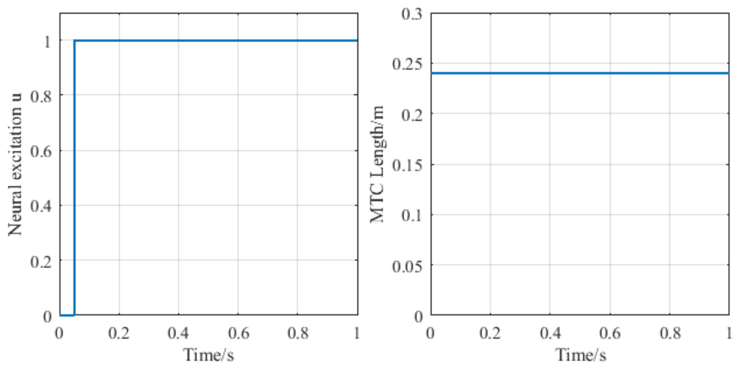


(c) (d)

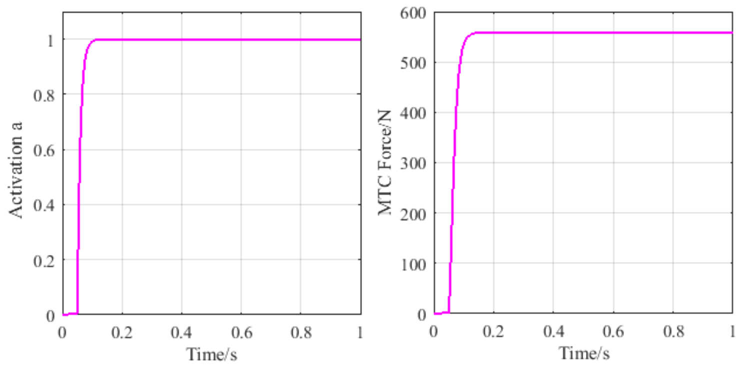
Figure 4. *Input and output in isometric twitch test :(a) Input signal of neural excitation that is a 2ms duration impulse signal that occurs at 0.05 seconds;(b) Input signal of MTC length;(c) A mediate state variable, activation signal that is the output of the activation dynamic module and is directly used as the input of the MTC contract dynamic module;(d) Output of estimated MTC unit force.*

(2) Isometric tetanus

The isometric tetanus task represents the ability of muscle to maintain a constant length despite producing a sharp increase in stiffness (i.e., output force) [49].In order to run this simulation, i.e., isometric tetanus task, we continue to change the switch position of the model shown in Figure 3 according to Table 2. For the isometric tetanus task, the neural activation input is the step function that makes the transition from 0 to 1 at 0.05 seconds. Other parameters are same with implementing the isometric twitch task. Its input and output signals are depicted in Figure 5.



(a) (b)

