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A sEMG-driven Musculoskeletal Model to Control Exoskeleton Robot Used in Lower ExtremityRehabilitation

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Abstract

A control system framework of lower extremity rehabilitation exoskeleton robot is presented. It is based on the Neuro-Musculo-Skeletal biological model. Its core composition module, the motion intent parser part, mainly comprises of three distinct parts. The first part is signal acquisition of surface electromyography (sEMG) that is the summation of motor unit action potential (MUAP) starting from central nervous system (CNS).sEMG can be used to decode action intent of operator to make the patient actively participate in specific training .As another composition part, a muscle dynamics model that is comprised of activation and contraction dynamic model is developed. It is mainly used to calculate muscle force. The last part is the skeletal dynamic model that is simplified as a linked segment mechanics. Combined with muscle dynamic model, the joint torque exerted by internal muscles can be exported, which can be used to do a exoskeleton controller design. The developed control framework can make exoskeleton offer assistance to operators during rehabilitation by guiding motions on correct training rehabilitation trajectories, or give force support to be able to perform certain motions. Though the presentation is orientated towards the lower extremity exoskeleton, it is generic and can be applied to almost any part of the human body.

Keywords: Rehabilitation Exoskeleton; Surface Electromyography (sEMG); Neuro-Musculo-Skeletal model; Muscle Dynamics Model; Skeletal Model.

1. Introduction

With the rapid arrival of the aging society and the increase of physical movement disorder patients caused by various disease, the demand for occupational therapists has increased drastically. The traditional rehabilitation mainly relies on therapist's one-by-one rehabilitation therapy, obviously which is gradually not in conformity with the needs. In parallel to this situation, researchers have been using robotic technologies to develop many kinds of assistive and rehabilitative devices for people with disabilities or to develop medical devices used by caregivers. Our research team's core work is just to use robot technology to develop a intelligent rehabilitative training system that can be used to do lower limb gait rehabilitation for patients following a disease or a neurological condition. For this purpose, we develop an exoskeleton device that can be worn around human lower limb to offer assistance to patients during rehabilitation of the locomotor system .Its recovery principle is that robot drives patients to simulate normal subjects walking to complete the rehabilitation training mission under the control of control system

To date, this kind of rehabilitation has been developed for many rehabilitation purposes by other researchers and many of the clinical trials also verify they are valid. Among them, the lokomat exoskeleton is an example of the early gait trainer[1, 2]. 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 [3, 4].Moreover, there are many other exoskeletons besides LOKOMAT. They were generally divided into two

categories: treadmill gait trainer and over-ground gait trainer. Other treadmill exoskeletons besides LOKOMAT have LOPES[5, 6], ALEX[7] , ANDROS[8] and so on .The developed over-ground gait trainers have Hybrid Assistive Limb(HAL)[9] from University of Tsukuba, EXPOS from Sogang University[10] and Vanderbilt exoskeleton[11].For these exoskeleton devices ,regardless of their different mechanical types, some common considerations must be paid on the design of their control system.

As a kind of wearable robot[12], the distinctive, specific and singular aspect of exoskeleton is its kinematic chain maps on to the human limb anatomy. Thus its controller design must be imposed strict requirements as regards safety, effectiveness and dependability. It must be designed as person-oriented device and is under the control of operators at all times. For control of the exoskeleton rehabilitation robot, Of course, a large number of control system have been proposed in earlier studies using various approaches, such as machine learning, decoders, pattern recognition, and proportional control[13, 14]. Except for proportional control, these control methods have two inherent drawbacks: (1) they only allow the subject to perform predetermined movements and (2) they limit the user's ability to control the magnitude of torque production. Alternatively, proportional myoelectric controllers use the subject's muscle activation to control the magnitude of joint torque for the powered device, which may be more beneficial in lower-limb control [15].But most of the previous work proposes complex mechanisms or systems of sensors. Meanwhile, many researchers also use the EMG directly to generate machine control commands for robot[16]. However, most of the previous works decode only finite lower limb postures from surface electromyography (sEMG) signals, which can cause many problems regarding smoothness of motion, especially in the cases where the robot performs everyday life tasks .Therefore, effective controller entails the necessity for continuous and smooth control. Besides, studies have shown that active involvement for operators in the production of a motor pattern results in greater motor learning and retention than passive movement[17-19].So in our system design, in order to make the patient actively participate in the task specific training, sEMG is adopted to decode intent of operator.

