10 The Bernstein Perspective: I. The Problems of Degrees of Freedom and Context-Conditioned Variability

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The perspective to be developed in this chapter and the two that follow might be termed the Bernstein perspective after the Soviet physiologist Nicolai Aleksandrovitch Bernstein (1896–1966). In other perspectives, both traditional and contemporary, the contribution of the kinematic and dynamic aspects of movement to its control and coordination are either simply ignored or terribly underestimated. For Bernstein, the obvious fundamentality of these aspects led him to characterize the study of movements in terms of the problems of coordinating and controlling a complex system of biokinematic links. He recognized that the focus of analysis could not simply be the muscular forces provided by the animal but must necessarily include inertia and reactive forces. In a nutshell, Bernstein recognized that any theory that ignores the totality of forces and considers only those contributed by muscles in its functional description of movements would be a theory of the *miming* of movements rather than a theory of movements themselves, for the very simple reason that any coordinated activity requires an environment of forces for its proper expression (Fowler & Turvey, 1978). The purpose of this first chapter is to identify the two major problems that shape the analysis of movement in the Bernstein perspective.

We begin with a view of motor control that was popular in the 19th century and that is depicted in Fig. 10.1. This view assumes an "executive" responsible for the control of movement, whose capabilities are not unlike those of a human being. To put it bluntly, the executive is a scaled-down version of a human being, and traditionally this "little man inside the head" is referred to as the "homunculus." At the disposal of this little man, or homunculus, is a memory bank containing programs for movement, where those programs can be likened to musical scores. To perform a movement the homunculus retrieves a score from

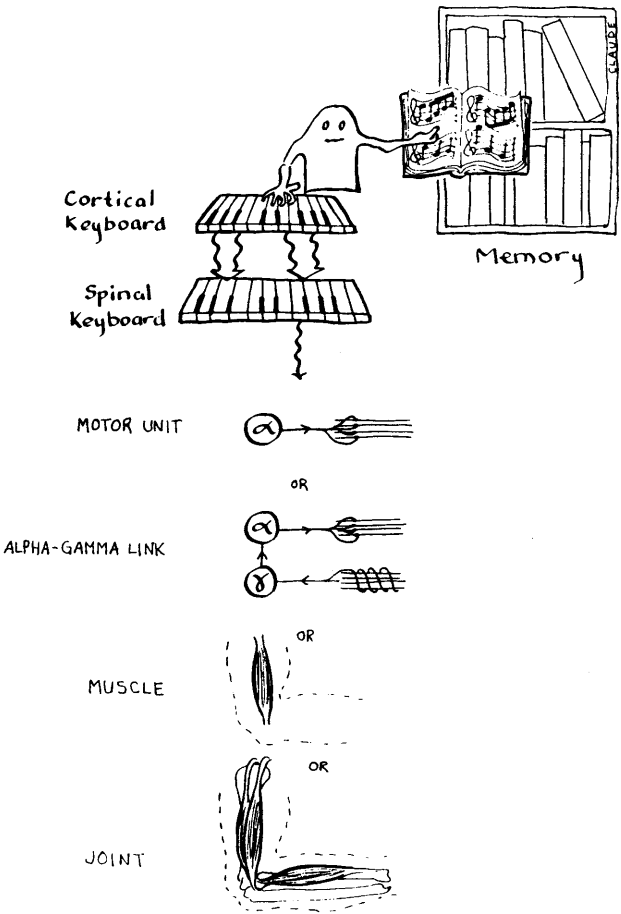

FIG. 10.1. A number of contemporary views of motor control are much like the 19th-century view of motor control depicted here. An executive system, a homunculus, selects from memory a plan for movement (analogous to a musical score) and implements the plan by manipulating the cortical motor strip (analogous to a keyboard). The details of the plan (or the notes in the musical score) might be expressed in terms of: (1) motor units; or (2) alpha-gamma links; or (3) muscles; or (4) joints.

