Dynamic Control of the Musculoskeletal System

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Summary. Impedance adjustment and dynamic control of the musculoskeletal system are considered. The dynamic characteristics of this system are described by using a bilinear model. Next, the coordinated action of two hands are considered, and it is shown by experiment and a bilinear control model that the impedance adjustment at the joint and muscular levels plays an important role in motor control. Finally, we discuss the neuroscientific standpoints of the precise and flexible motor control mechanisms.

Key words: Musculoskeletal system—Motor impedance—Bilinear model—Motor dynamics—Motor control system

1 Introduction

We perform various movements on a daily basis, such as upright posture control, locomotion such as walking and running, limb movements such as reaching and manipulation, and sports movements like tennis and basketball. All of these are characterized by the fact that a multiple-degrees-of-freedom system of the musculoskeletal system is controlled. Moreover, our body is a very redundant system having more than 100 joint-degrees of freedom and a complex nonlinear dynamic system. As a consequence, to achieve smooth and dexterous movements, these redundant degrees of freedom must be constrained in one form or another [1].

In general, three types of variables are involved in the control of human movement: positional variables (displacement, velocity, acceleration), force-related variables (force, torque), and motor impedance variables (stiffness, viscosity, inertia). The essence of movement control lies in the complex interactions

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between the environment and human movements. For example, when rotating, pinching, or grasping an object, we must control not only the positional variables but also the force variables according to the constraints imposed by the object. Therefore, smooth manipulation requires proper control of the motor impedance connecting these two variables.

In the control mechanism of the brain that has made these movements, a large number of neural circuits are combined in a complicated way and numerous functional modules are formed. In spite of the fact that each module receives different input information, the very act of information processing is localized and autonomous. In addition, spatiotemporal mapping of the information is taking place in parallel between the modules, and a coherent function as a whole is thus created in a self-organizing manner. The system structure is extremely flexible, and there are a variety of information transformations such as the fusion of information of multiple sensors, the generation of symbol-processing information like the motor program, and, moreover, the conversion of such information into the spatiotemporal motor pattern.

First, this chapter tackles the impedance adjustment and the dynamic control of the musculoskeletal system. It is shown that the system's dynamic characteristics can be described using a bilinear model. Next, the coordinated action of two hands will be taken up, and it will be shown by experiment and a bilinear control model that the impedance adjustment at the joint and muscular levels plays an important role in motor control. Finally, we discuss the neuroscientific standpoints of precise and flexible motor control mechanisms.

2 Motor Impedance

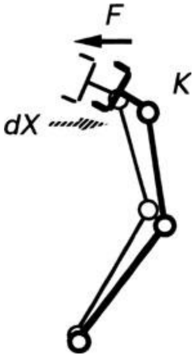
Motor impedance is a general term signifying stiffness, compliance, viscosity, and inertia and is a set of parameters for transforming the variables representing motion (displacement, velocity, acceleration) into force and torque.

(1) Stiffness: Displacement → Force $\boldsymbol{F} = \boldsymbol{K} d\boldsymbol{X}$ (1)
Compliance: Force → Displacement $d\boldsymbol{X} = \boldsymbol{C}\boldsymbol{F}$ (2)
(2) Viscosity: Velocity → Force $\boldsymbol{F} = \boldsymbol{B} d\dot{\boldsymbol{X}}$ (3)
(3) Inertia: Acceleration → Force $\boldsymbol{F} = \boldsymbol{M} d\ddot{\boldsymbol{X}}$ (4)

Here, $d\boldsymbol{X} = \boldsymbol{X}_e - \boldsymbol{X}$, and represents a vector showing the amount of displacement from the equilibrium point $\boldsymbol{X}_e$. In addition, $\boldsymbol{K}$, $\boldsymbol{C}$, $\boldsymbol{B}$, and $\boldsymbol{M}$ are matrices.