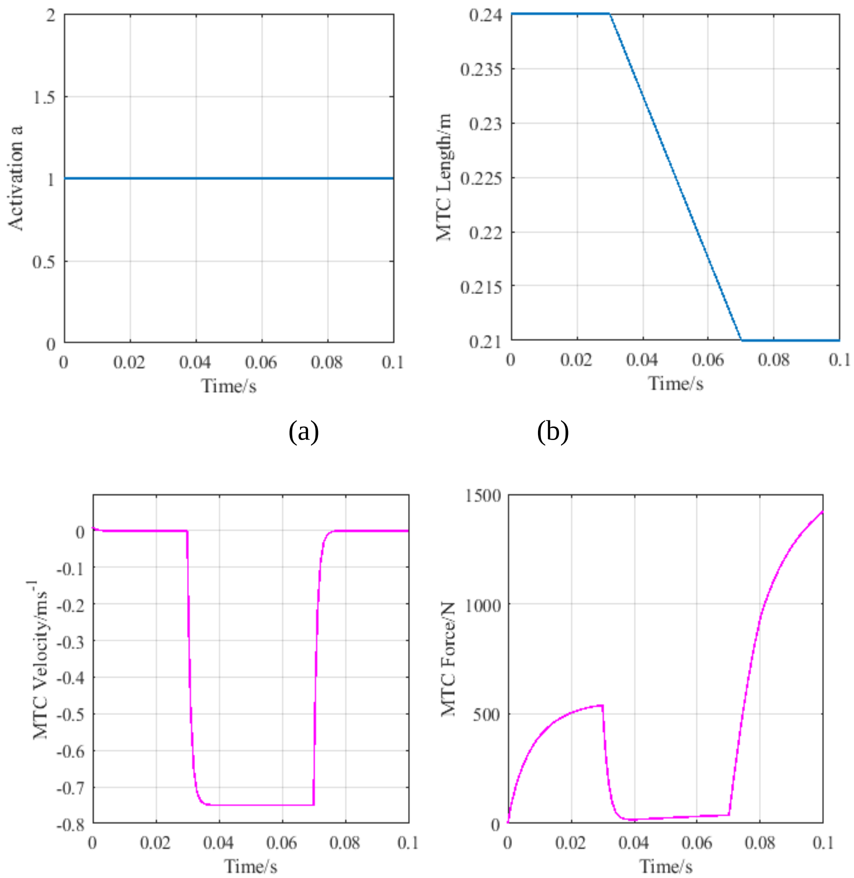


(c) (d)

Figure 5. *Input and output in isometric tetanus test :(a) Input signal of neural excitation that is a step signal;(b) Input signal of MTC length ;(c) A mediate state variable, activation signal that is the output of the activation dynamic module and is directly used as the input of the MTC contract dynamic module;(d) Output of estimated MTC unit force.*

(3) Max isokinetic

The maximum isokinetic task represents the ability of muscle to change length smoothly throughout a movement task. The simulation results are depicted in Figure6. The length input is the decreasing ramp; the neural activation input is set to unity throughout the task.



(a) (b)

(c) (d)

Figure 6. *Input and output in max isokinetic test :(a) Input signal of activation;(b) Input signal of MTC length;(c) A mediate state variable, MTC velocity that is derived from the MTC length and is directly imported into the MTC contract dynamic module;(d) Output of estimated MTC unit force.*

The muscle outputs for the selected tasks are compared to the results presented in paper [49] that uses a virtual muscle model to validate its results. These derived results indicate smooth motion and MTC output forces. They are similar with the results presented in other reference such as reference [49] except for some differences that are maybe caused by adopting different simulation parameter values.

3.2. Human-ERRobot Model Simulation

To conveniently operate and build interactive simulation environment, we always develop the corresponding control GUIs in Matlab environment. Therefore, all functional modules are organized and called by the GUI program. Figure 7 shows a manually operating GUI and a real-time showing window.

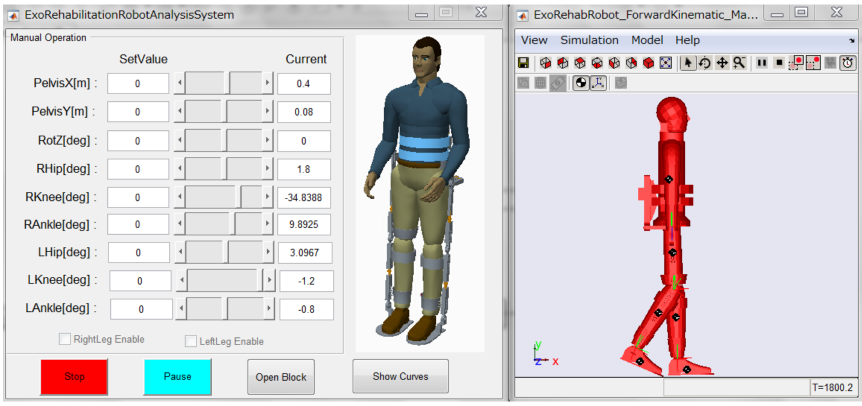


Figure 7. *A window manually operating a simplified model and a real-time showing window.*

