Non-linearity in the dynamic world of human movement

Non-linear dynamics, fractals, periodic oscillations, bifurcations, chaos, and other terminologies have been used to describe human biological systems in the literature for a few decades. The eight manuscripts included in this special issue discussed the historical background, selected theoretical frames, exemplar concepts, as well as some current applications in the field of non-linear dynamical systems. For example, in the first paper in the series, van Emmerik and colleagues\(^1\) have tried, very successfully in my opinion, to discuss the differences and commonalities among the terms of “variability”, “stability”, and “complexity”, and also how they all related to human biological system’s adaptability to human movement. Along this line, Williams III and his group\(^2\) have tried to compare the results approximate entropy, a non-linear measure of variability and its structure, and stability measured by the reaction of upright standing posture to external perturbation. These discussions can help us clarify some fundamental and important concepts when we investigate non-linearity in human movement dynamics.

An easier way to introduce non-linear system is comparing it to linear system. The following Eqs. represent the key features of a linear system:

\[
f_1(x) = ax + b
\]

\[
f_2(y) = cy + d
\]

\[
f(x, y) = f_1(x) + f_2(y) = ax + cy + e
\]

Eqs. (1) and (2) represent proportionality, where outputs \(f_1(x)\) or \(f_2(y)\), bear straight-line relationships to their inputs, \(x\) or \(y\), respectively. Eq. (3) represents superposition, output of the linear system, \(f(x, y)\), composed of multiple components, \(f_1(x) + f_2(y)\), can be fully interpreted by the outputs of their components and the definitions of their individual input–output relationships. A linear system’s behavior is the summation of its components’ behavior.

However, non-linear systems do not present the characteristics of proportionality and superposition. A simple yet well-studied example of non-linear Eqs. is the logistic Eq. in population biology:\(^3\)

\[
X_{N+1} = aX_N(1 - X_N)
\]

Where “\(X_n\)” is the population of generation “\(N\)”. In this Eq., the current value of the output (\(X_0\)) becomes the next input value (\(X_{N+1}\)). This simple logistic Eq. reveals extraordinarily complex dynamics of population growth. The outputs of the Eq. are highly dependent upon the value of parameter “\(a\)”. The population can reach steady state of decline or growth, sustained periodic oscillations, or even highly erratic fluctuations.\(^3\) The following example (Fig. 1) gives a simple illustration of this phenomenon. This chart illustrates how the value of “\(a\)” influences the population “\(X\)” developments from generation 1 to 10. A numeric change of “\(a\)” could lead a population to disappearance (\(a = 0.5\)), to reduction (\(a = 1.5\)), to increase (\(a = 2.5\)), or to oscillation in a large range (\(a = 3.5\)). The series of \(X_n\) (\(N = 1\) to 10, \(X_0 = 0.5\)) reveals: the population will be distinct after a few generations if \(a = 0.5\); decrease but could be stabilized with \(a = 1.5\); increase but soon be stabilized where \(a = 2.5\); but the population experiences great oscillation within 10 generations if we set “\(a\)” at 3.5. Thus, for non-linear systems, small changes within the system can lead to very different results. The effects of parameter “\(a\)” on the population growth have been referred to as the “butterfly effect” sometimes—small changes in the initial state of a deterministic non-linear system can lead to drastic differences in system behavior later on.

The interaction between the components of a non-linear system challenges the superposition paradigm.\(^4\) Examples that represent violation of the superposition principle from this series include the studies of movement\(^5\) or interpersonal\(^6\) coordination. The non-linear coupling between components generates behaviors that cannot be explained using traditional models. Therefore, the term “emergence” is often used when studying non-linear dynamic systems for the apparent pattern

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\(^{1}\) van Emmerik and colleagues

\(^{2}\) Williams III

\(^{3}\) logistic Eq.: \(X_{N+1} = aX_N(1 - X_N)\)

Fig. 1. Exemplar non-linear system — the population logistic Eq.: \(X_{N+1} = aX_N(1 - X_N)\); \(N = 1, 2, 3, \ldots 10\); with \(a = 0.5, 1.5, 2.5,\) and 3.5.
Bifurcation is one of the examples that sudden abrupt changes could happen within the non-linear system. Bifurcation is the phenomenon where a minuscule change in the control parameter could cause the behavior of the system to change qualitatively, such as walk-to-run gait transition occurs within a relatively small range of locomotion speed (for a brief discussion of walk-to-run transition, see Li and Ogden).

Dynamics systems can be studied using non-linear parameters. For example, the use of multiscale entropy (MSE) has been reviewed in the context of assessing physiological complexity, employing the complexity underlying the control of posture as example for applications. The authors demonstrated that MSE can be used to identify functional changes in posture fluctuations between clinically different subgroups of children with adolescent idiopathic scoliosis, and “loss of complexity hypothesis” in cases of aging and disease related declines in physiological functions. Further, Chagdes and co-workers demonstrated the emergence of limited cycle oscillators among people with mild Parkinson’s disease using non-linear parameters generated from anterior–posterior postural sway.

Non-linear parameters are more sensitive, at times, than traditional linear parameters in detecting coordination differences due to the dynamic nature of human movements. Seay and his group reported that people with history of low back pain, although symptom free for more than 6 months, still have different coordination patterns during lifting measured by continuous relative phase, comparing to people who had no history of low back pain. Measure of coordination variability was reportedly more sensitive than conventional kinematic quantities when studying kinematic characteristics of athletes who compete at different levels. Research suggests that the potential of non-linear measures, such as variability of continuous relative phase, could be very practical in the development of wearable technologies. Furthermore, a new technique, multifractal detrended fluctuation analysis, can be successfully used for investigating coordination between two people.

The application of linear and non-linear assessments to post-concussion postural control has been reviewed in details. Buckley and colleagues suggested that comparing to current widely used evaluation for acute concussion, i.e., the balance error scoring system combined with traditional linear assessments, non-linear parameters, such as approximate entropy, could be more sensitive to the recovery process for concussion injury.

As suggested by the authors of our first paper in the series, although it is evident that reduction of complexity due to aging, injury, or disease could happen, systematic studies are needed to assess and relate these reductions in complexity to adaptive capabilities to human movement. For example, aging leads to degradation of the complex biological system within the human body; non-linear dynamics analysis provides a promising tool when analyzing strategies of restoring the complexity of the system. Study of non-linear dynamics provides us an avenue to understand the complexity of human movement dynamics and to evaluate biological adaptivity to coaching, exercise, rehabilitation, and physical activity in general.

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