FROM THE EDITOR

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There Is No Motor Redundancy in Human Movements. There is Motor Abundance

It is suggested that the famous problem of motor redundancy is inapplicable to human voluntary movements. Such notions as "the elimination of biomechanical degrees of freedom" should not be used in human movement studies. During natural movements, elements within apparently redundant sets are all involved in solving motor tasks. The abundance of elements is a keystone forming the foundation of motor synergies. It allows natural movements to display both flexibility and stability.

The problem of motor redundancy was originally introduced by N.A. Bernstein (1947, 1967) as a problem of finding a unique solution when many elements participate in a motor task that can be described with a few parameters. Bernstein illustrated this problem with a task of pointing to a target in the three-dimensional space with the tip of a finger. The number of independent axes of joint rotation within the human arm is larger than 3 and allows an infinite number of joint configurations that can successfully accomplish the task. How does the central nervous system (CNS) select a unique joint configuration at each particular attempt? In contemporary literature, problems of this type are addressed as problems of inverse kinematics.

Similar problems may be formulated at other levels of the human system for movement production. For example: Which forces should be produced by each of the six major muscles crossing the elbow joint to generate a certain value of elbow joint torque? Or, Which motor units should be recruited by the CNS and at what frequencies to produce a certain level of muscle activation? Solving such ill-posed problems is equivalent to solving a system of equations with more unknowns than the number of equations. Apparently, such problems do not have unique solutions unless additional constraints are introduced into the task formulation.

Bernstein viewed the elimination of the redundant degrees-of-freedom (DOF) as the most essential problem of motor control. He was, however, somewhat vague in his writings on this issue, and it is unclear whether he seriously implied an elimination of biomechanical DOF. Let me make it clear that, for a natural movement, the only way to eliminate a biomechanical DOF is to perform a major surgery. The efficacy of a particular mechanical DOF can be modulated, explored, limited, etc., but one can never eliminate it. However, an elimination of biomechanical DOF is rather commonly invoked in contemporary studies of human motor behavior. In many studies, the presence or the lack of a visible motion of a joint has been viewed as a sign of a biomechanical DOF being either recruited or eliminated. Along somewhat similar lines, studies of motor learning commonly use notions of freezing and releasing DOF at different stages of skill acquisition with an implicit assumption that it is easier to control an object with fewer biomechanical DOF. Actually, "freezing" a joint within a multijoint motor task does not mean "easier control"; it is much more likely to require a very non-trivial control of muscles crossing the joint.

Many attempts to address the problem of motor redundancy followed the original formulation of Bernstein and involved, in particular, an application of optimization principles based on various engineering, physiological, psychological, or complex cost functions. However, the purpose of this note is not to compare different approaches to the problem of motor redundancy but to suggest that the problem itself has been inadequately formulated.

The main reason for this suggestion is a well known observation made in the 1920s by Bernstein himself in his famous study of blacksmiths hitting the chisel with the hammer (Bernstein, 1924). Bernstein used a very sophisticated method of movement analysis (kimocyclography) that he himself had developed. Within this method, small light bulbs were placed at certain important points on the subject's body, and the movements were photographed on a slowly moving film using a high-speed lens shutter. This produced a series of snapshots of the bulbs, allowing Bernstein to calculate the motion of individual joints and of particular points on the subject's body. Needless to say, all these measurements and calculations were done by hand. In his studies, Bernstein reached the frequency of over 500 snapshots per second (Bernstein & Popova, 1929), which is comparable to the most sophisticated optoelectronic systems used for movement analysis today.

In the study of blacksmiths, Bernstein noticed that the variability of the tip of the hammer across a series of trials was smaller than the variability of the trajectories of individual joints of the subject's right arm holding the hammer. He concluded that the joints were not acting independently but correcting each other's errors. This observation already suggests that the CNS does not try to find a unique solution for the problem of kinematic redundancy but uses the apparently redundant set of joints to assure more accurate (less variable) performance of the task.

Bernstein's ideas were further developed by I.M. Gelfand and M.L. Tsetlin (1966), who introduced a *principle of non-individualized control* which preserves the idea of hierarchical control but rejects prescriptive, authoritarian control by hierarchically higher levels. According to the principle of nonindividualized control, elements of a complex system are not controlled individually (i.e., no peripheral DOF are ever eliminated during natural movements) but united into task-specific structural units for purposes that can be termed synergies. Gelfand and Tsetlin introduced a few axioms to describe essential properties of structural units. Axiom #3b was: *All elements of a structural unit find their own places within a task.* This axiom illustrates the *principle of abundance*, when many more elements than necessary participate in the activity of a structural unit with respect to each task.

The principle of abundance renders the problem of redundancy irrelevant: Numerous elements should not be viewed as a source of computational problems for the nervous system but as a useful apparatus that requires proper organization and tuning.

By introducing this principle, Gelfand and Tsetlin made a step beyond the Bernsteinian understanding of problems of motor control, a step whose importance has not yet been fully recognized.

I hope the readers will forgive me, as I am not a native English speaker, for the following linguistic proposal: The word "redundancy" means something useless that needs to be eliminated, while "abundance" has a positive connotation implying something that may be used rather than thrown away. In the original writings, Bernstein used the Russian word *izbytochnost*, which can mean "redundancy" or "abundance," depending on the context. Isn't it amazing that a whole direction of research developed based on an imprecise translation of a single word?!

Respectfully,
Mark Latash, Editor

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