Chapter 5

Physiological Motor Control

INTRODUCTION

Body movements are controlled by the Central Nervous System (CNS) (figure 5-1), which is a complex hierarchically structured neural network. The CNS being conceived as the controller of body movement, is the focus of the current chapter.

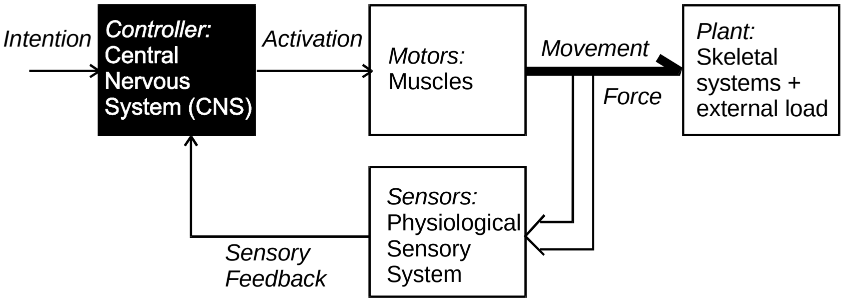

Figure 5-1 *Schematic block diagram of the human motor control system. Subject of this chapter is the controller, being the Central Nervous System (CNS).*

OBJECTIVES

This chapter will

- present the Central Nervous System as the controller of body movements
- present the hierarchical structure of the CNS
- describe the importance of reflexive control for ensuring optimal interaction with the environment

CONTENT

5.1 Functional overview of motor control by central nervous system

The Central Nervous System (CNS) is the control system for the human motor function. It acts as a hierarchical control system (figure 5-2).

At the *cortical level* motor control decisions are consciously made, at the level of the *brain stem* the control input from the cortical level is integrated with feedback sensory signals from the periphery. The control at this level is assumed to include predictive control using some kind of internal model of the motor system. At the *spinal level* the control of muscle activation is adjusted via the reflexive system to optimally interact with the environment and reject disturbances.

In the next paragraph the low level reflexive control will be further discussed. Also, the control of this low level system from a higher level will be presented, consisting of feed-forward control of learned tasks and modulation of the reflexive system in order to achieve optimal interaction with the environment under different conditions.

Additional reading concerning reflexive impedance control can be found in the paper of van der Helm and Brouwn, Proceedings of the International Biomechatronics Workshop (Van der Helm et al. 1999)

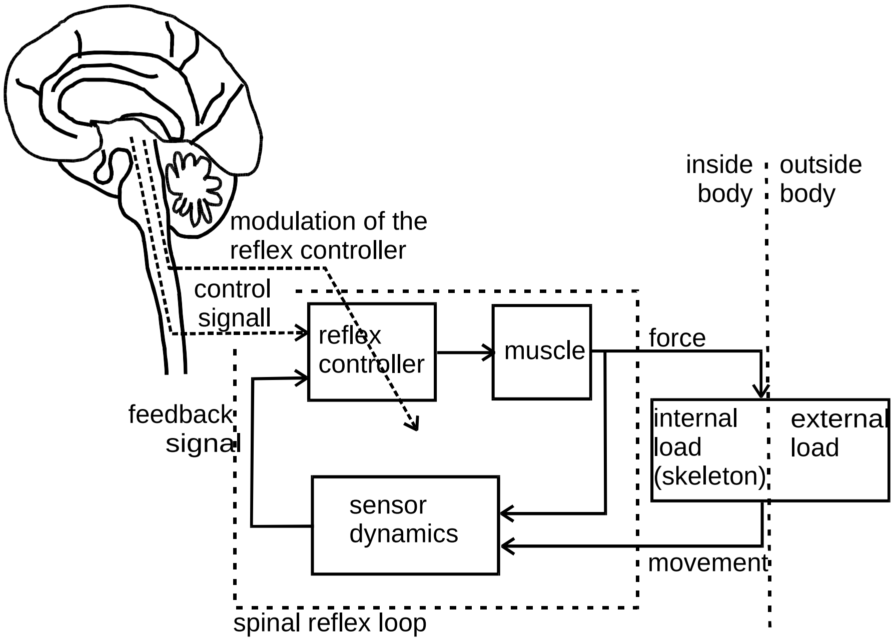

Figure 5-2 *The Central Nervous System (CNS) can be conceived as an hierarchical controller for the human motor function.*

