

# Motor Control: The Heart of Kinesiology

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This brief review presents the subjective view of the author on the history of motor control and its current state among the subdisciplines of kinesiology. It summarizes the current controversies and challenges in motor control and emphasizes the necessity for an adequate set of notions that would make motor control (and kinesiology) a science. Changes in the current undergraduate and graduate programs in kinesiology are suggested that would help prepare future faculty in this area. The article ends by describing the author's view on motor control in 2050.

## History of Motor Control

The origins of movement and the relations between human movements and their controller, the central nervous system (CNS), have been fascinating scientists at least since the times of the great Greek philosophers of the past. At that time, the problem of movement–CNS relation was more commonly formulated as that of the relation between the moving body and the controlling soul. For example, Plato viewed self-motion as a sign of immortal soul, which was apparently inherent to all animals capable of voluntary movements. Aristotle was arguably the first to pay attention to a distinguishing feature of biological movement, that is its coordination. In the second century A.D., the great Roman physician Galen suggested that voluntary movements of body segments were controlled by the soul, which sent signals to muscles via nerves conveying “animal spirits.” The classical Greek-Roman understanding of the relation between the soul and the body was summarized by St. Augustine: “The way in which souls are cling to bodies is completely wonderful, and cannot be understood by man; and this is man himself” (cited after de Montaigne, 2003, p. 489).

The great Renaissance philosopher René Descartes taught that every human being was composed of two independent entities, the soul and the body. The soul was responsible for thinking and other cognitive things, and the body obeyed the soul and the laws of nature. Some movements were apparently independent of the soul, for example, the beating of the heart. Other movements were induced by senses and mediated by the soul. The great Isaac Newton also contributed to the discussion on how biological movement was produced. Newton was a religious man, and his theory of motor control was also based on the soul controlling the body. He was quite aware of the problem of communication between the soul

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and the body, and as a true physicist, he solved it by introducing a medium, ether (unfortunately unobservable).

In the 19th century, the role of electric phenomena in the neuromuscular processes was appreciated, and studies of movements were helped with the invention and development of photography. However, the philosophical issue of whether movements are produced by a soul (you can call it *will* or *intention* if these terms sound more palatable) or represent responses of the body to external stimuli remained unresolved. I will return to this major controversy somewhat later.

Two great scientists contributed so much to the area of control of movements that they deserve to be called Fathers of motor control. One of them is a great British neurophysiologist, Sir Charles Sherrington, and the other one is a great Russian physiologist, Nikolai Bernstein. Sherrington's contributions to neurophysiology of movements are many and varied (reviewed in Stuart, Pierce, Callister, Brichta, & McDonagh, 2001). In particular, he introduced the idea of reciprocal inhibition as a method of coordinating agonist–antagonist muscle pairs, described the tonic stretch reflex, and developed a theory of movements based on coordinated changes in muscle reflexes. Bernstein's name is associated with the famous Bernstein problem of elimination of redundant degrees of freedom (Turvey, 1990), with the idea of hierarchical control of movements, and with the development of physiology of activity (reviewed in Bongardt, 2001).

In the early 1950s, arguably the first motor *control* hypothesis was formulated by Merton (1953), the so-called servo-hypothesis of motor control. It seems, however, that the term *motor control* was not used until the late 1950s (Granit, 1957; Salway, 1958). Since that time, this term has become accepted in the area of movement science and used not only in papers but in the names of laboratories, conferences, journals, and scientific societies.

Over the past two decades, the area of motor control has developed rapidly, leading to the creation of the International Society of Motor Control (ISMC, [www.i-s-m-c.org](http://www.i-s-m-c.org)), a series of biennial meetings of the ISMC called *Progress in Motor Control*, and a journal titled *Motor Control*—an Official Journal of the ISMC. Among the most recent developments are the Annual Motor Control Summer School (since 2004) and the *Bernstein Prize* in motor control, the highest prize of the ISMC (since 2005). Motor control is strongly represented in other professional organizations and meetings—to name a few, the Neural Control of Movement, American Society of Biomechanics, International Graphonomics Society, International Society on Gate and Posture, and Society for Neuroscience. In addition, there are regular national motor control conferences in a number of European countries including Bulgaria, France, Poland, and Russia.