The dynamic characteristics of stiffness can be described as follows. When the end-effecter of the arm is displaced, the reactive force generated at the end-effecter is determined by the stiffness and the amount of displacement (Fig. 1). Now, if the displacement is assumed to be constant, then the larger the stiffness, the bigger is the reaction force, constituting a stiff arm. Inversely, the smaller the stiffness, the smaller the reaction force, constituting a compliant arm. Moreover,

FIG. 1. Relationship among stiffness, amount of displacement, and reaction force



as can be seen from Eq. 1, once the stiffness $\boldsymbol{K}$ is determined, the force $\boldsymbol{F}$ and the displacement $d\boldsymbol{X}$ are no longer independent. It therefore follows that it is not possible to control the force and displacement in the same direction independently.

In addition, viscosity regulates the generated reaction force by a change in velocity, while inertia regulates the generated reaction force by a change in acceleration.

3 Impedance Adjustment Mechanisms

In the musculoskeletal system, the joint becomes compliant if both the flexor and extensor muscles are relaxed, so that they can be easily moved by the external force. Conversely, if they are contracted strongly, the joint becomes very stiff and is in a state of being locked. This implies that the stiffness or viscosity of the joint can be altered by changing the contraction level of the muscles. The degree of freedom about the joint is constrained not only on the basis of variable dynamic characteristics of the muscles but also by positively adjusting various forms of feedback at the spinal cord level, such as the stretch reflex or feedback coupling between the joints.

The relationship between the impulse input from the central nervous system to the muscles and the resulting muscular force depends on the length of the muscles, the contraction velocity, the type of muscles, and the degree of fatigue. However, it is well known that at the macro level the dynamic nature of muscles is represented in terms of the two fundamental functions of length–tension curves and force–velocity curves [2].

Figure 2 shows the tensile force generated when muscles of various lengths are activated with the resting length being set at 100%. These results provide the dynamic characteristics that the longer the muscle is, the greater the tensile force. In addition, as indicated by the broken curves in the diagram, the tensile force becomes larger as the level of muscular activity increases.

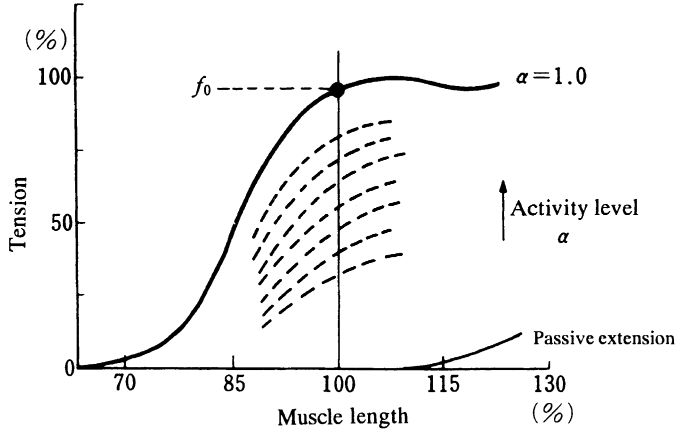


FIG. 2. Length–tension curves

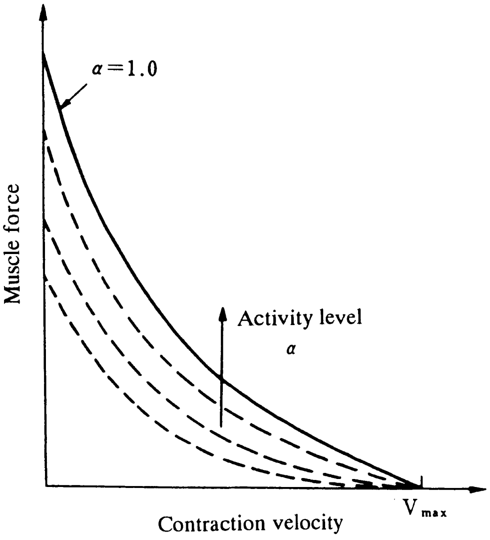


FIG. 3. Force–velocity curves

Figure 3 shows force-versus-velocity relations at various levels of muscular activity. The muscular force decreases in inverse proportion to the contraction velocity of the muscles, thereby indicating the muscle viscosity characteristics. In addition, the muscular force increases with the level of muscular activity.