memory and proceeds to "play" the score on the "keyboard" of the cortex, the motor strip. There was already evidence in the 19th century that different locations in the motor strip of the cortex were linked in some fashion to different movement consequences in different parts of the body; it was not very difficult, therefore, to think of the cortical motor strip as a keyboard. Each "key" on the motor strip was thought to cause a specific response in another keyboard, the spinal keyboard, which in turn brought about a certain muscular movement. The idea is much like that of striking a piano key, which, when depressed, causes a specific note by striking a string inside the piano. In this 19th-century view, the nerves that run from the brain into the spine were characterized as pipes through which one could drop balls, or through which one could send commands. If key 1 is pressed, then a command is transmitted to a specific key in the spinal keyboard, causing a particular movement. If key 2 is pressed, a command is transmitted to a different key in the spinal keyboard, causing a different movement, and so on. The job of the homunculus is similar to that of a pianist.

This 19th-century view is an open-loop conception of control: Any given movement is the result of a set program that is insensitive to changes in internal or external conditions. In keeping with the piano analogy, the homunculus plays a chosen musical score but is ignorant of the changes that are occurring as a consequence. No adjustments are made for changing conditions.

Notice also that the homunculus, by pressing the keys, issues a command to each of the units that control the movement; each unit is "addressed" individually. This style of control is called address-specific, or address-individualized, control. But what exactly is being addressed when a key is pressed on the cortical or spinal keyboard? The answer to that question tells us the "vocabulary" of the motor program, or score, because the symbols in the score must relate in one-to-one fashion with the keys in the cortex and the keys in the spinal keyboard. That vocabulary must be the vocabulary that is meaningful for the motor apparatus. Each "note" in the "score" (or instruction in the motor program) could represent, for example, "contract a certain muscle a certain amount!" or "move a particular joint to a particular angle!"

To what, then, do these symbols in the motor score refer? There are several possible candidates. When a cortical key is struck, we can imagine it bringing about a change specifically in a joint, a muscle, an alpha–gamma link, or a motor unit (see Fig. 10.1). To evaluate the candidacy of these entities, let us consider each in turn from the point of view of controlling an arm. We begin with the individual joints.

The shoulder, elbow, radio-ulnar, and wrist joints are schematized in Fig. 10.2. We can imagine the problem of designing an artificial arm that could be attached to, and controlled by, a human being. What sorts of problems does this pose? The shoulder joint can change on three axes: An arm that is fully extended and still can vary its position to the right and left, upward and downward, and it can rotate about its length. At any moment, therefore, the position of the shoul-

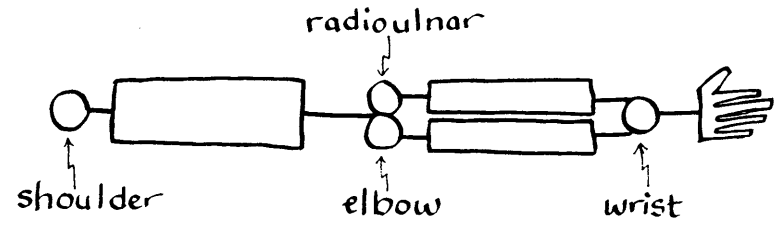

FIG. 10.2. A schematic of an arm.

der joint is given by its values on three coordinates—the horizontal, the vertical, and the longitudinal. Hence, we say that the shoulder joint has three degrees of freedom that need to be specified to describe its position. This puts a large demand on the homunculus, who, for any particular movement of the shoulder, must assign the desired horizontal value, the desired vertical value, and the desired value on the longitudinal axis for each moment in time.

The elbow joint has only one degree of freedom: The forearm can flex toward or extend away from the upper arm. The radio-ulnar joint has one degree of freedom: The forearm can rotate about its length. The wrist joint can move in both the horizontal and vertical axes—it has two degrees of freedom.