This rapid development has reflected a number of changes in the area of kineology, in particular, the formulation of new problems, the development of new methods of research, and the appreciation of the importance of understanding the neural mechanisms of control of movements by the USA federal granting agencies

including the National Institutes of Health. Currently, motor control is arguably the youngest and the most vigorously developed subdiscipline of kinesiology.

## Position of Motor Control Among the Subdisciplines of Kinesiology

First of all, what is *kinesiology*? Many professionals traditionally associate this name with physical education and sport, maybe in a slightly broader sense. This understanding of kinesiology follows the commonly accepted definition of its subject matter as “physical activity” (Newell, 1990). This attitude reflects the fact that in the USA and some other countries, departments of kinesiology emerged on the basis of departments of physical education and athletics and inherited many of the educational programs, research problems, and methodologies that had been used in those departments. This is not necessarily true, however, for other countries that contributed significantly to movement science. For example, the Russian school of movement science was developed mostly by physicists and neurophysiologists in laboratories housed in research institutes specializing in physics, mathematics, and biology.

As compared with more-traditional areas of kinesiology, such as physical education, sport psychology, exercise physiology, and biomechanics, motor control has relatively recently become an explicit area of emphasis in the graduate programs in departments of kinesiology. Despite its youth, however, motor control has positioned itself strongly in a number of programs. I would like to illustrate the success of motor control as an area of emphasis in graduate studies and research using, as an example, the Department of Kinesiology at Penn State where I work.

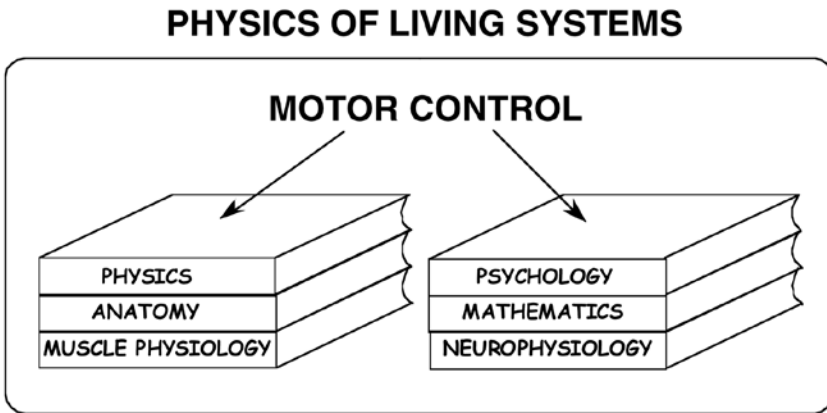
Table 1 summarizes the data over 6 years (2000–2005) for the six areas of emphasis in the Department of Kinesiology. Quantitative indices and rankings are presented. Motor control has been ranked #1 in virtually all categories related to graduate education, publications, and federal grants. These are the categories that dominate the ranking of the kinesiology programs developed by the AAKPE (Thomas & Reeve, 2006; Thomas et al., 2007).

The term *motor control* has two components to it, *motor* and *control*. Being an educator and/or a researcher in this area requires a solid background in disciplines related to these two components. These disciplines are illustrated in Figure 1. The *motor* part is based on anatomy, muscle physiology, and physics (in particular, mechanics), and the *control* part is based on neurophysiology, psychology, and mathematics (in particular, control theory). Taken together, these disciplines form what can be also called *physics of living systems*. Motor control has many applied aspects, in particular, those related to impaired control and coordination of movements in various neuromuscular disorders; effects of development, aging, and practice on motor control and coordination; and effects of motor rehabilitation.