Now, let us assume here that the muscular force f is proportional to the level of activation α ($0 \leqq \alpha \leqq 1$, normalized at the maximum value). Then the following expression can be obtained:

$$f = a \cdot g(L, V) \tag{5}$$

where $g(L,V)$ is a nonlinear function that represents the relation at the maximum activity level ($\alpha = 1$), while L and V are the length and the contraction velocity of the muscle, respectively. When $g(L,V)$ is linearly approximated at the point of equilibrium of the muscle and in the neighborhood of the contraction velocity $V = 0$, and the variables are rewritten, the following equation

$$f = u - kux - bu\dot{x} \tag{6}$$

is obtained [3,4]. Here, u is the contraction force of the force-generating element, f is the muscular force, $x = x_e - L$ is the change of the length of the muscle from the point of equilibrium, and k and b are constants. Eq. 26 is a model of the dynamic characteristics of the muscle, and has the characteristics that the elastic and viscous coefficients are not constant but in proportion to the contraction force u.

If the foregoing equation is applied to the horizontal rotational motion of a forearm having a flexor muscle (u_f) and an extensor muscle (u_e), then the equation of motion is given as

$$M/d \cdot \ddot{\theta} = u_f - u_e - \left(u_f + u_e\right)\left(k\theta + b\dot{\theta}\right) \tag{7}$$

where θ is joint angle, M is inertial moment of the forearm, d is the moment arm (Fig. 4). The foregoing equation forms a bilinear system in which the difference $u_f - u_e$ of the flexor and extensor muscles adjusts the driving force of the joint, and the sum of the contraction forces, $u_f + u_e$, adjusts the parameters (elasticity and viscosity).

In addition to the variable elastic and viscous characteristics of the muscle, the motor impedance is also controlled by the parameter adjustment mechanism at the spinal cord level and the posture selection of the limb utilizing the redundant degrees of freedom.

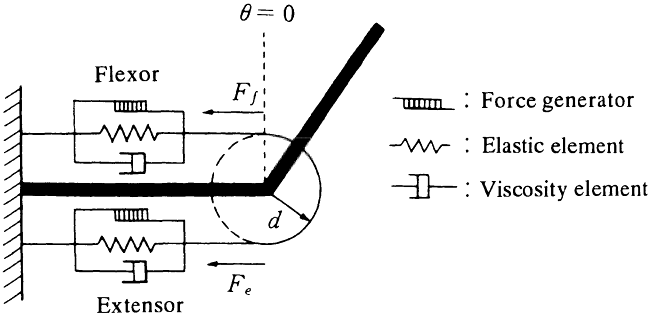


Fig. 4. Musculoskeletal system of the forearm

4 Coordinated Actions of Two Hands and Impedance Adjustment

4.1 *Experiment on Coordinated Actions*

In the case of holding a ball or a box with two hands, it is necessary to control not only the position and posture of the object but also the internal forces applied to it at the same time. In the case of a ball, which is easily deformed by external force (this will be referred to here as a dynamic object), it becomes necessary to set the impedance of the hand, joint, and muscle to appropriate levels corresponding to the impedance characteristics of the object.

To analyze the control characteristics of the coordinated actions of two hands, a dynamic object was made as shown in Fig. 5. The object is composed of a rigid body 0.25 m long ($m_c = 0.4$ kg) in the central section, two elements with the viscosity ($d = 6.82$ Ns/m) and stiffness ($k = 0.49$ N/m), and two endplates ($m_{cL} = m_{cR} = 1.125$ kg), and is deformed by the forces applied by two hands. The object is placed on a linear rail of negligible friction and can be easily moved by the forces from the two sides. Each end of the object was furnished with a distortion gauge (10 Hz in cutoff frequency), and the contact forces were measured. An encoder was installed in the center of the object to measure its displacement. In addition, electrodes were placed on the extensor and flexor muscles that drive the wrist joints of the subject and the surface electromyograph (EMG) was measured.

Each subject was asked to sit in front of the object and to move the center position of the object as quickly as possible by using only his wrist joints without oscillating the object. The displacement was set at 60 mm to the left and to the right. Three normal male students were selected as the subjects, and after 1000 rounds of practice, 10 trials were measured. No particular target value was set for the internal force.