5.3. Low level reflexive motor control

Muscles are activated by efferent signals (from spine to periphery) generated by the alpha motor neurons in the spine (figure 5-3). The motor neurons receive inputs from higher levels of the CNS, which can be conceived as reference motor activation patterns. The actual muscle activation patterns generated by the α-motor neurons depend on both these central reference patterns as well as on feedback sensory signals received from the periphery (afferent signals). Peripheral sensory inputs can even trigger motor responses irrespective of the central inputs (reflexes). Thus, a feedback control system is formed (figure 5-3). It should be noted that the signal paths between spinal cord and muscle are associated with a transportation delay, which is due to the limited conduction velocities of the signals along the nerve fibers, signal transfer between neurons and the activation processes in the neurons ("signal processing"). The conduction delays depend on the distance between spine and muscle and on the diameter of the nerve fibers (small diameter nerve fibers conduct slower than large diameter nerve fibers). The conduction velocity is approximately 50 m/s (Berne et al. 1993). The total delay in a reflex loop depends on the distance between spinal cord and muscle. It is approximately 60 ms for shank muscles (Veltink et al. 2000).

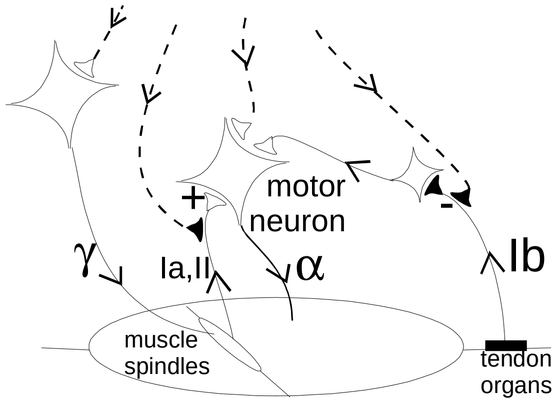

Figure 5-3 Motor servo system. Reference and modulating inputs from higher centres are indicated with dashed lines.

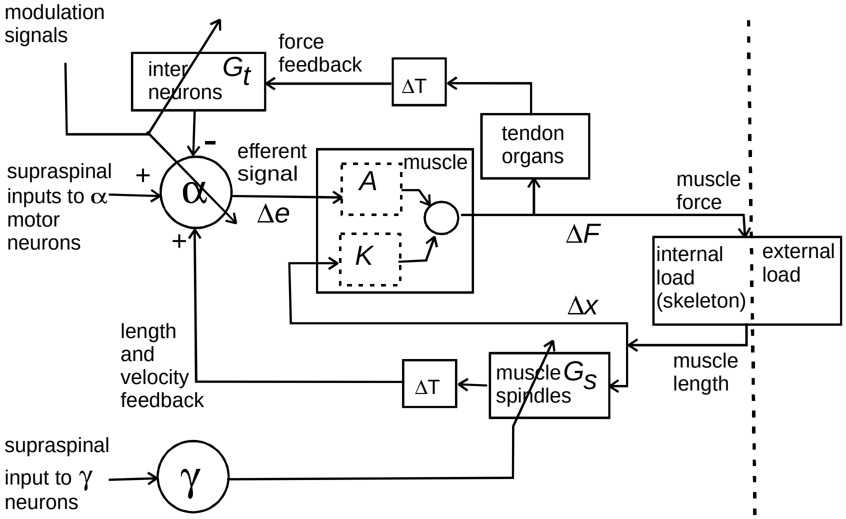

Figure 5-4 Motor servo system (after Houk, 1974; see further: (Van der Helm et al. 2000), (Van der Helm et al. 1999))