To move the arm via address-specific control, then, where the units addressed are joints, seven values must be sent out at a time: three values to the shoulder joint, one value to the elbow, one value to the radio-ulnar joint, and two values to the wrist. This system of joints has seven degrees of freedom (a more rigorous definition of degrees of freedom is given later).

Now think back to the task of building a functional arm. The job of controlling even a simple movement via the joints already seems quite difficult. But the job gets even harder if the units addressed are smaller than joints. A theorist in motor control might suppose (and this is the more common assumption) that what is being regulated are not the individual joints, but the individual muscles.

There is only one dimension on which an individual muscle can vary: the contractile state. In the case of the shoulder, there are 10 muscles working at the joint (excluding the many stablizers and the biceps and triceps). There are therefore 10 degrees of freedom. At the elbow there are six muscles, and hence six degrees of freedom. There are four muscles that move the radio-ulnar joint, and six that move the wrist. That makes a grand total of 26 degrees of freedom that need to be regulated. If control is in terms of individual muscles, the motor plan must specify 26 values at each moment, one value for each muscle involved, in a language "understandable" to the muscles.

The control problem is greatly compounded for theories that postulate plans written in terms of individual motor units (or, relatedly, alpha-gamma links). There are different numbers of motor units in different muscles, but an extremely conservative estimate would be 100 motor units per muscle (in some muscles

there are 6000. That would make 1000 motor units in the shoulder (100 motor units times 10 muscles), 600 in the elbow, 400 in the radio-ulnar joint muscles, and 600 in the wrist. On a conservative estimate, then, there are 2600 degrees of freedom to be regulated at a time.

Remember that the goal of this theoretical excursion is to build an arm that a human being could efficiently regulate, as if, for example, a person has lost an arm and this mechanical arm is to replace it. If this arm is to be controlled by the brain individually specifying values to each motor unit, thousands of degrees of freedom must be continuously regulated for the arm to function properly. If the brain is addressing individual muscles, 26 degrees of freedom must be regulated. If the basic units are joints, then there are only seven degrees of freedom. Obviously, the homunculus would have an easier job if he only had to determine seven values at a time.

We now want to consider whether it is plausible to use address-individualized control, even if there are only seven degrees of freedom to be regulated. As an analogy to the homunculus trying to control the body in this way, imagine a person trying to control a car that had been built according to such a principle. Suppose that when Henry Ford began mass-producing cars, he set them up under the principle of individualized control, where the individual units were the wheels; that is, for any moment in time the driver must independently assign the position of each of the four wheels, possibly by pressing keys that stand for the positions of the wheels. The four wheels are not connected—they are free to vary individually. It would be enormously difficult to regulate such an automobile. Indeed, we might suppose that the accident rate would triple if not eliminate us all!

The lesson is simple: If a task seems very difficult, even impossible for a human, then we ought to assume that it is at least equally as difficult for a scaled-down version of a human, that is, a homunculus. The preceding gives good reason for doubting that the homunculus of Fig. 10.1 regulates the body through an address-specific procedure. Of course, in principle the homunculus could regulate the body by other procedures, but prior to evaluating what they might be, let us take a moment to reexamine the role in which the homunculus has been cast. Does the homunculus notion aid our understanding of the control of movement? In the 19th-century story, in order to understand the coordination of movement, some device in the brain was proposed (a homunculus) that received information about the world and produced appropriate movements. But, notice, that is precisely the problem a student of coordinated movement is trying to understand. *How* can any agent receive information and produce the requisite movements? When trying to explain how it is that a person can, for instance, play tennis, you do not want in your explanation a person inside the head playing tennis. Our understanding of the control and coordination of movement will be directly correlated with the degree to which we can eliminate from our explanation an entity that has abilities approximating those of a fully fledged animal—that is, to the degree that we can trim down the homunculus concept.