4.2 *Experimental Results*

Figure 6 shows some representative EMG patterns for the case of a dynamic object. They are, from top to bottom, the EMG patterns of (a) the extensor

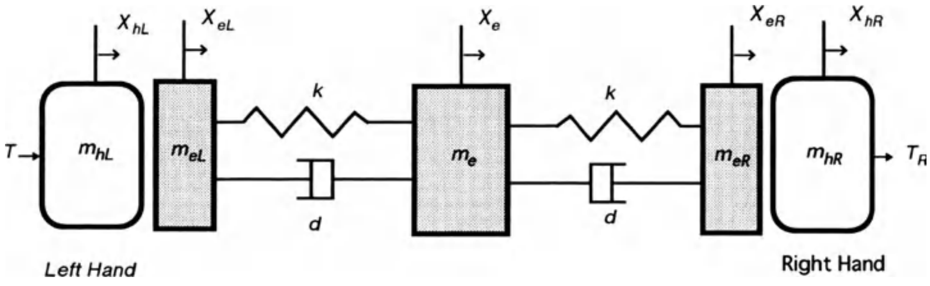


FIG. 5. Dynamic object for experiments on coordinated actions

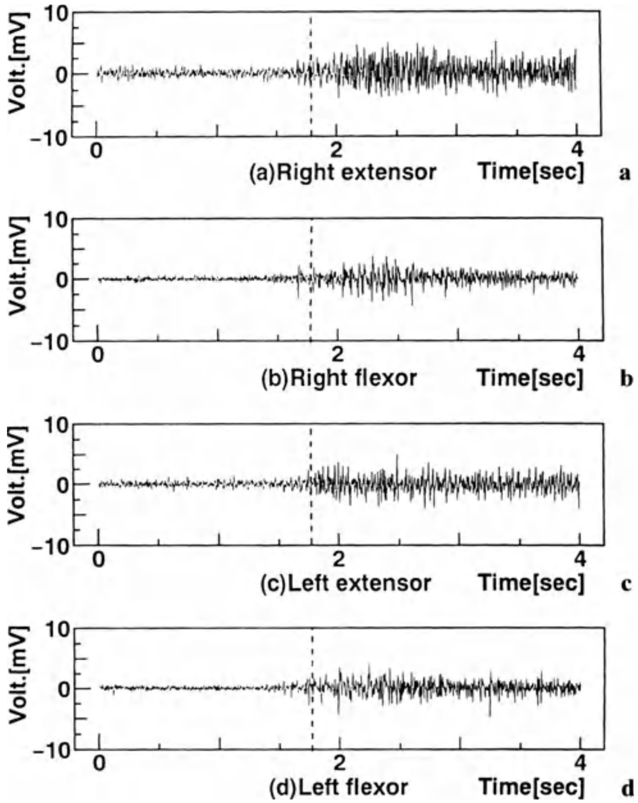


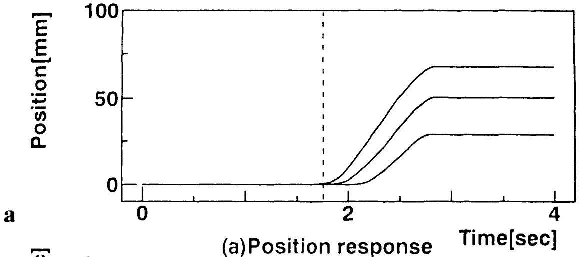
Fig. 6a–d. Electromyograph (EMG) patterns for a dynamic object. **a** Extensor muscle of right hand. **b** Flexor muscle of right hand. **c** Extensor muscle of left hand. **d** Flexor muscle of left hand

muscle of the right hand, (b) the flexor muscle of the right hand, (c) the extensor muscle of the left hand, and (d) the flexor muscle of the left hand. In addition, Fig. 7 shows (a) the displacement of the object, (b) its velocity, and (c) the internal force applied to the object under this condition. Figure 8 shows EMG patterns obtained when the object was replaced with a rigid body. The broken lines in the center show the time when the object began to move.