The sensory feedback pathways are modulated by central inputs (figures 5-2 and 5-4). The gamma system modulates the functioning of the spindles (see chapter 4). It ensures that the spindles are constantly working in their operating range for all muscle lenghts and movements (see chapter 4). More centrally, the influence of the movement feedback (the Ia and II afferents from the spindles) on the activity of the alpha motor neurons is modulated by central inputs to these sensory pathways before they connect with the motor neuron pool (presynaptic) or at the motor neuron pool (post synaptic). Also, the influence of the force feedback is modulated by central inputs to the interneurons between the Ib afferents from the tendon organs and the motor neurons. In general, these central inputs modulate the movement and force feedback in a non-linear manner (Kernell et al. 1990). However, in many studies, these influences are in first approximation considered as being linear, influencing the gain of the position and force feedback loops (postsynaptic inhibition of the position feedback and the modulating input to the interneurons of the force feedback) (see example 5-1). The gains of the velocity, position and force feedback influence the mechanical *impedance* (relation between movement and moment) at the joint on which the muscle acts. By varying these gains, the impedance of the joint can be varied from stiff (large moment change with external imposed movements) to compliant (small moment change with external imposed movements) and also the damping of the joint can be set. Additionally, if the joint is stiff, the position and velocity can be controlled using the movement feedback, for a compliant joint the moment can be controlled using the force feedback. This control is called *impedance control* (e.g. (Lemay et al. 1998), (Van der Helm et al. 2000), (Van der Helm et al. 1999)). This topic is further discussed in the course on Motor Control (second trimester).

EXAMPLE 5-1 LINEARIZED AND STATIC MODEL OF THE MOTOR SERVO SYSTEM.

Consider the behavior of the motor servo under static conditions, meaning that the positions and forces do not vary or only vary slowly with time. Under this condition, the dynamics of the subsystems and the conduction delays in the signal transmissions between spine and muscles need not be taken into account.

Assume: the efferent signal (Δe) changes linearly with the length signal (Δx) from the spindles (gain G_s) and the force signal from the tendon organs (gain G_t):

$$\Delta e = G_s \Delta x - G_t \Delta F \tag{5.1}$$

Furthermore, assume that muscle force changes linearly with a change in the efferent signal (Δe) (gain *A*) and also linearly with a change of muscle length (Δx)

$$\Delta F = A\Delta e + K\Delta x \tag{5.2}$$

The resulting effective muscle stiffness is:

$$S = \frac{\Delta F}{\Delta x} = \frac{K + AG_s}{1 + AG_t} \tag{5.3}$$

<u>Consider the following special cases:</u>

If $G_s << \frac{K}{A}$ and $G_t << \frac{1}{A}$: $S = K$ (the intrinsic stiffness of the muscle)

If $G_t << \frac{1}{A}$: : $S = K + AG_s$

If $AG_s >> K$ and $AG_t >> 1$: $S = \frac{G_s}{G_t}$ (effective stiffness is not influenced by the intrinsic stiffness of the muscle)

If we consider the motor servo system under dynamic conditions, we have to take into account the dynamics of the subsystems and the conduction delays in the signal transmission between spinal cord and muscle (Van der Helm et al. 2000). Furthermore, it should be noted that most of the feedback paths of the spinal reflexive systems have nonlinear characteristics. For example, the velocity feedback only provides signals to the motor neurons above a certain velocity threshold (figure 5-5). This offset is modulated by supraspinal signals (Sinkjaer et al. 1996; Sinkjaer 1997). It has been shown that these velocity offsets vary during gait and are different for sitting than for standing (Sinkjaer et al. 1996; Sinkjaer 1997).