A first step in trimming down the homunculus is to notice that some of the work assigned to him/her is unnecessary. He/she was being asked to do a very difficult job of selecting correct configurations from a large number of alternatives. But many of the possible configurations (like combinations of wheel positions for the car) are useless. Suppose the front wheels of the car are at a 90 degree angle to each other. The car could not move. Likewise, paralysis or chaotic movement would occur with many of the possible combinations of muscle innervations. Only some of them are useful; most of them are disastrous and self-defeating. We do not want to assume that the motor system has too many options. We want to do away with options irrelevant to the task, which complicate the problem of control and introduce a greater possibility of error.

To summarize thus far, we have set up a "straw man"—the 19th-century view of how a human or animal produces movement. We have highlighted three of its major features. Firstly, there is no feedback in the account; the system is open-loop and insensitive to changes in external conditions. Secondly, the style of control can be characterized as address-specific, individualized control. The homunculus (and motor program) must specify values for each individual variable. And thirdly, the keyboard model assumes that the vocabularies of the motor program, the cortex, the spinal machinery, and the motor apparatus stand in one-to-one correspondence.

The style of control we have been discussing highlights a particular type of problem that is called the "degrees of freedom" problem. There are too many individual pieces of the body to be regulated separately. What is to be appreciated is that the degrees of freedom problem constitutes a very difficult and fundamental puzzle to be solved by students of movement.

A formal definition can be given for the degrees of freedom of any system: They are the least number of independent coordinates needed to identify the positions of the elements in the system without violating any geometrical constraints. Consider a system of two elements—element A and element B (see Fig. 10.3). If there are two axes x and y (that is, we have a two-dimensional space), then two coordinates are needed to identify the position of each element. Element A must have a value on x and a value on y (for example, x_1 and y_1), and element B must have a value on x and a value on y (for example, x_2 and y_2). For this system of two independent elements (elements that are not connected), two coordinates are needed for each of the two elements, resulting in a system that has four degrees of freedom. This is the least number of independent coordinates needed to describe the positions of the elements of the system.

But now suppose that these two elements are connected by a steel bar, something that does not change in length. Call this connection a line of length L. What this means very simply is that element A and element B are not free to vary independently. So whatever position element A takes, element B must adopt some position that will be determined by the fact that A and B are connected by this link of length L. In fact, there is an equation that states the relationship that

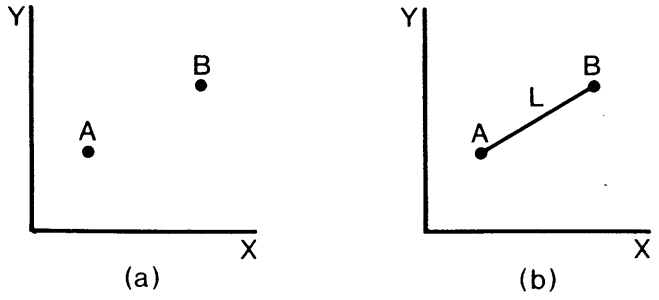

FIG. 10.3. Two simple graphs depicting two simple "systems" each composed of two elements, A and B, in a two dimensional space, x and y. System (a) has four degrees of freedom, whereas system (b), in which the two elements are linked, has only three degrees of freedom.

the coordinates of $A(x_1, y_1)$ and $B(x_2, y_2)$ must maintain: $(x_2 - x_1)^2 + (y_2 - y_1)^2 = L^2$. This equation is an example of an *equation of constraint*. It tells us how A and B relate.

Notice that when a line connects A and B, one is no longer free to choose any values of these coordinates. If the coordinates for A (x_1, y_1) are chosen, then only *one* of the coordinates for B (say x_2) can be chosen freely; having chosen x_2, y_2 is now determined. This system has only three degrees of freedom. The least number of independent coordinates that are needed is now three, because one of the coordinates is determined by the other three in accordance with the constraints of this particular equation.