**Table 1 Data for the Seven Areas of Emphasis in the Graduate Program in Kinesiology at Penn State**

Area	Doctoral degrees awarded	External graduate assists.	Total dollars external awards (K)	Total dollars per faculty (K)	Journal publications	Journal publications per faculty	Same with impact factors, 2005 only
Athletic Training	11	6	0	0	35	18	2.7
Biomechanics	15	22	2,500	420	185	31	15.3
Exercise Physiology	5	8	7,700	1,550	106	21	10.4
History and Philosophy	4	2	0	0	21	11	2.4
<b>Motor Control</b>	<b>18 (1)</b>	<b>33 (1)</b>	<b>7,000 (2)</b>	<b>1,750 (1)</b>	<b>206 (1)</b>	<b>51 (1)</b>	<b>20.8 (1)</b>
Pedagogy	0	2	0	0	17	9	2.5
Sport Psychology	3	3	250	85	69	23	12.6

*Note:* The data are presented over 6 years (2000–2005) except for the last column, which presents the data for 2005 only. The data for motor control are in bold; the number in parentheses shows the rank among the seven areas of emphasis. I am grateful to Dr. John Challis and Dr. Neal Sharkey who summarized these data and made them available for the faculty in the Department of Kinesiology at Penn State.



**Figure 1** — The discipline structure of motor control—physics of living systems.

Overall, it combines approaches across most (if not all) of the more-traditional components of kinesiology, and this allows me to claim that it is indeed in the center of kinesiology—representing its heart.

The crossroads of so many disciplines present challenges to both students and faculty who have to be knowledgeable in all these areas, but these same crossroads also contribute to the breadth and excitement of the field of motor control. I am not a big fan of fashionable buzzwords. In the field of motor control (and kinesiology, in general), one of such recent expressions has been *multidisciplinary approach* (there are also *interdisciplinary* and *transdisciplinary* approaches, but I do not want to turn this brief paper into a discussion on linguistics). I am afraid that, more frequently than not, all these expressions try to conceal (and simultaneously reflect) the fact that motor control (and kinesiology) is not yet a discipline; it does not have a developed set of exact notions that would form its foundation and make it comparable to, for example, physics or chemistry. By the way, very rarely would a physicist call his or her research *multidisciplinary* or *interdisciplinary* or *transdisciplinary* because these words make little sense within a well-defined discipline.

Researchers perform motor control studies for two major reasons. Some of them want to understand how natural movements are controlled by the CNS. Others want to understand the logics of the functioning of the CNS using movements as a tool, as relatively easily observable and objectively quantifiable manifestations of the CNS's functioning. Indeed, since the functioning of the CNS is not directly observable, the well-developed apparatus of classical mechanics makes movements very attractive manifestations of the CNS's activity. Movements are much easier to observe and quantify as compared with such phenomena as memory, emotions, abstract reasoning, etc. It is not surprising that many contemporary hypotheses on the organization of functionally important interactions among brain structures are based on observations of movements in healthy humans, patients with certain disorders, and animals with experimental lesions of the CNS.

## The Major Controversy in the Area of Motor Control

In this section, I would like to describe briefly what I see as the central controversy in the field of motor control. I am going to use this controversy to illustrate what kind of knowledge and research tools are expected from researchers in this area, which will lead me directly to the issues of what kind of educational programs would be appropriate to train such researchers. This controversy has already been mentioned in the first section on the history of motor control; it can be formulated in the form of a question: Are living beings active or reactive systems?

For centuries, voluntary movements of humans (and animals) had been viewed as driven by a soul, will, or intention. Accepting such unobservable factors as the main cause for movements was not very attractive to scientists of the 19th century who were inspired by the impressive success of physics in describing the behavior of the inanimate nature. This dissatisfaction led to the emergence of two very influential theories that viewed movements as combinations of reflexes. These very materialistic theories tried to describe all movements as consequences of the activation of reflex loops, relatively simple and perfectly predictable. The authors of these theories, Sherrington and Pavlov, had a lot of students and followers, and their theories dominated the thinking in neurophysiology for at least half a century.

The Pavlov–Sherrington team met resistance from a few nonbelievers who were much less decorated and did not look like dangerous opponents. I would like to mention two names, those of another British scientist and another Russian scientist, Graham Brown and Nikolai Bernstein. Both were dissatisfied with the obvious inability of the reflex-based theories to account for some of the experimental observations. In particular, Graham Brown showed that locomotor-like movements could be seen in an animal with the nerves carrying sensory information cut, that is, without reflexes. Bernstein emphasized natural movement variability, which could not lead to repetitive patterns of neural activity within the CNS that were a prerequisite for elaboration of new reflexes according to Pavlov's theory. Graham Brown and Bernstein insisted that natural voluntary movements could be generated within the central nervous system leading to the notion of a central pattern generator (Graham Brown) and the physiology of activity (Bernstein, see Meijer, 2002). Bernstein viewed movements as reflections of *engrams*, that is neural precursors of movements stored in memory and expressed in undefined variables that encoded essential movement features, such as its topology.

