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——Introduction to research on the human upper limb movement

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Preface

Humans are capable of performing impressive variety of movements that range from simple movements, such as looking at an object of interest by turning the head and eyes. Even the very basic ability to produce a stable walking pattern in rough unknown terrain, which is naturally generated by the biological motor control system, is an extremely difficult engineering endeavor.

From a control engineer perspective, the biological motor control system is amazing. Both scientists and clinicians desire to understand normal and pathological movement in human subjects in order to advance basic science and to devise and implement methods to treat and repair dysfunction. Recent research has shown that neural plasticity in the brain has the capability to allow stroke survivors to recover control of motor functions. There has been a continuous effort by engineers to develop robotic systems that can assist and improve the rehabilitation of patients with neuromuscular disabilities.

This book aims to provide a fundamental notion on the human arm control and rehabilitation robot control. This book includes seven chapters, divided into two parts, except the 1st Chapter, the brief introduction of the human motor control and rehabilitation robot. The first part is about the human motor control, including Chapter 2, Chapter 3, Chapter 5 and Chapter 6. The second part is about the rehabilitation robot control, including Chapter 4 and Chapter 7. Chapter 2 is a general introduction of the human motor control system and its mathematical model. In Chapter 3, some control methods according with the human motor are introduces. Chapter 4 describes the relationship between the human motor control and rehabilitation robot, and gives an overview of the rehabilitation robot control. In Chapter 5, two neural networks, the multi-layer perceptron network and the multivariable sliding mode-based fuzzy cerebellar model articulation controller are presented to simulate the upper limb posture control system. In Chapter 6, an evolutionary diagonal recurrent neural network and a sliding-mode-based diagonal recurrent cerebellar model articulation controller are proposed to realize the trajectory tracking control of the upper limb. Chapter 7 introduces the progress on the human-robot control system, Robotic Assisted Upper Extremity Repetitive Therapy.

I have been extremely fortunate in having the help of many people during the course of this project. First, I would like to express my sincere thanks to my advisor Dr. Wang Yongji and Dr. He Jiping, for their continued support and guidance throughout the most stage of the research. Their advice and encouragement are priceless. My deepest appreciation is to both of them.

Dr. Sivakumar and Dr. Jeffrey also helped greatly with the experimentations, giving me many helpful feedbacks.

I am grateful to the unlimited support from my family. I thank them for supporting and encouraging my decision in pursuing my study and giving me their endless love and help.

Last, I thank my friends, colleagues and the numerous people that have helped me in many ways throughout the duration of my work, study and research.

Dedicated To:

My husband, my love, Yong Gao.

My mother Mingxiu Yang and my brother Jian Liu.

Shan Liu

Contents

Chapter 1 Introduction

This chapter describes the motivation for the study of human motor control and rehabilitation robot control, and introduces the subject of this book. The main problem and thesis are stated, the organization of this book is outlined and illustrated, and the contribution of each chapter is briefly specified.

1.1 The Motivation

It is an unfortunate paradox that the advances in medical therapy, care and the increased life expectancy results in an expanding population of physically disabled persons. Despite medical advances in acute stroke care in recent years, more than half of the stroke survivors are still left with moderate to severe disability, imposing an enormous burden on the family and community. Many physically disabled suffer from neuronal damage (e.g., stroke or spinal cord injury) that prohibits or disturbs the control of movements; others are amputees that lack a limb or part of a limb. Conventionally, these programs rely heavily on the experience and manual manipulation of the therapists. Since the number of patients is large, and the treatment is time consuming, the challenge to assist these patients with artificial motor control and artificial limbs is enormous; it requires a multidisciplinary expertise in medicine and engineering, technology to help clinicians improve in effectiveness and efficiency is sorely needed, and it is a big advance if robots can assist in performing treatment. Stroke rehabilitation aims to reduce impairment and disability, to maximize functional independence, and to reintegrate the stroke survivor back into community. Therefore, the importance of stroke rehabilitation can not be overemphasized.

During the last few years, robot-assisted rehabilitation therapy for the stroke patients has been an active research area, which provides repetitive movement exercises and standardized delivery of therapy with the potential of enhancing quantification of the therapeutic process. Rehabilitation technology includes application of robotics devices and external control of muscles. One of the major difficulties in realizing robot-assisted rehabilitation is the controller design. The existing robotic rehabilitation system primarily uses some low-level controllers to assist the movement of the patient's arms. Designing a controller for rehabilitation robot should be difficult, because the external disturbance itself is subjected to another unsolved controller (the human control).