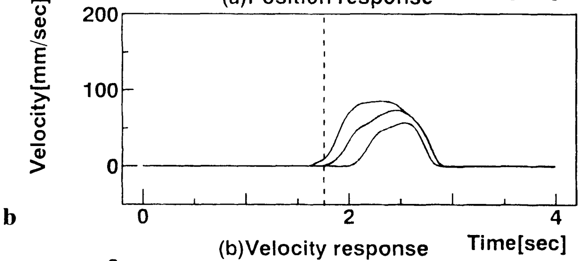
In the case of a rigid object, it is seen from the EMG that the extensor muscle of the right hand and the flexor muscle of the left hand are used to control the object. By contrast, in the case of a dynamic object, the flexor and extensor muscles of the left and right hands are coactivated. Why does the subject use such a control strategy? Let us analyze this by using a bilinear control model.

4.3 Bilinear Control Model

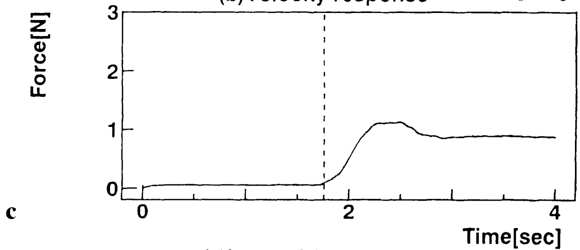
The equations of motion involving two hands and an object after the Laplace transformation are as follow:



(a)Position response



(b)Velocity response



(c)Internal force response

FIG. 7a–c. Coordinated actions for a dynamic object. **a** Displacement of object. **b** Velocity. **c** Internal force applied to object

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\begin{aligned}
m_e s^2 X_e &= Y(s)\left(X_{hL} + X_{hR} - 2X_e\right) \\
m_{hL} s^2 X_{hL} &= T_L(s) - F_{intL} \\
m_{hR} s^2 X_{hR} &= T_R(s) - F_{intR} \\
m_{eL} s^2 X_{hL} &= F_{intL} - Y(s)\left(X_{hL} - X_e\right) \\
m_{eR} s^2 X_{hR} &= -F_{intR} - Y(s)\left(X_{hR} - X_e\right) \\
Y(s) &= k + ds
\end{aligned}
\tag{8}
$$

Now, when the variable stiffness and viscosity of the muscle are approximated by a bilinear model of Eq. 7, then a block diagram as indicated in Fig. 9 is obtained. Here, the transfer function from the difference of contracting forces of the muscles $u_f - u_e$ (driving force) to a displacement X_e of the object is found to be

$$
X_e = \left(D_L D_R - G_e Y(s)\left(D_L + D_R\right)\right)^{-1}\left(G_e D_R\left(u_{Lf} - u_{Le}\right) + G_e D_L\left(u_{Rf} - u_{Re}\right)\right) \tag{9}
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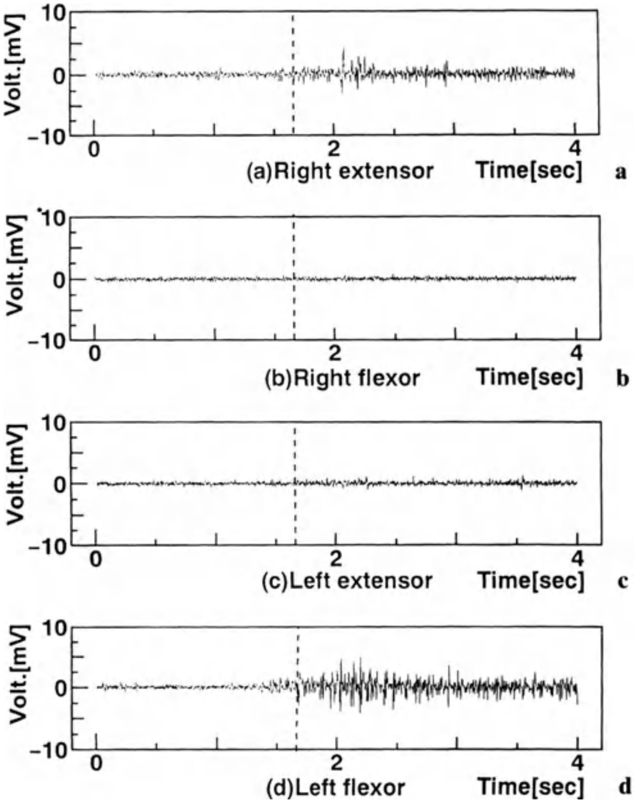
FIG. 8a–d. EMG patterns for a rigid object. **a** Extensor muscle of right hand. **b** Flexor muscle of right hand. **c** Extensor muscle of left hand. **d** Flexor muscle of left hand