About half a century later, in the 1970s and 1980s, a similar argument took place. Bernstein's idea of engrams was developed by Richard Schmidt in the form of the generalized motor program theory (schema theory, Schmidt, 1975). Schmidt assumed that motor programs stored in the brain could be scaled in time and magnitude and led to required force patterns in the periphery, resulting in coordinated movements. This view met resistance from a group led by Scott Kelso, Peter Kugler, and Michael Turvey who emphasized the importance of coupling between the environmental factors (both mechanical and perceptual) and processes within the CNS (reviewed in Kugler & Turvey, 1987). To formalize these coupling relations, the Kelso–Kugler–Turvey group used the computational apparatus of the theory of dynamic systems (developed by mathematicians and physicists in the 1960s). Both lines of thinking claimed success in accounting for experimental data.

Now, nearly 100 years after the great works by Sherrington–Pavlov and by Graham Brown–Bernstein, the discussion on the role of active versus reactive processes in the production of voluntary movements is still very much alive. The development of both experimental and computational tools has resulted in an updated and much more sophisticated version of the generalized motor program, which is known under the name of *internal models* (reviewed in Kawato, 1999; Wolpert, Miall, & Kawato, 1998). According to this view, the CNS imitates (emulates) the input–output relations (and their inverses) within the body and between the body and the environment. These computations are used to specify requisite forces for planned movements. An alternative to this view is the equilibrium-point hypothesis of motor control (reviewed in Feldman, 1986; Feldman & Levin, 1995), which views voluntary movements as resulting from centrally generated changes in parameters of reflexes, such as their threshold values. As such, the equilibrium-point hypothesis synthesizes the two views: The CNS can actively produce changes in control variables, but these variables do not define forces, displacements, or other output mechanical variables; instead, the control variables define parameters of equations that specify how the body is coupled to environmental variables and thus define its equilibrium states (for an update, see Feldman & Latash, 2005).

This brief description of the history and current situation in motor control illustrates the importance of deep knowledge in a variety of fields for future professionals in this area of kinesiology. To understand the dynamic systems approach, one has to have a solid background in the theory of nonlinear differential equations and in physics of nonequilibrium processes (particularly, related to issues of stability). Recent studies by advocates of the idea of internal models are based on branches of control theory and classical mechanics. Many of these studies use brain-imaging techniques and require knowledge of the brain anatomy, physiology, and methods of brain imaging. The equilibrium-point hypothesis requires deep understanding of neurophysiology and physics. All of these approaches use rather sophisticated statistical tools of data analysis and, naturally, require solid knowledge of statistics. So, here we come to what seems to be a major problem not only in motor control but across all kinesiology areas and programs: How should faculty educate future professionals?

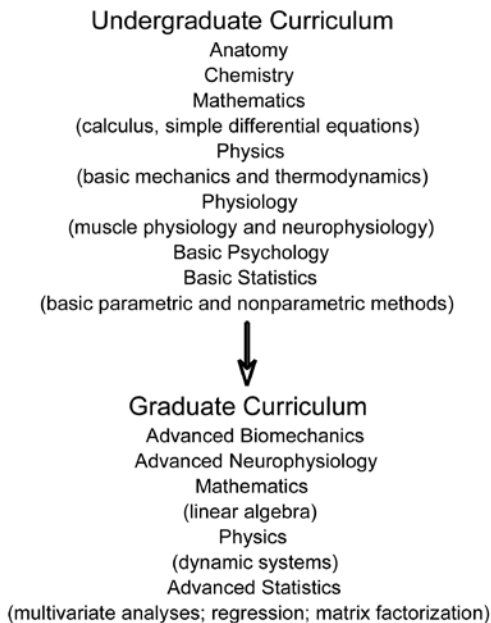
## **How Should Future Professionals in Motor Control Be Educated?**