In the work, we construct a hybrid control scheme that combines the model-based control system and sensor-based control system. For the design of sensor-based control system, you can complete the design by referring to the design methods of control system of traditional robots. Therefore, the work mainly talk about the other sub-control system of model-based control system. In the system, Neuro-Musculo-Skeletal model is adopted. The sub-control system is an intuitive interactive interface between exoskeleton and operator. Compared to the traditional control by way of an external device, for example, a keypad or a wheel and so on that has to be manipulated, intuitive interface can reduce operator's mental load, that is, the operator can focus on fulfilling a task with the exoskeleton rather than focus on mere control of the device[20].

This paper is organized as follows: Section II provides a brief description of physiology of Neuro-Musculo-Skeletal and human motion control; Section III focus on the description about the control framework based on Neuro-Musculo-Skeletal model developed in the work; Section IV gives a closing remarks and future work.

2. Physiology of Neuro-Musculo-Skeletal And Human Motion Control

Movements of the body are brought about by the harmonious contraction and relaxation of selectedmuscles. Rehabilitation referred in this article is mainly to rebuild human limbs motor function such as walking gait, so as to maximize the patient's quality of life (QOL). [21].

2.1 Generation, Transmission and Transformation of Nerve Impulses

In Neuro-Musculo-Skeletal model, the connection of the nervous and muscular system is the so called α-motor neurons originating from the spinal cord or brain stem. Neurons create an electrical impulse (nerve impulses or an action potential (AP)) that transmitted across neuromuscular junctions to the motor endplates sitting on top of the muscle fibers. At this time, the muscle is activated to contract by the nerve signal and human movement is finally driven by skeletal muscle contraction force.

The α-motor neuron, together with the axon, motor endplate, and the muscle fibers they connect to make up the fundamental block of motor control and are called a motor unit[22]. In general, motor units are fired in a random pattern and are not synchronized when a motor unit action potential (MUAP) is evoked .Studies on single motor units revealed that one stimulation pulse creates a single twitch response from the muscle. With increasing frequency of those pulses, the twitches start to merge and the force production of the muscle becomes continuous and increases. When the stimulation frequency is further increased, the twitches come closer to a permanent maximum contraction of the muscle at which point no further force can be generated. If this contraction is performed voluntary (no reflex, no spasm) it is called maximum voluntary contraction.

In my control scheme of the exoskeleton, the surface electromyography (sEMG) have been used as nerve control signal to identify voluntary movement from a patient. sEMG signal of a muscle is the summation of MUAPs evoked at the same time and can be directly measured invasively with surface electrodes located on top of the skin.

Figure.4 shows the main hardware composition that completes the process from the sEMG signal generation to the controlled object, whose details can refer to [23]

The time between the emission and detection of the sEMG signal can be neglected in the context of this work. But there is also a time between emission and force production. This time, called the electromechanical delay, is reported to be about 50–80ms[24, 25], mainly due to low muscle fiber conduction velocity and the chemical processes which lead to contraction. It allows the signal evaluation process to start before the force production begins, reducing the latency of control systems coupled to EMG signals. Effects of muscle fatigue are not taken into account in this work. An analysis of these effects can be found in [26].

So the control scheme is the ability to detect the user's intention prior to the actual contraction of the muscle .However, one of problems by using sEMG is the system will not work properly if it is applied to the user with muscle disorder. This is also why a hybrid control scheme is used. Figure 1 is a conceptual scheme of the Neuro-Musculo-Skeletal system from the perspective of control. The scheme shows a feedback control system.
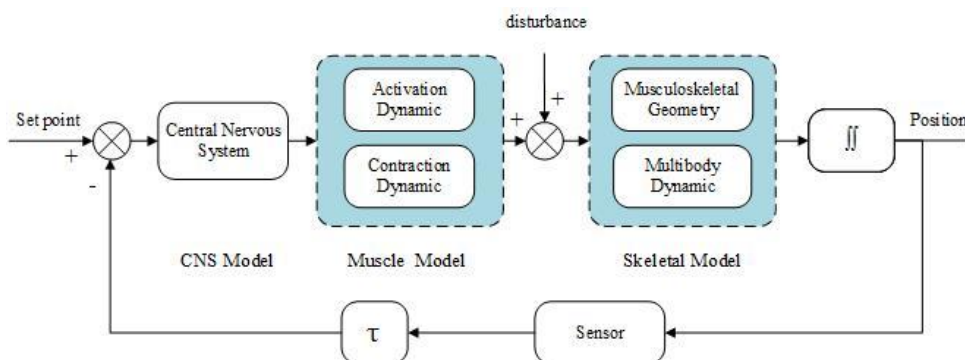