In general, the degrees of freedom of any system can be given by the following equation: degrees of freedom $= ND - C$, where N is the number of elements in the system, D is the dimensionality of the system, and C is the number of equations of constraint. By following this equation one can compute the degrees of freedom of any system. In the previous example we were dealing with a system of two elements ($N = 2$), two dimensions—the two axes x and y—($D = 2$), and one equation of constraint ($C = 1$). So the system's degrees of freedom were $(2 \times 2) - 1 = 3$. In the original example of a system without any equations of constraint (where A and B were not connected), there were four degrees of freedom: $(2 \times 2) - 0 = 4$.

Think of how this equation relates to our formal definition of the degrees of freedom of a system; (that is, the degrees of freedom is the least number of independent coordinates that are needed to identify the positions of the elements of the system without violating any geometrical constraints). By knowing the dimensions of the system, the number of elements, and the number of equations of constraint, the degrees of freedom of the system can be determined.

Let us attempt to pull these concepts together. We are considering one major problem that any theory of the control of movement must account for: How does

the nervous system regulate all its variables? There are many free variables—they can be the joints, they can be the muscles, they can be the motor units. But the problem is very straightforward: Regardless of the size of the unit controlled, how are all those independent units regulated? That is the problem of degrees of freedom. We have seen that when the variables, or elements, are constrained to relate in certain ways, the degrees of freedom of the system are reduced.

Now let us consider a second, closely related, class of problems. They are called the problems of context-conditioned variability. The homunculus in our 19th-century metaphor has an additional control problem that enormously compounds the problem of degrees of freedom. Recall that in the piano metaphor control is open loop. The homunculus is ignorant of what actually happens as a result of his/her commands. Unfortunately for the homunculus, his/her commands occur in a context—against a backdrop of ongoing conditions, and their end results will necessarily be modified by those conditions. In general, the circumstances in which any particular movement occurs are not completely fixed, and, in particular, each movement changes the context for the next movement. But with a fixed plan or motor score relating cortical "keys" to muscle innervation pattern, there is no way to modify the commands to take account of the changing circumstances into which those commands will be sent. We are going to explore what the consequences are of not being sensitive to the changes in context that accompany any movement. These changes allow a fundamental type of variability into the system. The variability is in the relationship between muscle states and movements.

Let us step back and see the nature of the problem. The objective is to produce a certain motor consequence. If it is the case that whenever certain muscles are brought into play they always produce the same consequence, then a particular movement can always be produced simply by activating muscle A this amount, then muscle B this amount, and so on. However, when any given muscle or muscle group is activated, the actual resulting movement differs with context. The relationship between muscle excitation and movement is variable and the variability is owing to context; the variability is context conditioned. A homunculus cannot simply call up muscles without knowing what the context is, because the role played by a muscle is dependent on the context in which the act is occurring.

Bernstein (1967) has defined three major sources of context-conditioned variability. Consider, firstly, the variability owing to *anatomical* factors. Suppose that you hold your arm at your side in a position below the level of your shoulder and you want to adduct your arm (bring it toward the midline of your body). A good muscle to use would be pectoralis major because its distal insertion is the humerus, and its proximal insertion is the clavicle. When you activate it, the arm adducts. If, however, you now hold your arm slightly raised above the horizontal axis of the shoulder joint and you again want to adduct your arm, activating the pectoralis major will not work; it will, instead, *abduct* it; that is, it will move