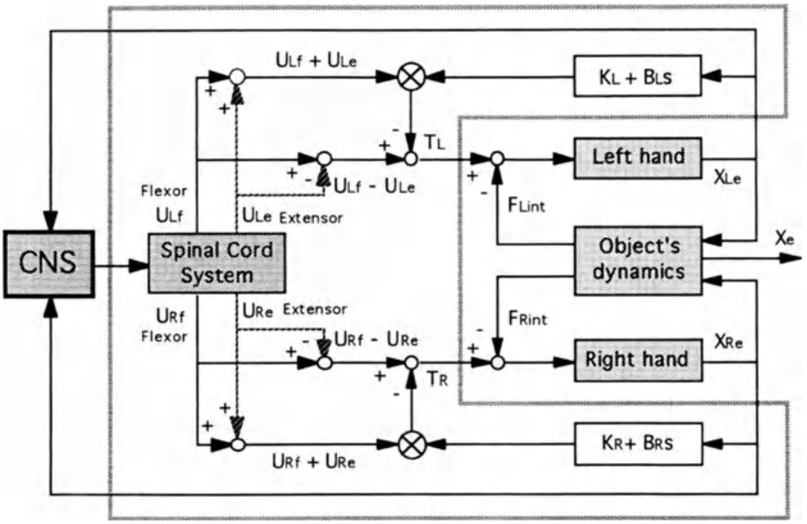


FIG. 9. Bilinear control model

where

$$D_L = \left(m_{hL} + m_{eL}\right)s^2 + Y\left(s\right) + \left(k_L + B_L s\right)\left(u_{Lf} + u_{Le}\right) \tag{10}$$

$$D_R = \left(m_{hR} + m_{cR}\right)s^2 + Y\left(s\right) + \left(k_R + B_R s\right)\left(u_{Rf} + u_{Re}\right) \tag{11}$$

$$G_e = Y\left(s\right) \Big/ \left(m_e s^2 + Y\left(s\right)\right) \tag{12}$$

Note that the transfer function is a sixth-order system.

When the flexor and extensor muscles of the wrist joints of the left and right hands are coactivated and their activity levels are raised, $(u_{Lf} + u_{Le})$ and $(u_{Rf} + U_{Re})$ become bigger. When root loci are drawn with $(u_f + u_e)$ as a parameter, it is found that three poles are dominant. In other words, as the activity levels of the flexor and extensor muscles are raised and the joint impedance is made bigger, the complex sixth-order system can be approximated by a third-order system. From the relationship between the hands and the object, the impedance of the dynamic object itself cannot be modified. However, the transfer characteristics integrating the object and the musculoskeletal system can be reduced in dimension by adjusting the impedance of the joints. This example suggests that humans regulate the impedance of musculoskeletal systems skillfully according to the aim of motion.

5 Coordination Among Subsystems

Let us remember the very first time we rode a bicycle. We all made very awkward movements by stiffening the muscles of our legs and arms. Also, we all tried to adjust the center of gravity of our body to the left or right so as not to fall with the swaying of the bicycle. In many cases, however, we fell. As we practiced, the stiffness of the entire body disappeared, and we began to predict the movements of the bicycle and skillfully regulate the movements of each section of our body.