Fig 1: A conceptual scheme of the Neuro-Musculo-Skeletal system.

During the whole process from the creation of nerve impulses that is based on feedback signal from sensor such as eyes to movement generation, the essential characteristic of human biological system is that it is converged in nature. About four levels of integration are included in the Neuro-Musculo-Skeletal system[27-29].But they are mainly divided into three parts from the perspective of biomechanical modeling and control in the work, that is, the central nervous system (CNS) model, muscle dynamics (activation and contraction dynamic) and skeletal dynamic model.

2.2 Musculoskeletal Model

The construction of musculo-skeletal model requires an understanding of the anatomy of musculoskeletal systems. According to [30],anatomy is the study of the structure of the human body and provides essential labels for musculoskeletal structures and joint motions relevant to human movement.

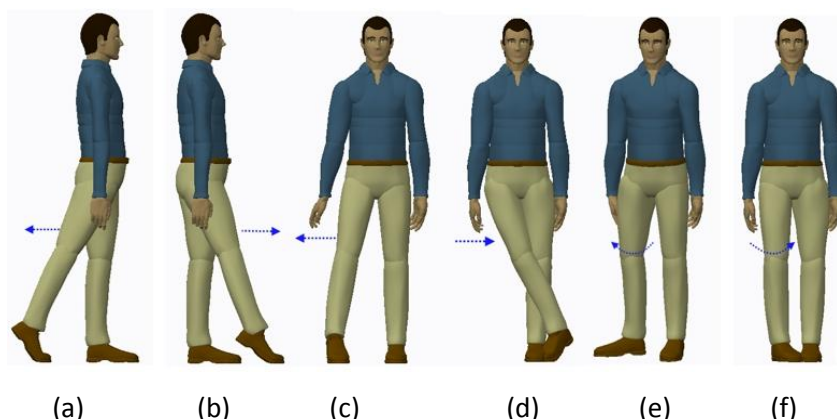(a)   (b)   (c)   (d)   (e)   (f)

Fig 2:Possible hip joint movements and their corresponding types are: (a)Extension(b) Flexion(c) Abduction(d) Adduction(e) External rotation(f) Internal Rotation. These movement occurs in three main planes, i.e., sagittal plane (movements of a and b), coronal plane (movements of c and d) and transverse plane (movements of e and f), which are introduced when researching motion related to human. For details such as definitions of these movement types and planes, you can refer to the relevant books[30].

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[31] joints. Among of them, the synovial joint is the main joint type associated with lower limb movement. Mobility varies considerably and a number of subcategories are defined based on the specific architecture and topology of the surfaces involved (e.g. planar, saddle, ball and socket). For different categories of joints, corresponding movements are permitted, e.g. flexion and extension, medial and lateral rotation and so on. For example, hip joint that is the link between the pelvis/trunk and the lower limbs is a ball-and-socket joint and has several kinds of movement, as shown in Figure 2.

