Control of Movements in Humans:

Systems and Mechanisms

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PREFACE

The textbook "Control of Movements in Humans: Systems and Mechanisms" was prepared for master students enrolled into the program Mechatronics for rehabilitation as an extract from the first three chapters of the book "Control of Movement for the Humans with Disabilities" published originally by Springer, London in 2000, and written by the same authors[1]. The textbook comprises the basics of the organization of the complex human skeletal systems driven by highly redundant muscular systems and controlled by a large network of sensory-motor systems in man.[2]

The textbook includes short summary of the diseases and injuries that are affecting the sensory-motor functions and that are relevant for rehabilitation.

The contents of the book aims to provide a coherent view that would allow engineers and clinicians interested in neurorehabilitation of humans with special needs (e.g., patients after cerebro-vascular accident, spinal cord injury or similar disease/injury) to have a common dictionary and better understand each other when designing methods for rehabilitation.

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[2] Several illustrations in this book are from the open access source: http://cnx.org/

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1. SYSTEMS AND MECHANISMS FOR CONTROL OF HUMAN MOVEMENT

The question of which mechanisms are controlled and how the nervous system control the movement has been investigated extensively and discussed at practically every stage of the history of motor control studies [e.g., Bernstein 1967; Granit, 1970; Arbib, 1980; Stein, 1982; Latash, 1993].

Bernstein [1967] was the first to address the motor control system as a "black box" with a virtually unknown internal structure that must control an effector apparatus of multiple links and degrees of freedom [Latash, 1993] and his experimental studies addressed the mapping of input and output variables of the motor system. The conclusions are the following: 1) the control system is a hierarchical structure with several levels; 2) feedback loops connect the lower levels with the higher ones in order to tune the descending (efferent) commands; 3) time delays in the feedback loops require combining feedback and predictive, open-loop modes of control; and 4) the number of degrees of freedom in a motor system is always excessive, and the process of control can be regarded as overcoming the ambiguity caused by redundant degrees of freedom.

The hierarchical scheme should not be considered a reflection of actual organization of the central nervous system controlling movement. It is rather a simplified model (Figure 1.1) that appears helpful for understanding some phenomena that are of interest for controlling artificial extremities and neuroprostheses. The upper level in the scheme is associated with production of a "voluntary central motor command," in most cases a combination of conscious and unconscious decision. There is an interface that “translates smart and experienced” commands to the lower level, which now distributes control signals to the appropriate actuators controlling a single or more joints. The actuators receive proprioceptive information from the afferent sources, combine it with information from the descending sources and generate relevant controls to drive actuators. There is a constant exchange of information between lower and upper levels of control.

The engineering methods include two phases: defining the problem and solving of the defined problem. Controlling movement seems as an already defined problem: identify structures that are involved in movement, and find the relationship between them. Solving the problem is a much more difficult task, since there are no engineering methods that are fully suitable for interfacing natural control mechanisms. A general scheme, which seems to be promising, that authors are advocating relies on learned lessons from motor control studies and integrating those with modern computing and other technological advancements.

In order to be able to design artificial control it is essential to understand the richness of biological mechanisms and tissues that are involved in movement. As it will be presented the hierarchical, yet with many parallel pathways, self-organized natural control system that relies on extreme redundancy of both the sensory and motor systems is what automatic control is aiming at in the field of rehabilitation technology.

1.1 Neuroanatomical Basis for Control of Movement

Human motor performance appears to be remarkably flexible and easy. Yet, the underlying neuronal operations are only vaguely understood, even for well studied movements [Jeannerod, 1988]. Given the flexibility and the large number of degrees of freedom in the motor system, one might wonder what happens for simple motor tasks such as grasping a nearby small object. An object in the same position can be grasped in various ways by different combinations of joint angles in wrist, elbow, and shoulder, and by using different grasps (e.g., palmar, pinch). Is the same motor task realized by movement that are chosen randomly from the available repertoire, or is there a consistent reproducible patterns of behavior?