Thus, in the initial stage of motor learning, we coactivate the principal muscles and antagonist muscles and raise the impedance level. A high level of impedance results in making the movements of the arm and leg more robust against unexpected changes in the environment and, at the same time, results in lowering the degree of freedom of the entire body by making the joints stiff.

In movements after training, the complex impedance adjustment is carried out by skillfully controlling the variable elasticity and viscosity of the muscles, the reflection programs at the spinal cord level, and the posture adjustment of the skeletal system. In other words, it may be said that the purpose of training itself is to learn how to set up the impedance. This fact, however, does not necessarily mean the lowering of the impedance level; there are cases of raising the impedance of the wrist joints after training, as in the coordinated actions of two hands for a dynamic object. This suggests that the acquisition of a motor skill is not to learn the feedback parameter corresponding to a change in the environment but rather to create new relationships among lower subsystems (musculoskeletal system + reflection system). It is not that the degree of freedom is lowered dynamically simply by stiffening every joint, as in the initial stage of learning, but rather that the degree of freedom is reduced as a result of creating new relationships among various parts of the body via motor impedance. Such new dynamics created by the lower subsystems are here called "goal-directed motor dynamics" (see Fig. 10).

6 Functional Modules of Motor Control System

Let us now consider the reaching action when you move your hand to a cup in front of you. Figure 11 shows the information flow of the motor control system [5]. The visual information captured in the receptive field of the retina is sent to the primary and secondary visual areas. After processing, it is converted into the spatial position and velocity representation (parietal association area), which are not influenced by eye and head movements and pattern representation (temporal association area), such as shape and size. They are encoded on the visual space map.

At the same time, sensory information from the proprioceptive sensors at each part of the body is encoded on the proprioceptive map as the body coordinate representation (such as the joint angle). In addition, the hand positions on the visual space map and the body coordinates on the proprioceptive map are coupled through coordinate transformation. The relation between the hand and the other body parts, as well as the relation between the hand and the object, are represented thereon. It has been confirmed that the positioning accuracy of your hand depends greatly on whether or not you can see. This coordinate transformation corresponds to the forward and inverse kinematics.