3. Control Framework Based on Neuro-Musculo-Skeletal Model

The work aims to develop an innovative neuromuscular control theoretic formulation to control a exoskeleton rehabilitation robot for the lower limb. The approach adopted here in developing the interface of human-robot sensorimotor control is based on an inverse model (dynamic and kinematics) coupled with nonlinear feedback. As the nervous system plans and regulates movement, it does so by taking into account the mechanical properties of the muscles, the mass and inertial properties of the body segments, and the external forces arising from contact with the environment. The overall system can be represented schematically as in Figure.3, which is subdivided into three distinct parts: the motion intent parser, lower-level controller and controlled object. Among of them, the motion intent parser that computes the suitable support torque is the most important composition part .So the following mainly give a description for it.
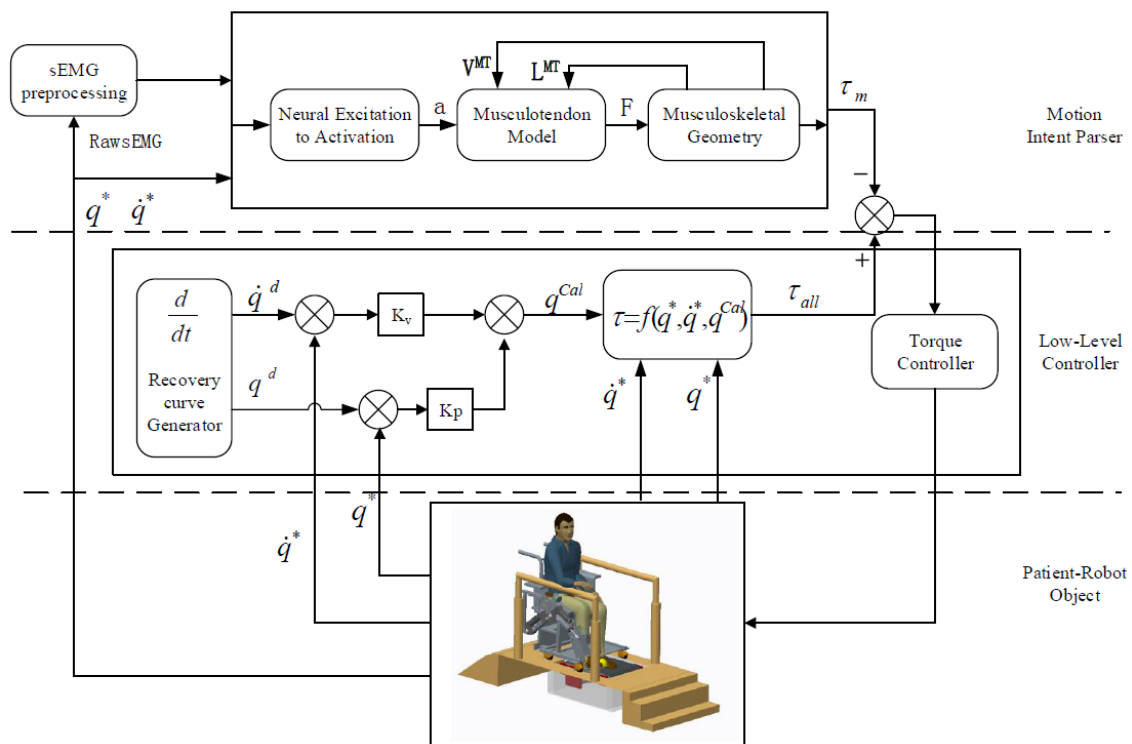

Fig 3: The framework of overall control system

The part of the motion intent parser mainly comprises of three distinct parts, which are signal acquisition of surface electromyography (sEMG), muscle dynamic model and skeletal dynamic model.