From a control engineer perspective, the biological motor control system is amazing. Even the very basic ability to produce a stable walking pattern in rough unknown terrain, which is naturally generated by the biological motor control system, is an extremely difficult engineering endeavor, as any student who tried to stabilize an inverted pendulum can testify.

Both scientists and clinicians desire to understand normal and pathological movement in human subjects in order to advance basic science and to devise and implement methods to treat and repair dysfunction. Human arm movements are smooth, have generally symmetrical velocity profiles, and can be described well using mathematical models maximizing smoothness. However, even the most common, everyday movement requires numerous skeletal joints and muscles coordinated. Studies of sensorimotor control of movement require measurements from neurons, muscles, and limbs in moving subjects, but these measurements are difficult and limited to only a subset of movement variables. Researchers are forced to make assumptions and inferences about what is happening in the unmeasured parts of the system.

Although the use of control theory to provide insight into neurophysiology has a long history, the complexity associated with control of human arm movements arising from the highly redundant and nonlinear dynamics has not been perfectly resolved. In neurophysiology, how the brain solves this complex control problem remains a mystery. Due to the similarity in the control problem, revealing the neural control mechanism will have a profound impact on the fields of human rehabilitation and robotics.

The main theme of this book is the study of the biological motor control system that is performed by building some models of operation process to understand the arm movement mechanism of the healthy person in the sagittal plane, and to search suitable rehabilitation therapy based on the principles underlying the production of upper limb movement.

Three different reasons motivate the study of human motor control and rehabilitation robot control: the patient, the robot and the brain: (1) Crippled and paralyzed patients can improve their quality of life by artificial limbs or with external stimulation of their muscles. In order to design these aids, we need a deep understanding of the human motor control system. (2) Robots are inferior to people and animals in many aspects. One of the promising directions of improving our technology is by imitating nature and learning from its ingenious solutions. (3) The main outputs of the nervous system are the muscles, and the motor control is the salient evolutionary drive for the development of the brain. Therefore, the act of modeling and understanding the motor control system can be symbolized as polishing the window to the secrets of the brain.

Therefore, as the name of this book implies, we describe some results for learning motor control of redundant systems, apply some control models to the rehabilitation therapy and examine their performances.

1.2 The main problem and the main thesis

Motor control is the study of humans' and animals' movements and postures. It deals with how the central nervous system processes sensory information to select a suitable movement trajectory and how it organizes the individual muscle to perform the selected trajectory. The movements may be either genetically-defined such as reflexes, or voluntary-learned skill such as playing a piano. The former refer to the movements that result from biological development and the latter refer to the movements that are learned during the learning process.

Strictly speaking, to understand why or how a human subject produces a movement with certain characteristics, we would first need a good understanding of how the environment and goal are perceived, what the motivational or emotional state of the subject is, what cognitive process (and in particular reasoning about the physics of the world) are involved, what the "preferred" patterns of movement are, etc. clearly motor control could not make much progress if researchers waited for satisfactory answers to these questions. The way around such complications is usually the following: postulate a rather strict separation between motor control proper and the rest of the processing involved in movement production, i.e. assume the rest of the brain is somehow figuring out in sufficient detail what needs to be done (constructing a plan), and the motor system is responsible for implementing that plan.

Why is it necessary to emphasize such seemingly obvious fact? Indeed, although human movement appears to be a relatively simple attribute, it is a very complex and challenging phenomenon to understand. Over the last century, many researchers in different disciplines have made an extensive effort to discover how the central nervous system (CNS) controls an action and how it learns a new movement. What the literature provides just are numerous descriptions of geometric properties of movement trajectories, sequences of muscle activations, etc., with rather sparse explanations of how these movement characteristics arise in the process of trying to achieve a certain goal.

The general question is how the human motor control system learns to master many possible solutions, how it chooses a single solution for the specific execution of a given motor task, and how the learning and choosing process is converted into some fit rehabilitation therapies. We address some aspects of this question in this work and in order to describe them properly we have to narrow the scope of the problem.

We concentrate on close-loop back-forward control. This view is justified for natural or slow movements where there is some time for effective use of the sensory information in spite of the large delays in the biological system.