If the latter, can we then understand the constraints that are imposed in order to reproduce the same motor behavior every time when we repeat the same motor task [Bernstein, 1967]? The spectrum of functional motions, which a human can master during his lifetime, is impressive. Most of these movements are learned in early childhood, but the repertoire is increased on a daily basis if so required. As far as is known at present, this is possible because each functional motion relies upon perceptuo-motor coordination that involves three major components: the intake of sensory information, the internal coding of this information in a format that is adequate for driving a motor action, and the generation of movement itself. The last statement supports several interesting findings about the organization of the motor control with respect to the activity of neural cells within the premotor and motor cortex [e.g., Georgopoulos et al., 1982, 1993].

Since the work of Evarts [1966] it has been possible to monitor the activity of cells in the motor cortex of exhibiting monkeys. Initially, studies were restricted to simple movements about a joint, but Georgopoulos and his colleagues have extended these studies to reaching movements in two and three dimensional space [Georgopoulos et al., 1983b]. Many of these findings were confirmed and expanded at later date [Schwartz et al., 1988]. These results suggest that the motor cortex is concerned with the general planning of the direction of movement, rather than the details of the load or the muscles that will have to be activated to produce a desired end point.

Clearly, these signals must be transformed to produce the right movements under various conditions, but the mechanisms underlying these transformations remain unknown. Some aspects must arise from the pattern of anatomical connections from the motor cortex to the spinal cord and others from the variety of input that impinges on the motor neurons from sensory pathways and from other brain centers involved in the control of movement. Nonetheless, the generality of the signals available at the level of the motor cortex is intriguing. If one could record chronically from a number of cells in the human motor cortex, this technique might be used to control a prosthesis or for functional electrical stimulation of paralyzed muscles.

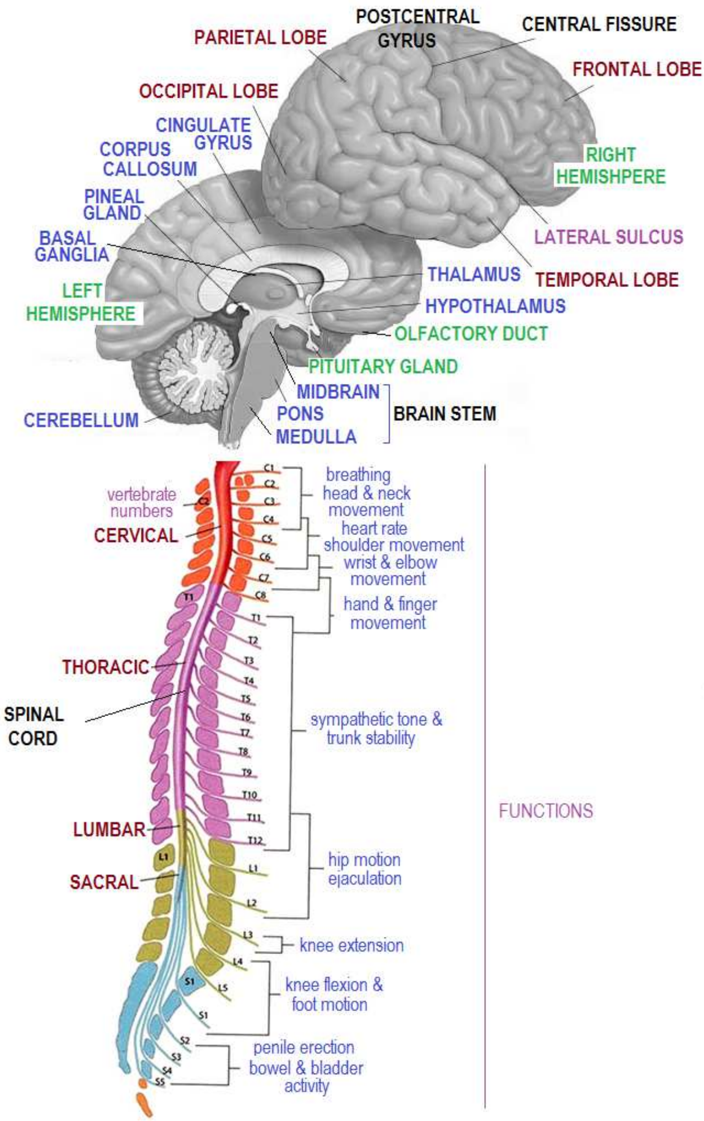

Fig. 1.1: The major division of the central nervous system: brain and spinal cord. The top portion is a brain with the following parts: cerebral hemispheres, diencephalon, midbrain, pons, medulla and spinal cord.The bottom portion showd the spinal cord and the fucntions regulated from specific regions.