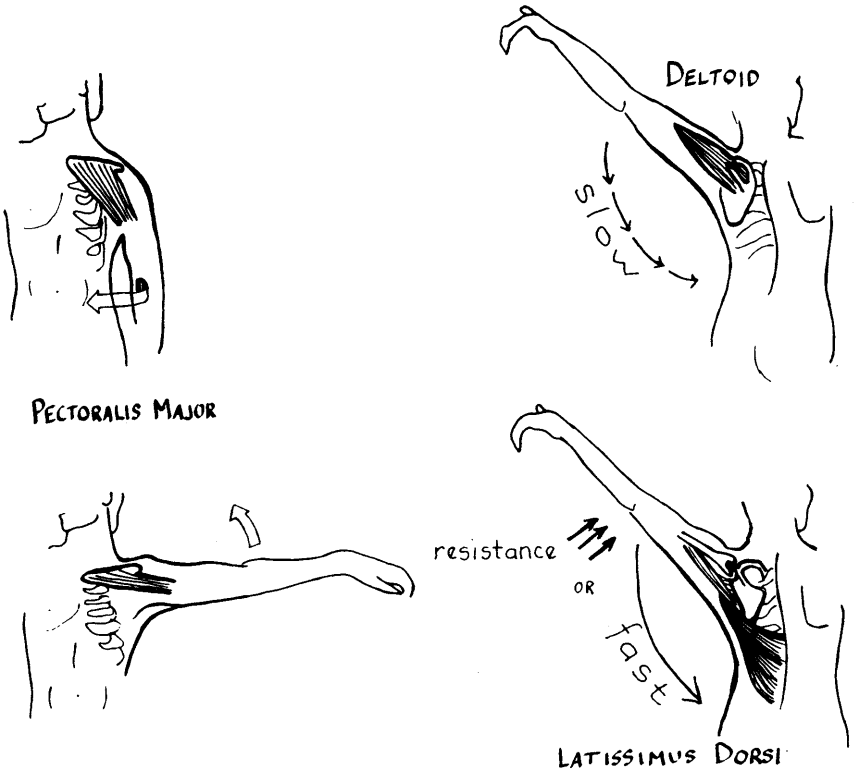

FIG. 10.4. The role of a muscle is context dependent. Given one relation between the angle of pull of the pectoralis major and the axis of the joint, contraction of the muscle adducts the arm (upper-left figure); given another relation, contraction of the muscle abducts the arm (lower-left figure). The deltoid is used to lower the arm slowly (upper-right figure); to lower the arm quickly or against a resistance, the lattissimus dorsi is exploited (lower-right figure).

your arm *away* from the midline of your body. Pectoralis major changes its role as a function of the angle of its pull with respect to the axis of the joint (see Fig. 10.4). The role of the muscle depends on the context.

Consider another very simple example. Suppose that you wanted to move your arm slowly downward against a resistance. The lattissimus dorsi plays an important role in this particular movement (see Fig. 10.4). But suppose you slowly lower your arm with exactly the same kinematic motion, but with no resistance. Now the lattissimus dorsi is not involved at all. You can demonstrate this yourself by palpating the lattissimus dorsi during the two movements. When

there is no resistance, the deltoid muscles of the shoulder extend to control the movement of the arm downward (see Fig. 10.4). Although the kinematic details of the movement do not change in the two cases, the muscles that will be used depend on whether there is resistance to the movement.

Consider this problem of context-conditioned variability with respect to the anatomical sources of variability more closely. Most theories of motor control have revolved around a very simple conception of agonists and antagonists working at hinge joints. A fixed agonist and a fixed antagonist can be identified for a simple hinge joint but not for more complex joints, like the shoulder joint or the hip joint. In those joints, which muscles play the role of agonist and which muscles play the role of antagonist are not fixed but change, depending on the trajectory of the movement and the context in which it occurs. Paul Weiss underscored this puzzle in a classic paper written in 1941. He asked how the muscles that are to be agonists and those that are to be antagonists are selected for a given trajectory. When you lower your arm, which of the 10 or 12 muscles of the shoulder joint are to play the role of agonist and which are to play the role of antagonist? These problems are expressions of anatomical sources of variability. The role that a muscle plays is context conditioned.