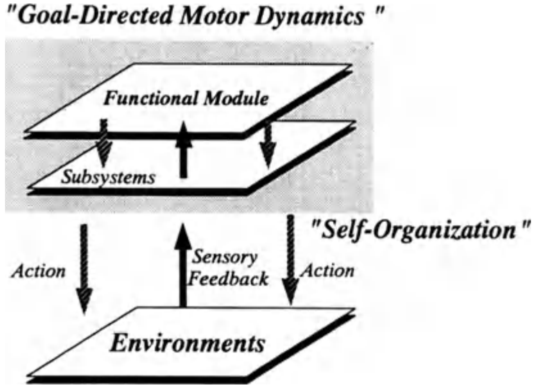


FIG. 10. Goal-directed motor dynamics

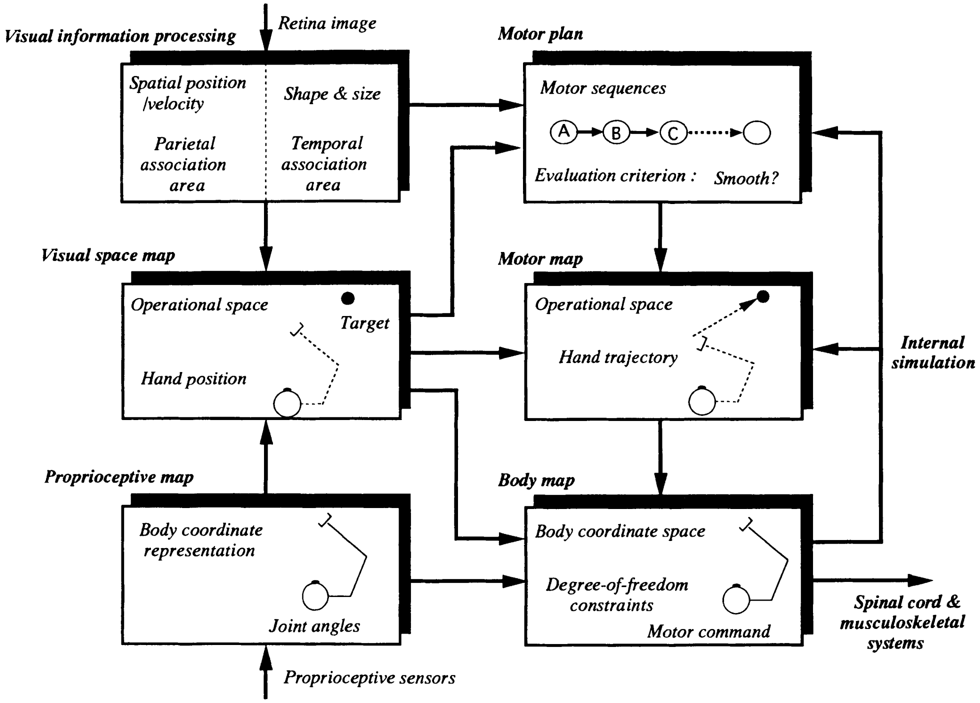


Fig. 11. Architecture of motor control system

In the motor planning module, not only are the motor sequences for achieving the intended motion generated but the evaluation criterion for realizing the individual motions is also set up on the basis of information from the visual space map and the proprioceptive map and other internal representations.

Next, in the motor map, the spatiotemporal motor pattern is produced from the motor sequences based on the given evaluation. It is hard to believe that this motor pattern is directly generated about the entire multiple-degrees-of-freedom dynamic system. It may be more reasonable to imagine, as mentioned earlier, that the motor pattern is produced in a certain low-dimensional operational space (the hand space in the case of the reaching action of the forearm, and the phase-difference space, in the case of locomotion). It is one of the important problems of motor control to define this abstract operational space and to analyze the mechanism for generating the motor pattern coupled with goal-directed motor dynamics.

The generated motor pattern is mapped into the body coordinate space (the joint–muscle space). A variety of degree-of-freedom constraints are necessary for defining this mapping. The motor impedance will be one of the constraint conditions. In addition, the motor pattern at the body coordinate is not only sent to the servomechanism at the spinal cord level as the motor command, but is also simulated internally using the forward kinematics and dynamics models and is fed back to the motor map or motor plan.

As described earlier, the spatiotemporal mapping of information is conducted in parallel among the modules. Information mapping among the different functions is made in the same way as fusing the information from different sensors or the formation of a motor map by converting the symbol processing information such as the motor plan into the spatial or temporal pattern. Furthermore, a group of homogeneous subsystems are activated cooperatively or competitively inside each module, e.g., in the body coordinate space, the dynamic subsystems such as the trunk, forearms, lower limbs, and hand coordinate with each other to generate a motor pattern.

Therefore, the problem is how to provide for the coordination and competition of the respective module outputs. For example, in the subsumption architecture of Brooks [6], each module autonomously takes in the information flowing from the sensor side or other module to execute its own information processing. Whether or not the action command of each module becomes available depends on the presence or absence of a suppression signal from the upper level. In the motor control system, various motor outputs from a simple motion like the bending reflex up to a high-degree voluntary movement are formed in parallel. This can be clearly seen from an athlete's skillful body actions. Our next step is to consider the frameworks of coordination and competition among the motion modules in addition to the suppression of the lower level by the upper level.

7 Conclusion

The phenomenal finger movements of a pianist, the dynamic carriage of a soccer player, and the dexterous hand movements of a potter are all worthy of the highest admiration, and the complexity and dexterity of their motion capabilities are of incalculable value. The motion/action of such a biological system is controlled on the basis of programmed motion patterns. In addition, a majority of those functions have been gained in a self-organizing manner through interactions with the environment.

In this vein, the recent study of complex adaptive systems by the Santa Fe Research Laboratory in the United States is attracting attention [7]. This study concerns the complexity generated by the competition and coordination of simple and local primitive elements, as represented by chaos, evolution, or artificial life, in other words, by the macrocosmic complexity caused by microcosmic behavior. It is important to clarify its principle and structure and to seek its applications to various fields, including the dynamic control of the musculoskeletal system.

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