3.1 Signal Acquisition of sEMG

sEMG is the summation of motor unit action potential (MUAP) starting from central nervous system (CNS).So that it can be used to decode action intent of operator to make the patient actively participate in specific training .Figure 4 is a sEMG signal acquisition system adopted in our experiment. It is a multi-channel wireless telemetry system that is a product of NIHON KOHDEN Corporation in japan. Before starting to obtain signal, a lot of preparations must be done, which is very important if a good quality signal is to be obtained. In my experiment, it includes (1) shaving the excess hair to obtain even lower skin resistance;(2) Using alcohol to removal of dirt, oil, and dead skin in order to reduce any skin resistance and allow electrodes to be attached without coming loose;(3) a part of subjects whose skin surface are dry use electrode gel (Elefix Z-181BE made in NIHON KOHDEN corporation
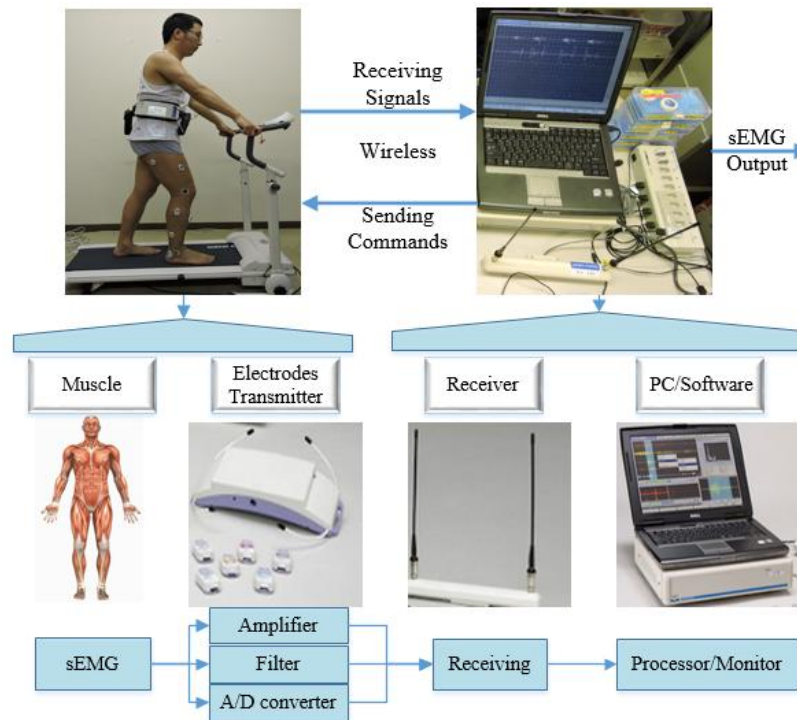
Fig 4: The key elements of the system from SEMG to robot

in japan) rubbed into the skin, which can dramatically improve the quality of the recorded signal;(4)In the decision of the specific site for the electrode, in order to assure repeatability for different subjects, various bony landmarks are used as a reference .After finding the position for one subject, marks are made so as to assure that the electrodes are over the same muscle fibers in different trials; (5)The inter-electrode distance is a important parameters and you should make sure that this distance is consistent throughout all subjects and trials. In my experiment, this step is skipped because the electrodes has fixed electrode geometries.

3.2 Muscle Dynamic Model

Act as the input, sEMG signals get into the muscle dynamics and estimate the current joint moment contribution of the operator based on the resulting muscular forces. The module consists of activation dynamic and contraction dynamic model. Activation dynamic corresponds to the transformation $u(t)$ of sEMG to activation $a(t)$ of contractile and a modified non-linear first-order dynamic model[32, 33] is used in the system, as shown in Equ(1) (2).

$$\frac{da}{at} = \frac{u - a}{\tau_a(a, u)} \qquad (1)$$

Where, u is excitation, a is activation, $\tau_a(a, u)$ is a variable time constant that varies with activation level and whether the muscle activation level is increasing or decreasing.

$$\tau_a(a, u) = \begin{cases} \tau_{act}(0.5 + 1.5a) \\ \dfrac{\tau_{deact}}{0.5 + 1.5a} \end{cases} \qquad (2)$$

Where, τ_{act} is the activation time constant and τ_{deact} is the deactivation time constant. Typical values for activation τ_{act} and deactivation τ_{deact} time constants are 10 ms and 40 ms, respectively.

The raw sEMG signals are acquired and need to do some preprocessing before calculating a (t). The preprocessing mainly includes rectification, filter, smoothing[23]. And during the process of modeling, all parameters are derived through scaling values found in the literature. And in order to do analysis for different persons and muscles conveniently, no dimensional method is implemented, that is, all parameters used in the calculation is normalization value .For instance, all forces and length quantities are normalized to maximum isometric muscle force (F_0^M) and

optimal muscle fiber length (L_0^M), respectively. That is to say, $F_{norm}^M = F^M/F_0^M$ and $L_{norm}^M = L^M/L_0^M$ .The details can refer to [21].

Once we have obtained the activation of the muscle, we can compute the resulting force exerted by the muscle using a muscle model. In this work, a type of Hill-type[34] muscle model that is based on the work of [32] is used to model muscle contraction dynamics. This type of hill muscle tendon model consists of three components: an active contractile element (CE), a passive parallel element (PE) and a passive series element (SE)[35].