A second source of context-conditioned variability is what Bernstein termed *mechanical* variability. Imagine that a muscle is excited to a given state, so that there is a particular amount of contraction, which we call X. What we need to appreciate here is that a given innervational state of a muscle does not have a fixed movement consequence. Given X under some conditions, one kind of movement will result; however, under other conditions, X will result in a different movement. The relationship between the muscle's degree of activation and the joint or limb movement that occurs is not fixed. It is ambiguous. Suppose, for example, that your arm is extended at the elbow and that you innervate the brachialis muscle (see Fig. 10.5) to yield state X. As a consequence of X, your arm flexes at the elbow joint. But observe what happens if the context changes. Suppose that the intial position of your arm is flexion at the elbow joint, and you progressively extend the arm at the elbow. If you now set state X for the brachialis muscle, it will not necessarily result in elbow flexion. In fact, depending on how fast the arm is moving, state X in this muscle may stop the arm, it may simply slow down the movement, or it may cause a movement in the direction opposite to the movement, that is, flexion. Notice that depending on the condition of the limb, the value X of this muscle will have different movement consequences. Mechanical sources of variability mean that the relationship between the state of a muscle and the movement consequence is variable—it depends on context.

The pervasiveness of mechanical sources of variability can be illustrated further. An appendage such as an arm or a leg is a biokinematic chain—that is, it consists of several connected links, so that a change in any one link affects the other links. If you actively move only the shoulder joint, the rest of your arm will

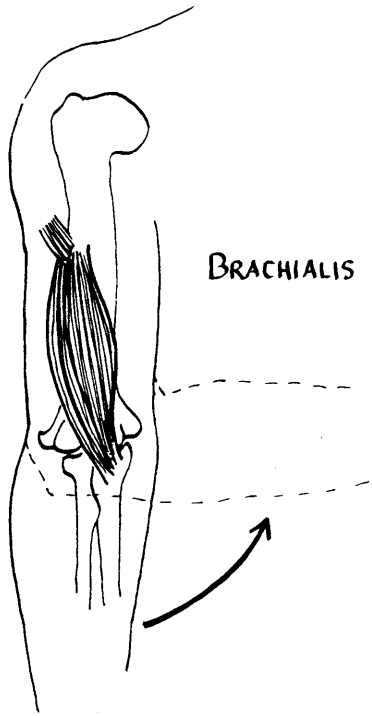

FIG. 10.5. The brachialis muscle.

necessarily change in certain ways because the joints are linked. These changes generate kinetic energy. The generation of kinetic energy in the distal links—the forearm and hand—works back against the shoulder joint. In brief, the forces operating on a limb are not simply muscular forces. There are nonmuscular forces, such as forces due to gravity, changes in the moments of inertia of the limb, and changes in the reactive forces that one joint exerts against another joint. The recognition that nonmuscular forces greatly influence any movement is devastating for a story in which the command sent to the muscles is ignorant of these nonmuscular forces (as in our 19th-century metaphor). It could, of course, be argued that the commands must be structured so as to overcome the nonmuscular forces. But a different approach is to build a theory that says that movement is controlled and coordinated by allowing muscular forces and nonmuscular forces to complement each other. The nonmuscular forces are to be taken advantage of; they are not to be compensated for. Let us pause for a moment to repeat the story just told before we carry it through to its next step.

We have been looking at the mechanical sources of context-conditioned variability. Fundamentally, we realize that it is impossible to have a program written

in terms of contractile states of muscles, because the movement consequences of any such program will be altered by the context of forces in which it is taking place. In most theories of motor control, the biomechanical properties of the body are often just ignored. In an alternative theory of control, the nonmuscular forces are recognized and are treated not as a hindrance to be overcome but as a complement to the muscular forces. In skilled activity, the muscular and nonmuscular forces are seen as fitting together like two pieces of a jigsaw puzzle.