As of now, many of the most productive and influential researchers in the field of motor control come from areas outside of kinesiology (movement science, exercise science, etc.). These researchers were trained as physicists, physiologists, engineers, physicians, psychologists, physical therapists, mathematicians, etc. This situation is not atypical or unexpected: When a novel field of study is being developed, it attracts adventurous young professionals from many better-developed disciplines. When a field of study claims to have established itself as a discipline, however, one would expect the best professionals in this field to be trained in this very field. Nearly all successful physicians have been trained in medicine, nearly all physicists in physics, and nearly all mathematicians in mathematics. Kinesiology (and

motor control) should strive to develop a program of education that would produce more-successful professionals as compared with those who had been educated in a different area and then decided to switch to kinesiology.

This requires, as the vital first step, realizing that old educational programs that were developed decades ago to educate future professionals in physical education and athletic training have to be changed qualitatively. Research in motor control is based on two pillars, physics and physiology. Hence, a successful professional has to know laws of inanimate nature and specific features of the design and functioning of the human (animal) body. These two pillars have to be solid, as solid as those produced by the current programs in the departments of physics and physiology. Giving students superficial information “about physics” and “about physiology” is doing more harm than good. The students learn to repeat right words in right combinations with little understanding of what these words mean. I would challenge my colleagues to perform an experiment I have been performing for years at Penn State. At the beginning of a 400-level course, ask your seniors to define such basic notions as *mass*, *stiffness*, *linear relation*, *variance*, and *reflex*. Nine out of ten cannot do this adequately. It is no surprise that most graduate students in kinesiology come with an undergraduate degree not in kinesiology but in a variety of other, better-established disciplines.

Let me suggest the following structure (Figure 2) that, I hope, will look attractive to most of my colleagues who are involved in both education and research in kinesiology (in particular, in motor control). In the following, when I write, for example, *Physics*, I mean not some softened “*Physics for Kinesiology*” but good, old, solid physics, possibly illustrated with problems from movement science.



**Figure 2** — The proposed scheme of undergraduate and graduate education in motor control (kinesiology).



## Undergraduate Courses

Students would begin with introductory courses (100 level): *Biological Basis of Movement* and *Physical Basis of Movement*. These would be followed by 100- to 300-level courses: *Anatomy*, *Chemistry*, *Mathematics* (calculus, simple differential equations), *Physics* (basic mechanics and thermodynamics), *Physiology* (muscle physiology, neurophysiology), *Basic Psychology*, *Statistics* (basic parametric and nonparametric methods).

After taking all these courses, the students will be ready for special topics that deal with advanced aspects of kinesiology (in particular, with motor control). Just imagine how great it would be if our students who take 300- and 400-level courses such as *Biomechanics*, *Exercise Physiology*, *Movement Disorders*, *Science of Training Athletes*, *Motor Development*, *Motor Control*, etc. knew all the mentioned material! Many of the graduates of such a program would be very competitive in applications to graduate schools. We would not be forced to look outside the area of kinesiology for well-prepared graduate students.

## Graduate Courses

At the graduate level, students would take *Advanced Biomechanics*, *Advanced Neurophysiology*, *Mathematics* (linear algebra), *Physics* (advanced mechanics, nonequilibrium systems), *Statistics* (analysis of variance, multivariate analysis, regression methods, matrix factorization techniques), and then—*Advanced Motor Control*.

## Major Challenges in Motor Control

The main challenge of motor control (and kinesiology in general) seems to be turning it into an exact science, just like physics. In fact, motor control is physics that deals with variables that are hard to measure and, sometimes, hard to define. For any science, an absolutely necessary first step is to introduce an adequate language, a few central notions that are inherent to problems of the new science and make it different from other sciences (Gelfand, 1991; Gelfand & Latash, 1998). Ancient Egyptians knew quite a bit of applied geometry. We associate the science of geometry, however, with the name of Euclid, who was brave enough to introduce the notion of point as something that has no width, length, or height. It was obvious to everybody, including Euclid, that such objects did not exist. This seemingly meaningless notion, however, was very fruitful leading to the notions of line, plane, etc. and resulting in the development of geometry as a science. Classical physics started with the introduction of the notion of force as something that changes movement of objects with inertia. This is a circular definition, of course, because inertia is defined through force. Nevertheless, physics would not be the science we know it without this ill-defined notion.

