Hot Topics in Motor Control and Learning: Introduction

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The Dynamic Systems Approach to Motor Control and Learning: Promises, Potential Limitations, and Future Directions

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The three papers that follow comprise the content of a symposium presented at the 1997 meeting of the North American Society for the Psychology of Sport and Physical Activity. The primary objective of the papers is to provoke discussion concerning the benefits and possible limitations of what is generally termed the “dynamic(al) systems approach” to the study of motor behavior. Much of the material included here assumes a rudimentary understanding of the tenets of this approach and a passing knowledge of the more often cited findings. At the same time, we have attempted to provide at least some information that may prove interesting for a more general readership. We will begin with a very broad introduction to this approach as a preface for the three papers that follow (for a more in-depth depiction see, for example, Kelso, 1995).

Classical mechanics comprises the study of statics and dynamics, with the latter further dichotomized into kinematics (pure motion) and kinetics (forces underlying motion). This traditional definition of dynamics, however, does not accurately convey the flavor of the dynamical systems approach or, more specifically, the interdisciplinary area of research referred to as nonlinear dynamics. The term dynamical system has been attributed to the influential work of the mathematical topologist Stephen Smale in the 1960s–70s (Stewart, 1989). But the roots of this approach extend to Poincaré’s creation of topology, a geometric approach to the study of continuity (smooth, gradual changes), at the turn of the century (Garfinkel, 1983). The problem addressed by Poincaré was whether or not the solar system is stable. Newton previously provided the means for an analytic description (differential equation) of the dynamics of a system of two heavenly bodies, but the stability of three or more point masses (i.e., the “three body problem”) proved to be accessible only to topological techniques pioneered by Poincaré. An example of such a technique is the use of a surface now termed a “Poincaré section,” which portrays the state of a periodic system at a given point of successive cycles. This method of examining a cross section of trajectories allows one to determine whether a system exhibits stable, periodic behavior. This technique is still extremely useful today.

In dynamical systems terminology, behavior is described as a flow in “phase space” rather than as a time series. Phase space comprises a multidimensional representation of the state of a system. A dynamical system can be characterized as a “vector field” that depicts predictable change in behavior (a vector) as a function of cur-
rent state (Abraham & Shaw, 1982). It is critical to note that this descriptive form applies to “autonomous” systems, implying time-independent control (i.e., it is assumed that time is not a parameter of movement that is directly controlled). Relevant constructs include the characterization of the preferred behavior a system eventually settles into (an “attractor”), the behavior in the “neighborhood” of an attractor (i.e., its “basin of attraction”), and boundaries between basins (“separatrices”). All these can be identified formally, if they are present.

Tools provided by the dynamical systems framework have been useful for studying systems sufficiently complex to defy attributing their behavior to individual system components and their linear interactions. Initial applications were limited to physical systems, but dynamical descriptions of living systems and their interactions have appeared in the last decades (see Strogatz & Stewart, 1993). Advocates contend that the appeal of these new methods for understanding biological systems in general and, for present purposes, human motor behavior, in particular, is that a range of phenomena previously beyond a physical understanding now appears to be within the realm of a deterministic description. With the concept of stability at its center, transitions from one stable regime to another (e.g., gait transitions) can be understood as bifurcations caused by the continuous change in a single parameter. The phenomenon of equifinality (i.e., the attainment of a goal state despite perturbations) can be understood as point attractor behavior in which perturbations are compensated for automatically. And the ubiquitous cyclic behavior found in nature can be interpreted as the limit cycle attractor of a nonlinear system, with synchronization among rhythms acknowledged as a fundamental characteristic of nonlinear coupled oscillations.

These parallels between properties of nonlinear dynamic systems and fundamental phenomena of biological systems motivated some researchers in movement science to interpret coordination from this theoretical vantage point. The overarching theme is that a number of phenomena seeming to require the control of some intelligent homunculus may arise from the flow of a deterministic nonlinear dynamic system. Once initial conditions and a particular dynamic regime are established, the inherent dynamics of a system generate action; control is autonomous. This approach to movement coordination is firmly situated in a physical analysis and cast in formal mathematical language, so it affords precise predictions that allow rigorous testing of their validity. Moreover, as this approach shares a theoretical language, formal tools, and universal concepts with many other sciences, proponents emphasize that it provides a unique opportunity for an interdisciplinary and comprehensive account of biological behavior. The following contribution of Sternad demonstrates the application of such a nonlinear analysis to the complex task of bouncing a ball on a racket. On the basis of a task analysis, predictions are made as to whether subjects are sensitive to dynamic stability properties. Variations in intra- and interindividual performances are modeled as systematic variations of one dynamic regime rather than resorting to an executive controller responsible for these properties.

As noted above, the dynamical systems approach assumes that control is autonomous (i.e., human movement evolves as a function of current state rather than as the result of a preorganized time series). Relatedly, it posits that the role of cognition in motor control and learning should not be assumed a priori. Alternative accounts involving motor programs assume that cognition is important and typically invoke time as a component of control. The subsequent papers by Lee and Walter explore hybrid views of the role of dynamical systems constructs in motor behavior. These views assume that, in and of themselves, dynamical descriptions do not necessarily imply a particular theoretical stance regarding the substrates of motor behavior. Employing dynamical systems concepts to describe motor behavior (or components of behavior), in other words, does not necessarily preclude invoking cognitive mechanisms to explain motor behavior. Note that in this regard the control mechanism proposed in Adams’ closed-loop theory (1971), a classic information processing account of motor behavior, yields a “point attractor.” But had he chosen to use this term in his paper (which, of course, he didn’t), the theory itself would still have been firmly entrenched in the cognitive camp. It is important to recognize this distinction because it suggests that the tools of dynamical description may be useful for investigators adopting any number of theoretical perspectives. The assumption that system dynamics inform control (i.e., the proposition that control must accommodate intrinsic dynamics), for example, would appear to hold true regardless of the type of control hypothesized. Dynamical constructs are often used metaphorically in this more hybrid approach, but formal modeling is not excluded. This perspective broadens theoretical discourse to include the possibility of complementary roles for autonomous and cognitive components of control.

Mindful of Nietzsche’s caveat that “a hammer is in an unsuitable position to assess its usefulness as a tool,” the present contributors were assembled to represent a relatively broad spectrum of theoretical commitment to the dynamical systems framework. The first commentator (Dagmar Sternad), the most ardent advocate of the dynamical systems framework of the three authors, provides a brief background and overview of this approach as applied to motor behavior, followed by an example of its formal instantiation with respect to issues of movement stability, individual differences, and motor equivalence. The second paper (Charles Walter) addresses the tenability of a number of statements regarding the “strong” version of the dynamics approach as it currently stands and suggests that a more conservative, delimited view of the role of
dynamic pattern formation in motor control and learning should be considered. The final commentary (Tim Lee) notes that there are, in fact, a number of consistencies between the predictions of the dynamic systems approach and the more traditional cognitive approach at the descriptive level. A number of empirical and conceptual problems regarding the former are then discussed.

The exchange of ideas is perhaps best facilitated by provocative comments; therefore, this collection of papers includes content ranging from novel empirical findings to intentionally controversial assertions. Above all, the papers are intended to serve a heuristic function. We hope this collection may in some small way further the discussion regarding the relative merits and potential limitations of this expanding approach to the study of motor behavior.

References


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