3.3 Skeletal Dynamic Model

The skeletal dynamic model is simplified as a Linked Segment Digital Human Model (LS-DHM) in the work. For the sake of generality, the template model LS-DHM is developed firstly, which is based on the model presented in[36],as illustrated in Figure 5(side view and front view).There are three branches in the body frame. The first branch is the right leg, the second is the left leg, and the third is the spine. In the spine branch, there are child branches and so on. So the topological structure of presented LS-DHM is a tree-structure.
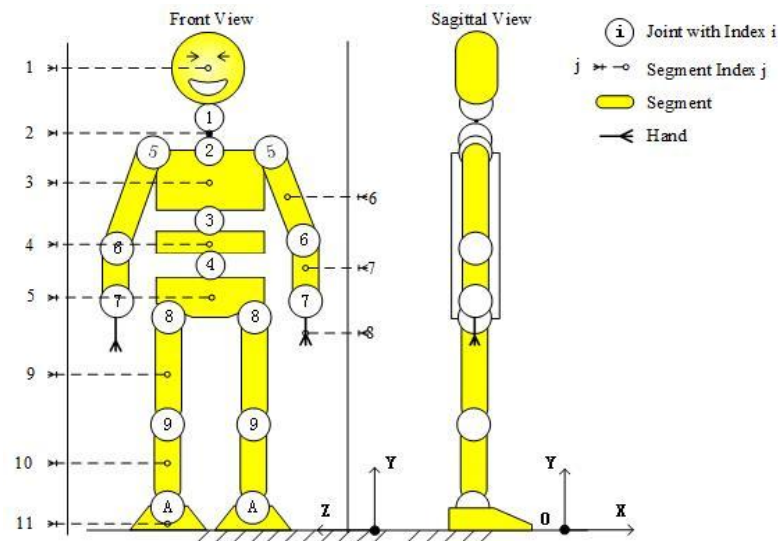

Fig 5:Illustrative view of humanbody decomposition and labeling. Circles with numbers represent kinematic joints. Their corresponding joint type and DOFs are shown in Table 2.

In Figure 5,yellow parts are simplified as rigid segments and assigned unique numbers to index them in program,as shown in Table 1. Circles with numbers represent kinematic joints in Figure 5. Their joint type and degrees of freedom are shown in Table 2. It should be note that the ground is also viewed as the segment in the work, in order to model.

Table 1 Segment Information

Name	Segment Label	Index Id in program
Static ground(SG)	S0	1
Dynamic ground(DG)	D0	2
Head	1	301
Neck	2	300
Thorax	3	31
Abdomen	4	30
Pelvis	5	3
Upper arm	6R/6L	100/200
Forearm	7R/7L	101/201
L/R Hand	8R/8L	102/202
L/R Thigh	9R/9L	10/20
L/R Shank	10R/10L	11/21
L/R Foot	11R/11L	12/22

and process data conveniently, the ground is broken into static ground (SG) and virtual dynamic ground (DG)whose index Id are assigned to 1 and 2, respectively. Based on Table1 and Table2, it is known that the template LS-DHM comprises 19 segments and 46 DOFs.

Table 2 Joint Information

Joint Label	Joint Type(Name)	DOF	Mom Segment Index	Child Segment Index	Id in program
S0	Translation(SG-DG)	3	S0	D0	2
D0	Spherical(DG-Pelvis)	3	D0	5	3
1	Spherical(Neck -Head)	3	2	1	301
2	Spherical(Thorax- Neck)	3	3	2	300
3	Spherical(Abdomen-Thorax)	3	4	3	31
4	Spherical(Pelvis -Abdomen)	3	5	4	30
5R/5L	Spherical(Shoulder)	3×2	3/3	6R/6L	100/200
6R/6L	Revolute(Elbow)	1×2	6R/6L	7R/7L	101/201
7R/7L	Spherical(Hand)	3×2	7R/7L	8R/8L	102/202
8R/8L	Spherical(Hip)	3×2	5/5	9R/9L	10/20
9R/9L	Revolute(Knee)	1×2	9R/9L	10R/10L	11/21
AR/AL	Spherical(Ankle)	3×2	10R/10L	11R/11L	12/22