In this chapter we present the organization of both the nervous and muscular systems that is necessary for understanding of the complexity of controlling rehabilitation systems that restore movement.

A relatively simple set of functional and organizational principles governs the architecture of the nervous system, although that is in itself complex. These principles provide a foundation for understanding the control of movement. A review of the parts of the central nervous system considering their functional relevance to movement is given in this section.

1.1.1 The Central Nervous System

The brain and spinal cord are organized along the long axis of the human. The long axis of the nervous system bends at the juncture between the brain stem and the region just above it, the diencephalon (Figure 1.1). The central nervous system

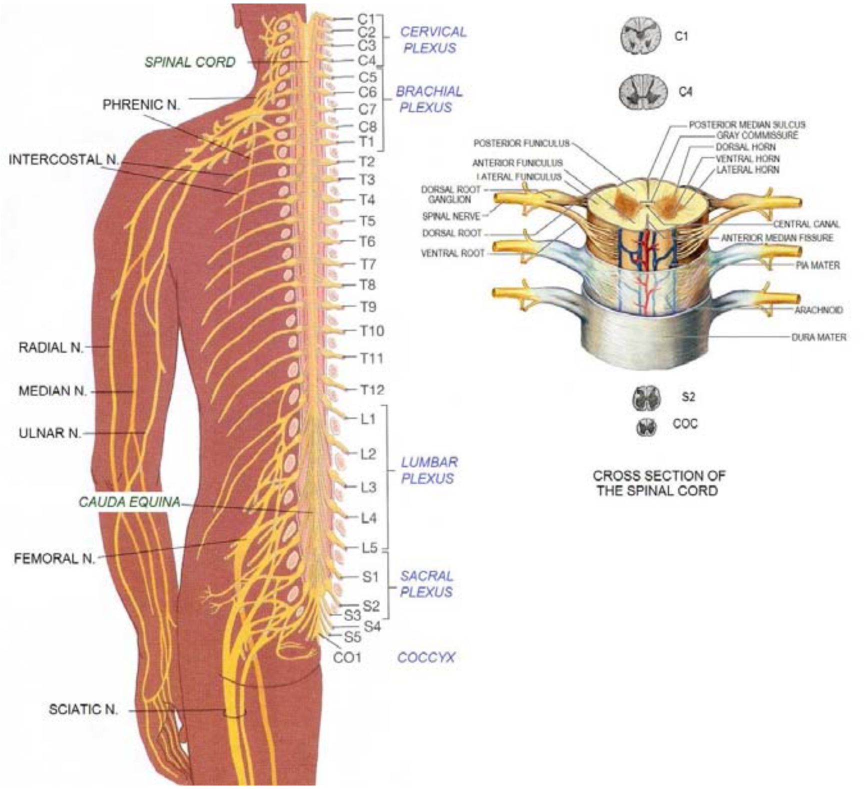

Fig. 1.2: Cross section of the spinal cord (top left), cauda equina (bottom left) and lateral view of the spinal cord and its location in the spinal canal (right panel).

consists of six main regions: the spinal cord, medula oblongata, the pons, the midbrain, the diencephalon and the cerebral hemispheres.

The spinal cord, the most caudal part of the central nervous system receives information from the skin, joints, and muscles in the trunk and limbs, and it is the final station for issuing commands for movement. In the spinal cord (Figure 1.2) there is an orderly arrangement of motor and sensory nuclei, controlling the limbs and trunk. In addition to nuclei, the spinal cord contains afferent pathways for sensory information to flow to the brain and efferent pathways for commands necessary for motor control to descend from the brain to motor neurons. Afferent pathways carry information to the central nervous system; efferent pathways carry commands out of the central nervous system. The spinal cord also receives sensory information from the internal organs and controls many autonomic functions. The spinal cord has several functions: 1) it is a relay for sensory information; 2) it carries both ascending afferent pathways and descending motor tracts that serve the trunk and limbs; and 3) it contains the interneurons and motor neurons that control the movements of the trunk and the limbs.

A transverse section of the spinal cord shows that it is organized into a butterfly-shaped central gray area, where the cell bodies of spinal neurons are located, and a surrounding region of the white matter that contains afferent and efferent axons, most of which are myelinated (Figs. 1.2 and 1.3).