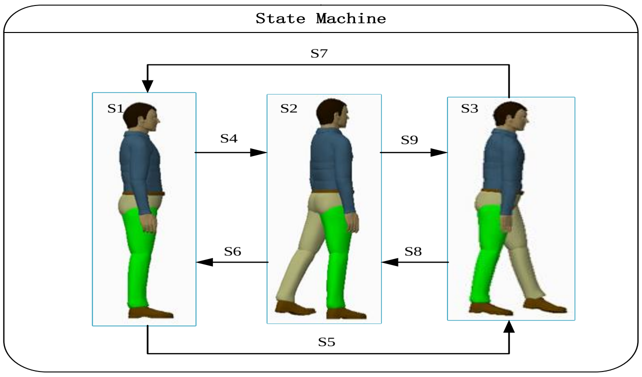


Figure 8. *Gait state designs for the stance and gait assistance.*

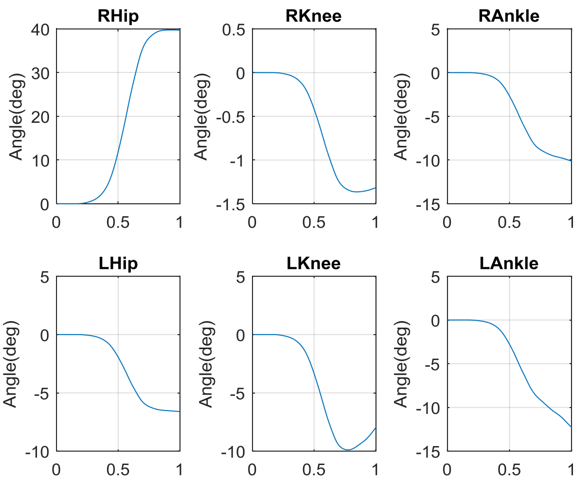


Figure 9. *Transition From State S1 to S2 (i.e., the trajectory of state S4).The unit of Y-axes is degree. X-axes represent the scaling time: Time = 0(0%) denotes reference data at state S1, and Time = 1(100%) denotes the reference data at state S2.*

This work validates the model by performing walk task. Walking is a mixture of discrete and continuous control problems. The discrete control problem is the transition between events such as starting, stepping, and stopping, and the continuous domain is the continuous angle changing in each discrete state. We adopt Finite State Machine (FSM) method to link both of them. For simplification, we only study the gait assistance in sagittal plane. In the work, 9 states are defined for walking control in sagittal plane, shown in Figure 8. For more detailed state division, you can refer to paper [46].

The walking trajectories are divided into three parts; stance/double stance (S1, S2, and S3), half step swing (S5, S7, S4, and S6) and total step swing (S9, S8). The developed model is driven by the reference curves are obtained from normal gait data of those healthy people [43]. For stance/double stance state, their reference data adopts the boundary data of those adjacent state transition curves. These reference data must make the Human-ERRobot system being in an equilibrium posture. In the simulation experiment, a healthy man (70 kg, 0.90 m leg-length) with walking velocity of 1m/s took part in the experiment.

After a walk cycle is performed, we can get the joint angle trajectories in sagittal plane by using sensor block in SimMechanics environment. We plot the curve of half step swing state S4 ,that is, state transition from S1 to S2, which consists of swing right leg joint curves (RHip, RKnee and RAnkle) and stance left leg joint curves(LHip, LKnee and LAnkle). Other reference trajectories of state transition can also be acquired. By comparison with actual acquiring joint data, we can validate the model's validness.

4. Closing Remarks and Future Work

As the preparations for further study for control system, this work presents the simulation model of Human-ERRobot system that aims to those people who have lower-extremity weakness or paralysis. The ERRobot 3D mechanical model is developed by CREO2.0 software, then import it into Matlab/Simmechanics to prepare for the controller development and model validation.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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