Note:SG-static ground;DG-dynamic ground;R-right;L-left

Combined with muscle dynamic model, the joint torque exerted by internal muscles can be exported by Equ(3) .Using an inverse dynamic model of LS-DHM derived from equations of motion, a exoskeleton controller can be designed[21].

$$\boldsymbol{M}_k(t) = \sum_{i=1}^{Ne} \boldsymbol{F}_e^i(t) \times \boldsymbol{d}_e^i(t) - \sum_{j=1}^{Nf} \boldsymbol{F}_f^j(t) \times \boldsymbol{d}_f^j(t) \tag{3}$$

Where, k is the joint identifier.for lower limb,$k$could be hip ,knee ,ankle and other joint indetifier.Ne is the number of extensor muscles for k joint;Nf is the number of flexor muscles for k joint;$F_e^i(t)$ is the force produced by$i-th$ extensor muscle at time$t$; $F_f^j(t)$ is force produced by $j-th$ flexor muscle at time$t$;$d_e^i(t)$ and$d_f^j(t)$are moment arm of $i-th$ extensor and $j-th$ flexor muscle at time t, respectively.

The equation of motion is formulated by using Lagrangian dynamics[37], as shown in Equ(4).

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{G}(\boldsymbol{q}) = \boldsymbol{Q}_{nc} \tag{4}$$

Where, $\boldsymbol{q}, \dot{\boldsymbol{q}}, \ddot{\boldsymbol{q}}$ are n × 1 vectors of displacement, velocity and acceleration; $\boldsymbol{M}$ is a pose-dependent n × n inertia matrix comprising body anthropometry, and comes from taking the second derivative the kinetic energy. The next factor$\boldsymbol{C}$ represents what are called the coriolis and centrifugal or coupling effects of the manipulator system on joint torques, which is a n × 1 vector. Note it includes both angular position and velocity terms. The n × 1 $\boldsymbol{G}$ matrix includes forces based on the influence of gravity. $\boldsymbol{Q}_{nc}$ is non-conservative force (internal dissipative forces, any external forces).

4. Closing Remarks And Future Work

The work mainly develops a control system framework based on Neuro-Musculo-Skeletal model. The control framework can make exoskeleton offer assistance to patients during rehabilitation by guiding motions on correct training, rehabilitation trajectories, or give force support to be able to perform certain motions. sEMG is adopted as an indicator of subject's voluntary intention in the system, so it is an intuitive interactive interface between the exoskeleton and operator. Compared to the traditional control by way of an external device, for example, a keypad

or a wheel and so on that has to be manipulated, intuitive interface can reduce operator's mental load, that is, the operator can focus on fulfilling a task with the exoskeleton rather than focus on mere control of the device.

Though the presentation of the framework of control system is orientated towards the lower extremity exoskeleton rehabilitation robot, the method is generic and can be applied to almost any part of the human body. In the future, we'll apply the interface in prototype machine so as to validate and make it better meet the real system requirements.

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Lei Shi received the B.S. and M.S. degrees in mechanical engineering & automation from Xihua University, Chengdu, China, in 2009 and 2012, respectively. He worked into the Chongqing Jiangdong Machinery Co. Ltd as a mechanics engineer in 2012 .A year later, he came to japan to study in Nagasaki Institute of Applied Science, Nagasaki, Japan and he will be expected to get his doctorate in 2016.

His early research career was involved with the mechanical design theory and the study of robot intelligent control method. His current research interests include exoskeleton robot mechanics and control by using bioelectricity (i.e.,sEMG),limb rehabilitation theory and methods by way of robot, human-robot interface and so on.

Among his many honors include the fellowship awarded by Heiwa Nakajima Foundation, Japan; Excellent workshop paper award, the 9th IEEE International Conference on Mobile Ad-hoc and Sensor Networks, Dalian in china; The champion of the 11th FIRA robot soccer competition, Peking in china; The outstanding undergraduate and graduate honors, by Sichuan province education department in china; The china national scholarship two times awarded by china national education department; One Leshan Phoenix Scholarship awarded by LESHAN-PHOENIX Semiconductor Company Limited, china; The Chongqing Alumni Scholarship one time awarded by Xihua University Chong Qing alumni association; Seven consecutive first-class scholarship from Xihua University, Chengdu in china; The gold medal in the 3th Sichuan Division National University Students Machine Innovation Contest, China and so on.