The gray matter is divided into a dorsal horn, an intermediate zone, and a ventral horn (Figure 1.3). Each of these zones can be subdivided into nuclei. Six nuclei are particularly important: 1) the marginal zone, which is located in the outermost region of the dorsal horn and serves as an important relay for pain and temperature sense; 2) the substantia gelatinosa of the dorsal horn, which integrates afferent information from unmyelinated afferent fibers; 3) the nucleus proprius, which is located in the base of the dorsal horn and integrates sensory information with information that descends from the brain; 4) Clarke's nucleus, or cell column, which lies in the intermediate zone and relays information about limb position and movement to the cerebellum; 5) the intermediolateral nucleus, or cell column, which is located in the intermediate zone and contains autonomic preganglionic neurons; and 6) the motor nuclei of the ventral horn, which contain motorneurons that innervate the skeletal muscles.

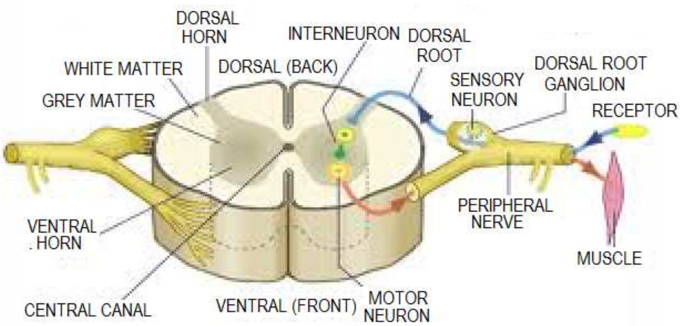

Fig. 1.3: The cross-sectional view of the spinal cord. The gray matter is divided into the dorsal and ventral horns, which are concerned respectively with receiving sensory and sending motor output of the cord.

The white matter is divided into three bilaterally paired columns, or funiculi: 1) the dorsal columns, which lie medial to the dorsal horns, contain axons that relay somatic sensory information to the medulla; 2) the lateral columns, which lie lateral to the spinal gray matter, contain axons descending from the brain that control sensory, motor, and autonomic functions as well as somatic sensory pathways ascending to the brain; and 3) the ventral columns, which lie medial to the ventral horns, contain axons of the motor neurons that control the axial muscles of the body.

In addition to the major ascending (sensory) and descending (motor) tracts that make up these columns, the spinal cord contains pathways for the axons of propriospinal neurons that connect different regions of the spinal cord.

Dorsal root fibers, whose cell bodies are in the dorsal root ganglia, enter the spinal cord at its dorsolateral margin.

The largest cells have large myelinated axons that are up to 20 μm in diameter, and these fibers enter the spinal cord medially. The smallest cells have small unmyelinated axons less than 1 μm in diameter, which enter the spinal cord more laterally. After entering the spinal cord, the dorsal root fibers branch to ascend and descend in the white matter and arborize in the gray matter. Some ascending branches project to the medulla. The axons from large and small cells, carrying information from different somatic modalities, have different distributions.

There are two major ascending systems for somatic sensation: the dorsal column-medial lemniscal system, and the anterolateral system. These systems relay afferent information to the brain for perception, arousal, and motor control.

The dorsal columns relay information about somatic stimuli to the medulla. This tract runs ipsilaterally in the spinal cord. It originates both from the ascending axons of large-diameter primary afferent fibers and from the axons of neurons in the dorsal horn.

The axons of the dorsal columns ascend to the caudal medulla where they synapse on the cells of the dorsal column nuclei. From there, by means of the medial lemniscus, a brain stem pathway, information is relayed first to the contralateral thalamus and then to the anterior parietal lobe. The dorsal column-medial lemniscal system mediates tactile sensation, including vibration sense, and proprioception from the contralateral side of the body. Proprioceptive information from the contralateral arm ascends in the dorsal column, whereas information from the contralateral leg ascends in the dorsal part of the lateral column, a region termed the dorsolateral funiculus.

The anterolateral system carries information chiefly about pain and temperature. It originates from cells in the dorsal horn. These cells send their axons to the contralateral side of the spinal cord and ascend in the anterolateral portion of the lateral column. In addition to pain and temperature, this ascending system also relays some tactile information. Parallel pathways are advantageous for two reasons: they add subtlety and richness to a perceptual experience by allowing the same information to be handled in different ways, and they offer a measure of insurance. If one pathway is damaged, the others can provide residual perceptual capability.