Consider this form of control—as Bernstein did—in relation to someone learning a skill. When you are first learning a skill, one of the things that is bothersome is that the parts of your body seem to have a will of their own. You are trying to control one link, but, in controlling one link, other links necessarily change. These unwanted changes follow from the forces generated by the movements of the links. Bernstein realized that in any skilled movement, from dangerous acrobatic routines to simple walking, what actually occurs is that the person or the animal is taking advantage of these nonmuscular forces. A highly skilled performer is in fact *exploiting* the nonmuscular forces and not compensating for them. Ther performer has found a way of ideally relating forces, those that the muscles supply and those that are supplied reactively by the body parts and the environment. An understanding of movement control will include an understanding of how muscular and nonmuscular forces complement each other.

Let us now consider one final source of context-conditioned variability—*physiological* variability. Again, observe the main theme: A fixed relationship cannot be assumed between muscle states and movements. We might imagine that a cortical command is communicated by a transmission line that runs to some location in the spinal cord, where it excites a particular cell or group of cells. This cell or group of cells in turn transmits the command to a muscle, producing a certain degree of muscle contraction. Notice that in this story it is assumed that the relationship from cortex to muscle is rather like a pipe, a passive relay that simply transmits instructions that are then faithfully followed by the motor units. By the very nature of the nervous system, however, it is not possible for instructions coming from the cortex and going to the muscles to be transmitted "faithfully," that is, without modification. The spinal cord does not simply relay instructions from the brain.

What influences other than cortical are exerted on the motoneurons, the final neural links between brain and muscles? Inside the spinal cord are a large number of neural entities called interneurons that interconnect parts of the spinal machinery. Interneurons connect with other interneurons within a segment of the spinal cord and between segments of the spinal cord. These horizontal and vertical connections among interneurons give the spinal cord an integrity and organization of its own. Acting on any motoneuron are inputs from a large number of places in the spinal cord. The state of the spinal cord will determine what actually occurs in the motoneuron. Hence, the signal to the motoneuron

does not depend solely on the message from the cortex; the motoneuron is sensitive to, but not subservient to, the signal from the brain.

The point is that we do not want to conceive of the supraspinal mechanisms as dominating the spinal mechanisms: The spinal cord and the brain relate to each other like two diagnosticians, two highly skilled people trying to figure out a problem. It's not that one of them is commanding the other. They relate between themselves like experts, cooperating on a problem.

In this chapter we have considered two fundamental problems in the Bernstein perspective: The problem of degrees of freedom and the problem of context-conditioned variability. Let us conclude by seeing how these two problems relate to skill acquisition.

When you are just beginning to learn a skill, one of the first things you will notice is that you eliminate, as it were, some of your degrees of freedom—put simply, you keep a good part of your body fairly rigid. You do not exhibit the flexibility of the skilled performer. Watch a child learning how to hit a baseball. Initially, he or she stands quite rigid, facing the ball, holding most of the body stiff. This posture simplifies the problem, but it does not allow a very efficient swing. As the child gets slightly better, one of the things that he or she will do is allow shoulder movements into the swing. Several degrees of freedom are "unfrozen." Nevertheless, there is still a ban on many degrees of freedom because they constitute so much trouble for the child. The child is trying to avoid creating too many reactive forces, the forces that are nonmuscular. For example, the beginning batter finds that the swing throws the body off balance—this is a reactive consequence of the movement, a mechanical source of context-conditioned variability. As skill increases, and the child learns to work *with* the reactive forces, he or she will release the ban on the degrees of freedom, allowing additional degrees of freedom to creep in. If the batter's hips rotate, that guarantees a certain rotation in the upper part of the body. The batter does not actually have to push the body through every part of the movement but can exploit the reactive forces to regulate this rotational degree of freedom. Why is the batter attempting to regulate more degrees of freedom? Fundamentally, the skill demands it. A good baseball batter must allow flexibility of the hips, shoulders, and wrists. The additional degrees of freedom are very important in giving power to the swing. In summary, acquiring a skill is essentially trying to find ways of controlling the degrees of freedom and of exploiting the forces made available by the context.

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