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Review

Comparing dynamical systems concepts and techniques for biomechanical analysis

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Abstract

Traditional biomechanical analyses of human movement are generally derived from linear mathematics. While these methods can be useful in many situations, they do not describe behaviors in human systems that are predominately nonlinear. For this reason, nonlinear analysis methods based on a dynamical systems approach have become more prevalent in recent literature. These analysis techniques have provided new insights into how systems (1) maintain pattern stability, (2) transition into new states, and (3) are governed by short- and long-term (fractal) correlational processes at different spatio-temporal scales. These different aspects of system dynamics are typically investigated using concepts related to variability, stability, complexity, and adaptability. The purpose of this paper is to compare and contrast these different concepts and demonstrate that, although related, these terms represent fundamentally different aspects of system dynamics. In particular, we argue that variability should not uniformly be equated with stability or complexity of movement. In addition, current dynamic stability measures based on nonlinear analysis methods (such as the finite maximal Lyapunov exponent) can reveal local instabilities in movement dynamics, but the degree to which these local instabilities relate to global postural and gait stability and the ability to resist external perturbations remains to be explored. Finally, systematic studies are needed to relate observed reductions in complexity with aging and disease to the adaptive capabilities of the movement system and how complexity changes as a function of different task constraints.

Keywords: Adaptability; Complexity; Dynamical systems; Nonlinear dynamics; Stability; Variability

1. Introduction

Bernstein[1] presented research paradigms that led investigators to explore the rich patterns of movement that the human system is capable of producing. Traditional methods in biomechanics and motor control often have focused on discrete movement variables or linear relations in the times series of the components of the system. However, these methods lack the fidelity to fully explore this richness in movement patterns and led researchers toward a dynamical systems approach to the study of human behaviors. A dynamical system is one in which behaviors evolve over time. Current analysis methods from a dynamical systems perspective focus on the spatio-temporal evolution of the system dynamics over a period of time that can encompass steady state as well as abrupt qualitative changes in behavior.[2] Many of these analysis techniques derive from the study of nonlinear methods as opposed to the traditional linear approach. To illustrate the differences we will first discuss the distinction between linear and nonlinear methods.

Linear methods interpret the structure of data through linear correlations.[3] The implication is that the intrinsic dynamics of a system are governed by the fact that small changes in the system result in small effects. Linear equations can only lead to solutions that decay, grow, or maintain a steady state. If we use as an example the population of an animal species (N), the linear equation will take the form of a straight line with growth rate R:

$$N_{i+1} = RN_i \quad (1)$$

where N_i is the present population value and N_{i+1} is the value of N at the next instant in time (or generation). The system is decaying (i.e., N_i is getting smaller) when $0 < R < 1$, growing (i.e., N_i is getting larger) when $R > 1$ and is at steady state (i.e., N_i remains constant) when $R = 1$. Traditional approaches in

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biomechanics are based in linear methods that have brought the discipline to its current state, but to move forward we need to incorporate alternative analysis techniques and interpretations.

Over the past several decades researchers have moved toward a dynamical systems approach to the study of human movement. In this case, human movement is determined by nonlinear responses. For example, tissues such as tendons show nonlinear characteristics in response to stretch. For our population example, these nonlinearities emerge when we make the growth rate R dependent on the population size through the function $(R - bN_i)$; when the parameter b is positive the growth rate decreases as the population grows. This provides the following nonlinear finite difference equation:

$$N_{i+1} = (R - bN_i)N_i \tag{2}$$

Since the parameters R and b can vary independently, the only variable that can affect the dynamics of the system is:

$$x_i = \frac{bN_i}{R} \tag{3}$$

If we substitute x_i and x_{i+1} into the previous equation, we get:

$$x_{i+1} = Rx_i(1 - x_i) \tag{4}$$

The nonlinear logistic equation is an example of a quadratic map and demonstrates how complex dynamics can result from (sometimes simple) nonlinear equations. In the logistic map we can observe steady state dynamics, bifurcations to periodic regimes, and chaotic dynamics that show bounded aperiodic behavior with sensitivity to initial conditions. These bifurcations and different system dynamics all occur as a function of a single parameter (R) change. Note that chaotic dynamics emerge in deterministic systems in which future states should formally be predictable but where uncertainty in initial conditions impacts prediction of future states. Human movement systems are not governed by these deterministic dynamics and more likely present stochastic behaviors governed by probabilities of states that can be impacted by deterministic and random processes.[4]

The formal examples above demonstrate the distinctive features of linear and nonlinear systems. By understanding these differences we can acknowledge that there are many physiological responses that have a nonlinear behavior: e.g., biological tissue, human behavior and human movement. These nonlinearities suggest that to accurately interpret human movement we should move toward nonlinear analyses. The dynamical systems approach focuses on how systems: (1) maintain their current state, addressing questions related to stability, (2) change or transition between states, addressing aspects of variability and adaptability, and (3) regulate complexity or fractal dynamics, characterized by interactions across different spatio-temporal scales as well as invariance of processes across these scales. Research on human movement in general and biomechanics in particular inspired by this dynamical systems approach has incorporated these concepts extensively but has often used terms such as stability, variability, and complexity interchangeably. The purpose of this paper is to compare and contrast the concepts of variability, stability, and complexity and how these impact movement adaptability. We will demonstrate that, although these concepts are clearly related, each presents different aspects of the system dynamics that requires careful *a priori* definition and consideration of their use in biomechanical research.

2. Variability and human movement

Many researchers have been concerned with the variability of movement.[5] It has been demonstrated many times that, even with expert performers, movement behaviors cannot be replicated from one trial to the next with any degree of accuracy.[6] Variability has been defined from a statistical point of view and is expressed as the variance (or the square root of the variance, that is, the standard deviation) about the mean.[4] It should be noted that the variability of a performance may not simply be additive in the form of "measurement noise" but can be essentially part of the signal. The physiological variability or the actual variation from iteration to iteration can be explained by examining the following equations.[3] If we define a system as:

$$x_{n+1} = F(x_n) \tag{5}$$

then the following equation adds measurement noise that is additive:

$$x_{n+1} = F(x_n) + \mu_n \tag{6}$$

where μ_n represents the process or measurement noise added to the system. Additive process noise can never be completely removed from the signal but can be attenuated using various signal processing techniques. However, the variability resulting from multiple trials of the same performance may actually be part of the signal and cannot be removed from the signal. This is expressed in the following equation:

$$x_{n+1} = F(x_n + \beta_n) \tag{7}$$

where β_n characterizes "dynamical noise" instead of measurement noise and may represent inherent physiological variability that is part of the system dynamics.

While this definition is widely used for all sources of variation in a performance, the meaning of the variability must be understood in the context of the measurement. There are essentially two types of variability that can be determined: (1) end-point variability (i.e., the variability at the goal level) and (2) coordinative variability (i.e., how the performance was conducted over a number of iterations). End-point variability, the traditional focus of most research on variability, determines the outcome of the performance and has been used as an indicator of the level of performance skill. For example, in pistol shooting, keeping the barrel of the gun aimed precisely at a target with little or no variability is essential for the outcome (i.e., to hit the target accurately).[7] However, low end-point variability (and high level of task performance) is not necessarily accompanied by low variability at the level of the coordinative dynamics. This was shown by Arutyunyan and colleagues[7] in 1968 in an experiment on expert marksmanship performance (Fig. 1).