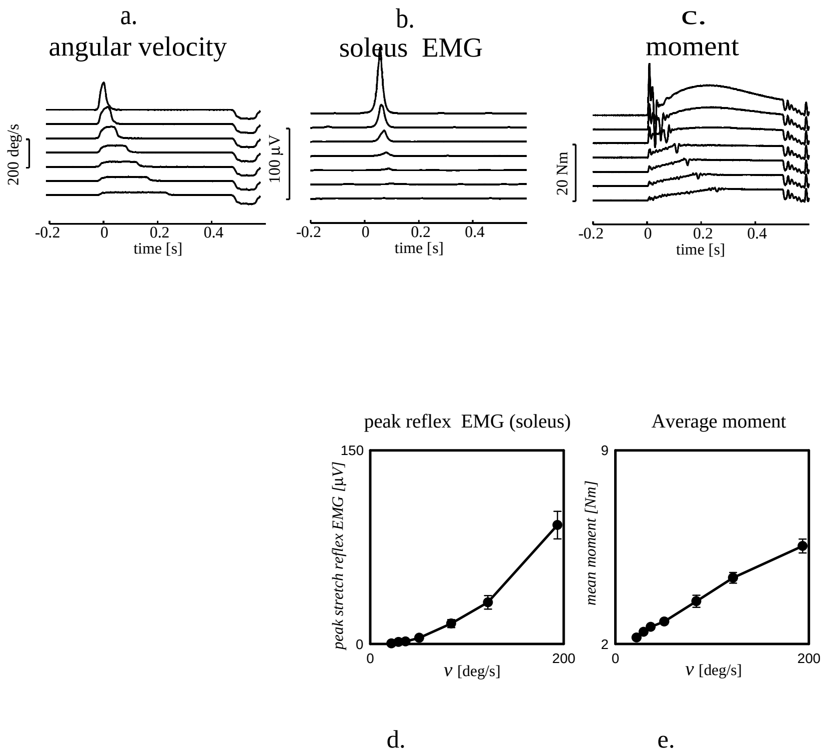

Figure 5-5 *Stretch reflexes are elicited above a velocity threshold. The figure shows stretch reflexes in the soleus (part of calf muscle) for ankle angular perturbations of several velocities (a). (b) soleus EMG responses, (c) ankle moment responses, (d) peak stretch reflex EMG in soleus as a function of ankle angular velocity, (e) average ankle moment as a function of ankle angular velocity (Veltink et al. 2000).*

5.4. Modulation of reflexes

As stated, the dynamic characteristics of the peripheral sensory feedback control can be modulated by central inputs. These modulating inputs may vary during a task. For example, it has been shown that the sensitivity of the stretch reflex varies depending on task (Nielsen et al. 1998), the phase of gait (Sinkjaer et al. 1996), (Kearney et al. 1999) (figure 5-6) and expected perturbations. This modulation depending on the phase of gait is functionally important, because the load on the muscles and joints of the leg are very different during the swing phase compared to the stance phase, and therefore, the optimal output impedance at the joints should be different. The reflexes contribute markedly to this output impedance (Sinkjaer et al. 1988). However, also the intrinsic mechanical characteristic of the muscle and passive structures around the joints contribute to this output impedance (Sinkjaer et al. 1988).

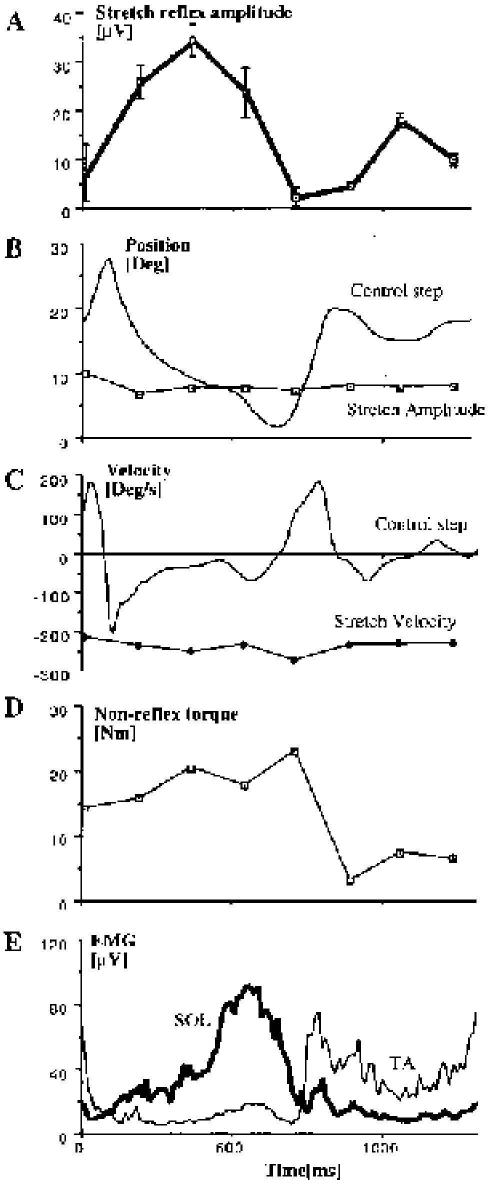

Figure 5-6 *Modulation of the stretch reflex sensitivity as a function of the phase of gait (Sinkjaer et al. 1996): (a) stretch reflex amplitude, (b) amplitude of the imposed stretches and ankle angle in undisturbed steps, (c) ankle angular velocity of imposed stretch of the calf muscle and ankle angular velocity during control steps, (d) non-reflexive moment, (e) EMG of soleus (SOL) (one of the calf muscles) and tibialis anterior (TA) (a muscle that lifts the foot)*

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