Currently, movement science is filled with loose terminology. Textbooks and papers operate with expressions such as *motor program*, *schema*, *muscle tone*, *synergy*, *internal model*, etc. Typically, none of these is provided with a clear and unambiguous definition. Well-established notions from physics and mathematics such as, for example, *stiffness* and *dynamic system* are used in a fuzzy, imprecise way. Such texts create an impression of the author winking at you and saying:

“Certainly, you understand what I am talking about, right?” It is very difficult to answer No, in particular, if you are a student reading a book or a paper by an established professor. It is tempting to accept the rules of the game, to start juggling the same terms, and to join the club.

The worst possible way to investigate a complex phenomenon is to discuss it with hints. Unfortunately, movement science is currently based on a lot of hints and very few exactly defined notions. It lacks clarity and exactness—the two absolutely necessary prerequisites for true progress in science.

Therefore, the most urgent task seems to be developing a set of adequate notions that are well defined and operationalized such that they can be identified and measured in at least a mental experiment. The natural next step would be developing appropriate methods to measure variables relevant to the adequate notions.

I should probably not have drawn such a bleak picture of motor control. In fact, given the complexity of the object of study, progress in this area has been substantial. I would like to mention several directions of research that try to bring motor control closer to becoming an exact science. The first is the equilibrium-point hypothesis that was introduced by Anatol Feldman in the mid-1960s (Feldman, 1966; reviewed in Feldman & Levin, 1995). This hypothesis is based on the solid experimental support from neurophysiology and on the solid theoretical foundation from physics. Another encouraging example is the study of stability of motor behavior, in particular using the methods developed within the dynamic systems (reviewed in Schöner, 2004). The third one is the recent attempts to introduce an exact definition for one of the traditionally used terms, *synergy*, and to develop an experimental and computational approach that allows us to quantify synergies (reviewed in Latash, Scholz, & Schöner, 2002, 2007).

## Motor Control in 2050

Our current undergraduate students will be approaching retirement in 2050. So, it is their students who will define the state of motor control (in this section, *motor control* can be in most places substituted with *kinesiology*). If we could take a peek at the state of motor control in the middle of the 21st century, what would we like to see and what would we hope not to see?

The field of motor control becomes a science. We hope that it manages to develop a set of adequate notions that will make it different from other areas including physics. If, after a series of honest attempts to develop such a set of notions, all these attempts fail, motor control should merge with physics of the inanimate world and stop pretending to be a separate discipline. The undefined terms should either disappear or become defined in an exact and unambiguous way.

Tools are developed that allow us to measure variables directly related to the introduced adequate notions (assuming that they exist). For example, if the equilibrium-point hypothesis survives the test of the next 40 years, as it has been successfully doing so far, reliable tools for measuring control variables (“lambda-meters”) have to be invented.

We would like to see leading researchers in the area being well educated in all the aspects of motor control. We hope that these leaders will be vocal and

charismatic, but maybe not too charismatic. In particular, churches in motor control should disappear. Under *churches* I mean directions of research that are led by charismatic leaders who insist that using an impressive sounding set of keywords (or equations) is necessary and sufficient to be a good scientist.

Both undergraduate and graduate programs in motor control are established and show consistency similar to that among the undergraduate programs in physics in our days. This means that new textbooks are written based on the accepted set of adequate notions. The undergraduate education produces students who take 90% of all the available vacancies in the graduate programs simply because they are better prepared to do graduate-level research in motor control and kinesiology in general.

This picture may look utopian, and maybe it is. But it seems better to pursue a not-very-realistic goal than to not pursue any goal at all. Motor control is a young and energetic subfield of kinesiology. It is in desperate need of well-trained professionals who will not expect other, better-established disciplines to formulate problems of motor control and offer solutions. Motor control (and kinesiology) should help itself and by 2050 become a respected science.

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