In this book, we examine some different approaches to analysis the motor control problem in the sagittal plane. The first puts the emphasis on the dynamic posture control of the human arm; the second emphasized the trajectories tracking control of the dynamic system, and the third apart deals with the control problem of rehabilitation robot. We suggest that there is no contradiction between these approaches since we apply them in different goals.

We use engineering and mathematical tools in order to develop some control algorithms from the human motor system. In this combination we aim to contribute to three disciplines: to the biological motor control research by introducing rigorous definitions and analyzable models, to the rehabilitation medical engineering and to control engineering by new ideas of using the system dynamics and exploiting redundancy.

1.3 Organization of the book

The rest of this book is organized as follows (see also Figure 1.1):

Chapter 2 is a general description of the human motor control system from both biological and engineering points of view. The dynamic characteristic of the human arm in the sagittal plane is analyzed, and then the arm is modeled as a musculoskeletal model with two degrees of freedom and six muscles.

Chapter 3 describes the control problem and the approaches that are suggested in order to learn to control the human motor control systems.

Chapter 4 discusses the relationship between the human motor learning and rehabilitation robot control, and introduces some control strategies for rehabilitation robot.

Chapter 5 focuses on the posture control algorithms of the human arm. The kernel idea of the algorithms is explained and two control methods are simulated in order to demonstrate the effectiveness in the musculoskeletal model. A multilayer perceptron network containing feed-forward and feedback control modes is used. Based on cerebellar model articulation controller, fuzzy control, sliding mode control scheme, and the dynamic characteristic and the control requirement of the human arm, a sliding-mode-based fuzzy cerebellar model articulation controller is investigated.

Chapter 6 presents some dynamic controllers for trajectories tracking control of the human arm system. An evolutionary diagonal recurrent neural network is presented for trajectory tracking control of the human arm in the sagittal plane, in which hybrid genetic algorithm and evolutionary program strategy is applied to optimize the network architecture and an adaptive dynamic back propagation algorithm with momentum is used to obtain the network weights, Lyapunov theory can be implemented to guarantee the convergence of the control system. And trajectory tracking control in real time of the human arm in the sagittal plane is further discussed. A sliding-mode-based diagonal recurrent cerebellar model articulation controller is presented, in which recurrent units are introduced in the association layer to add the dynamic mapping ability of the network.

Chapter 7 introduced the results of the posture control and the trajectory tracking control of the rehabilitation robot for the upper terminal, and discusses some problems in applying the control algorithms into rehabilitation robots. The functions of patient's active action are designed depending on the motion ability of their arms.

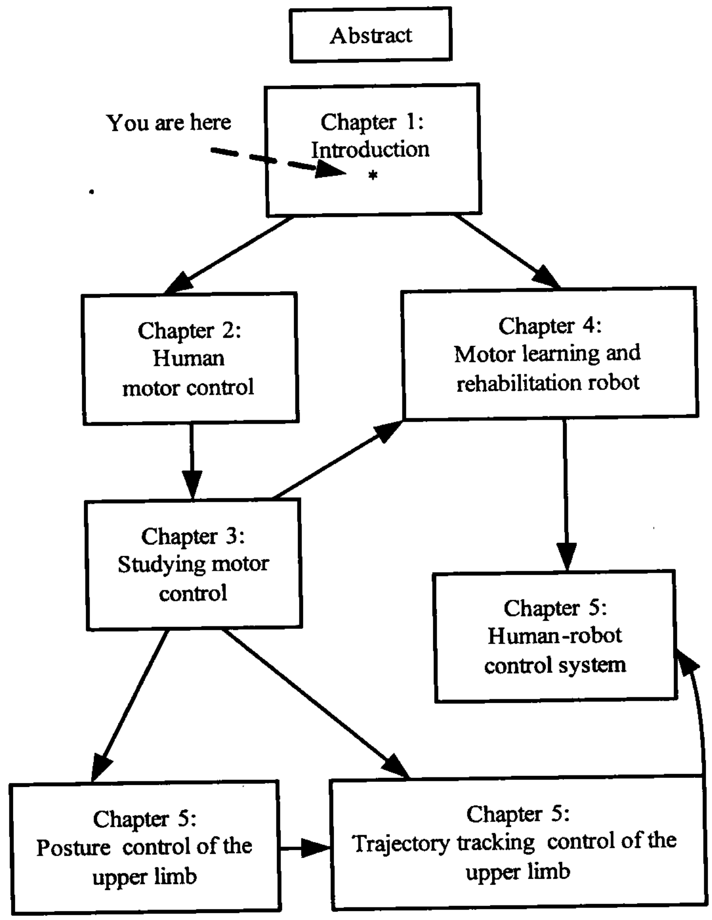

Figure 1.1 The structure of this book. The arrows represent possible sequences of reading.