The proprioceptive information from the limbs is used at least in two ways. First, it mediates reflex responses through a local circuit in the spinal cord. Some of this information is relayed through the spinocerebellar pathways to the cerebellum, which modulates the actions of reflexes and voluntary movement.

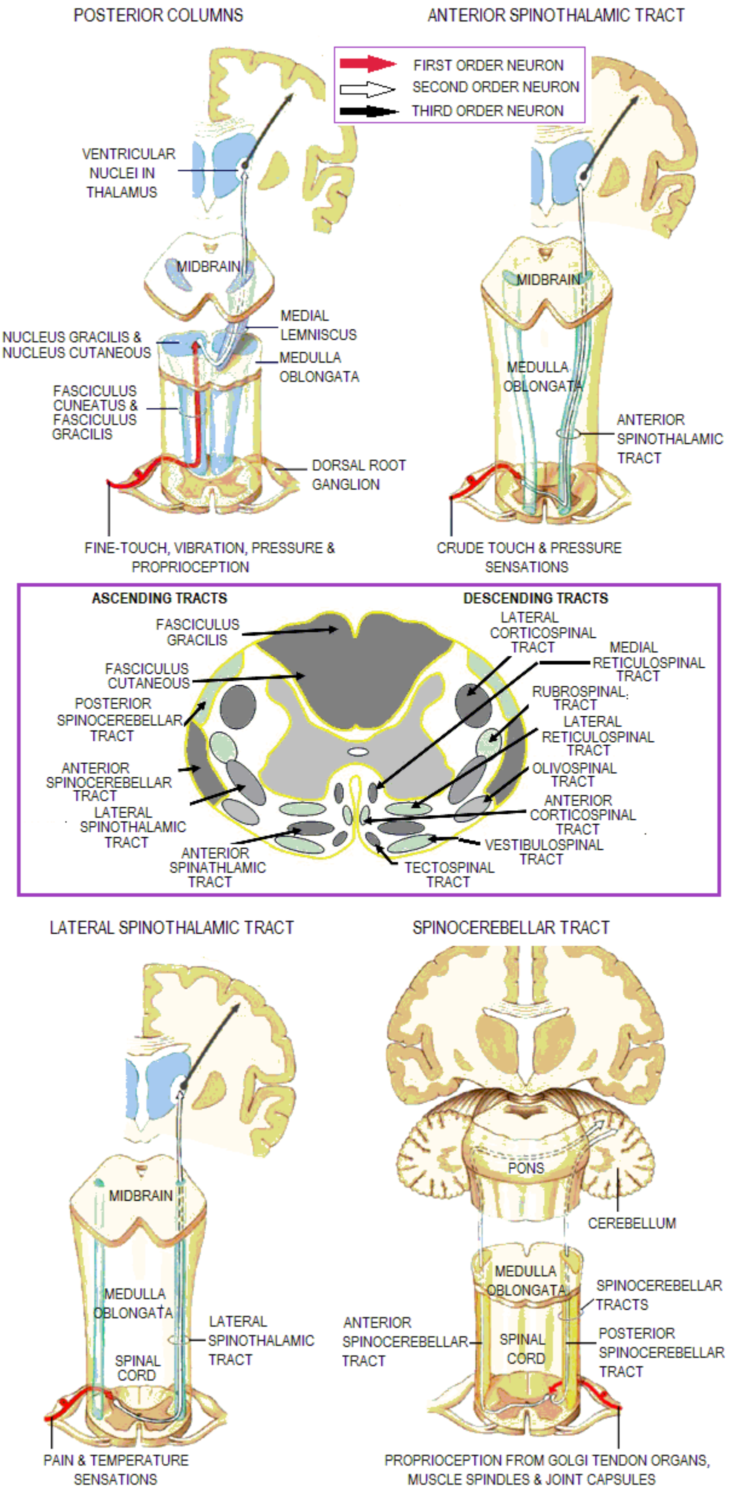

Fig. 1.4: Ascending tracts: posterior column, anterior and lateral spinothalaim and spinocerebellar tracts.