Chapter 2 Human motor control

This chapter is a survey of some relevant topics from the current state of the art in the engineering research of human motor control. It briefly describes the anatomy and physiology of human motor control, some analytic and engineering tools for the human motor control system, its characteristic and mathematical model.

2.1 Introduction

The study of motor control is fundamentally the study of sensorimotor transformations. For the motor control system to move its effectors to apply forces on objects in the world or to position its sensors with respect to objects in the world, it must coordinate a variety of forms of sensory and motor data. These data are generally in different formats and may refer to the same entities but in different coordinate systems. Transformations between these coordinate systems allow motor and sensory data to be related, closing the sensorimotor loop. Equally fundamental is the fact that the motor control system operates with dynamical systems, whose behavior depends on the way energy is stored and transformed. The study of motor control is therefore also the study of dynamics. These two interrelated issues (sensorimotor transformations and dynamics) underlie much of the research in the area of motor control.

In order to determine the behavior of the system in response to this input, an additional set of variables, called state variables, must also be known. For example, in a robotic model of the arm the motor command would represent the torques generated around the joints and the state variables would be the joint angles and angular velocities. Taken together, the inputs and the state variables are sufficient to determine the future behavior of the system. It is unrealistic, however, to assume that the controller in the central nervous system (CNS) has direct access to the state of the system that it is controlling; rather, we generally assume that the controller has access to a sensory feedback signal that is a function of the state. This signal is treated as the output of the abstract computational system.

In a very simplified manner the human motor control system can described as an interaction of three systems: Nervous, Muscular, and Skeletal. The nervous system integrates sensory information about the environment and about the state of the muscular and skeletal systems; it issues motor commands to the muscles that generate torques upon the skeletal system, which interact with gravity and external forces.

2.2 The biological system

There is a widespread research trying to model and understand the biological motor control system. The motivation and applications of this research come from various disciplines such as medical study, sports research, engineering, and pure intellectual curiosity. In this section, we briefly describe the anatomy and physiology of the biological motor system from an engineering point of view. The aim of this section is to give a general view for the layman.

2.1.1 The central nervous system

The mammalian nervous system is a complex network of neurons that receive, store, and process afferent information to control its and other body systems. It is divided into the CNS and peripheral nervous system (PNS). The CNS is comprised of the brain (cortex, cerebellum, and brainstem) and spinal cord. The PNS contains motor and sensory neurons and their respective sensory receptors. Neural impulses are transmitted along nerve fibers (or axons) as "action potentials", which are temporary reversals of electrical polarity across the neuron plasma membrane.

From an engineering perspective the motor system can be considered as a system whose inputs are the motor commands emanating from the controller within the CNS (Figure 2.1).

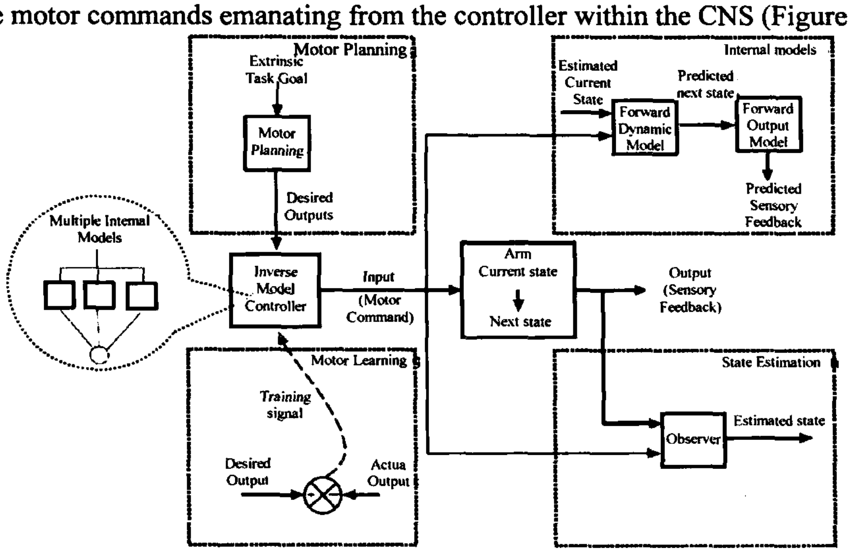

Figure 2.1 The motor system is shown schematically along with the five themes of motor control. The motor system (center) has inputs (the motor commands) which causes it to change its states and produce an output (the sensory feedback). For clarity not all lines are shown.

The central nervous system is a general term that virtually includes all the brain. In this work we do not wish to review all the massive literature about the structure of the CNS, we just mention the basic structures that have an important role in the control of movements. The primary motor cortex contains a detailed map of the muscles in the body and can send a specific command to small groups of muscles. A similar sensory map is located in the primary somatic sensory cortex. This notion of mapping was modeled in artificial neural networks for robotics control. The firing rate of some neurons in the motor cortex can also indicate the direction of the planned movement. The cerebellum also has some internal maps, and it has a role in coordinating and timing of movements. The cerebellum is also hypothesized to contain the inverse and forward models of the musculoskeletal system that are supposed to assist in the generation of the motor command. The cerebellum has a regular structure and many computational models for its operation were suggested. There are many other areas such as the basal ganglia that have an important role in the execution of human motor control; Figure 2.2 is a rough sketch that describes the main areas and their interconnections.

The specific role of each part of the CNS in motor control is still under research and although vast literature and information is available, we still do not clearly understand its operation.

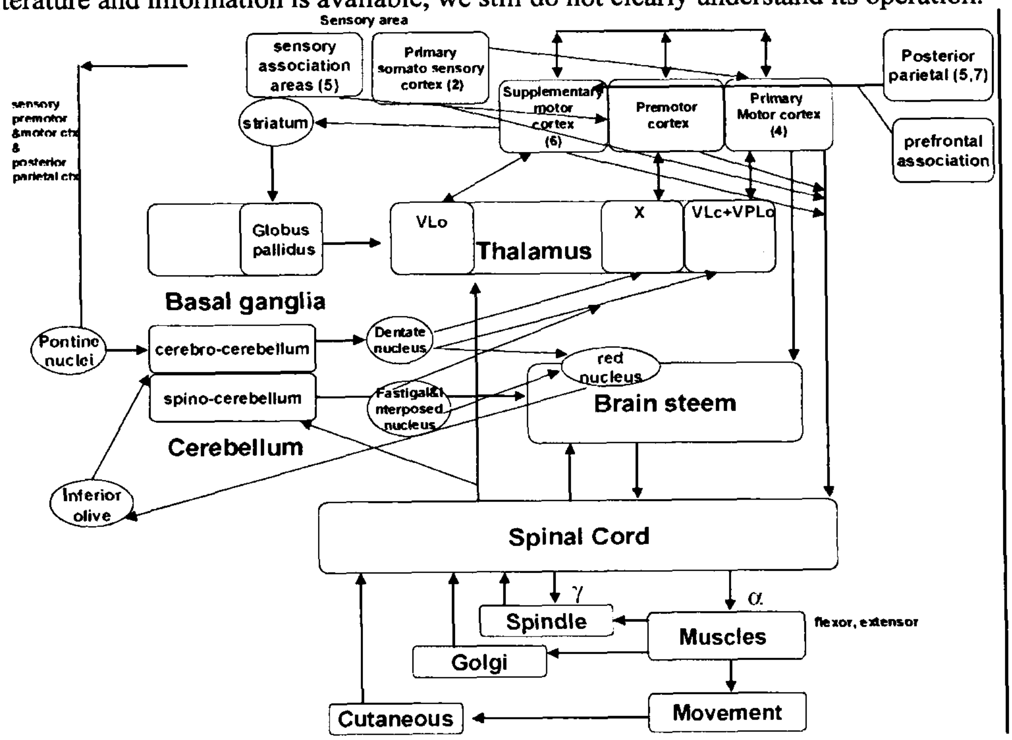

Figure 2.2 A schematic description of the main neural structures that participate in the execution of human motor control. It is definitely incomplete, however, it dose give a general idea of the main pathways.

2.2.2 Proprioceptors and the spinal cord

There are various kinds of proprioceptors that send sensory information to the spinal cord and to the CNS. The muscle spindle senses the length and the extension velocity of the muscle. The Golgi tendon organ senses the force in the muscle, and there are receptors in the joint and on the skin that send further information about the status of the motor system. This information is