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DYNAMICAL SYSTEMS THEORY: a Relevant Framework for Performance-Oriented Sports Biomechanics Research

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Dynamical systems theory has emerged as a viable framework for modeling athletic performance, owing to its emphasis on processes of coordination and control in human movement systems. Here we review literature on the performance aspects of fast bowling in cricket to exemplify how the qualitative and quantitative analysis tools of dynamical systems theorists–variable-variable plots, continuous relative phase analysis, cross correlations, and vector coding–can enrich the analysis of segmental interactions in performance-oriented sports biomechanics research. We also indicate how multiple-individual designs combined with analysis tools such as coordination profiling and self-organizing neural networks will help reveal the nature and role of movement variability that is often obscured in conventional studies of groups of subjects. KEYWORDS: control, coordination, cricket, methodology, research design, synthesis. Reprint pdf · Reprint doc · Reviewers' Comments

Dynamical systems theory has emerged in the movement sciences as a viable framework for modeling athletic performance. From a dynamical systems perspective, the human movement system is a highly intricate network of co-dependent sub-systems (e.g. respiratory, circulatory, nervous, skeletomuscular, perceptual) that are composed of a large number of interacting components (e.g. blood cells, oxygen molecules, muscle tissue, metabolic enzymes, connective tissue and bone). In dynamical systems theory, movement patterns emerge through generic processes of self-organization found in physical and biological systems (see Chapter 7 of Williams et al., 1999 for an overview).

Dynamical systems theorists claim that the number of biomechanical degrees of freedom of the motor system is dramatically reduced through the development of coordinative structures or temporary assemblages of muscle complexes (Turvey, 1990). The reduced dimensionality/complexity of the motor system encourages the development of functionally preferred coordination or "attractor" states to support goal-directed actions. Within each attractor region (the “neighborhood” of an attractor) system dynamics are highly ordered and stable, leading to consistent movement patterns for specific tasks. Variation between multiple attractor regions, however, permits flexible and adaptive motor system behavior, encouraging free exploration of performance contexts by each individual. The paradoxical relationship between stability and variability explains why skilled athletes are capable of both persistence and change in motor output during sport performance. Indeed, variability in movement behavior permits performers to explore task and environmental constraints in order to acquire stable motor solutions over time and enhance motor learning. Handford et al. (1997) provide a more detailed explanation of the stability-variability paradox in skill acquisition.

In this position paper, we discuss some implications of dynamical systems theory for performance-oriented sports biomechanics research. A concern aired for some time by many influential investigators is that biomechanical research, and more notably sports biomechanics research, needs to move from its descriptive phase to a more analytical level (Baumann, 1987; Norman, 1989; Nigg, 1993; Elliott, 1999). Indeed, Bartlett (1997) suggested that most performance-oriented sports biomechanics research lacks a sound theoretical rationale and seldom makes reference to motor control theory, universal biomechanical principles, or the fundamental laws of physics that govern them. We have argued previously that dynamical systems theory could provide a relevant theoretical framework for performance-oriented sports biomechanics research, as it offers an interdisciplinary approach to the processes of co-ordination and control in the human motor system (see Glazier et al., 2002). In the present article we use fast bowling in cricket to demonstrate the utility of this interdisciplinary approach for sport scientists.

Fast bowling has received considerable research attention during the past decade. Much of the existing literature has focused on factors that contribute to lower back injuries, but research on the basis of successful fast bowling performance is scarce. A good fast bowling technique is one that allows the fast bowler to bowl quickly with a low risk of injury (Bartlett et al., 1996). It is now well established that the "mixed" bowling technique, which is characterized by a counter-rotation of the shoulder axis relative to the hip axis during the delivery stride, is strongly related to lower-back injury. However, there is no consensus on the relative contributions of biomechanical, physiological, physical and anthropometric factors to ball-release speed.

A key theoretical concept–yet to be fully explored in fast bowling, but integral to many throwing, kicking and striking activities–is the kinetic chain (Atwater, 1979; Bartlett, 2000; Elliott, 2000). This phenomenon is defined as a proximal-to-distal linkage system through which energy and momentum are transferred sequentially, achieving maximum magnitude in the terminal segment (Fleisig et al., 1996). Although several researchers have empirically verified the kinetic chain in fast bowling (e.g. Elliott et al., 1986; Stockill and Bartlett, 1994; Glazier et al., 2000), it is still unclear how body segments are coordinated to optimize energy and momentum transfer. This apparent lack of understanding may, in part, be due to the methods used by investigators to examine body-segment dynamics. For example, previous studies have merely described the kinetic chain in terms of the peak resultant velocities (Elliott et al., 1986) and the peak horizontal velocities (Glazier et al. 2000) of upper extremity body-segment endpoints. Although these procedures clearly provide evidence of a progressive proximal-to-distal increase in segmental velocities, neither study reported the temporal occurrence of peak segment endpoint velocities in relation to ball release, therefore providing an insufficient description of temporal sequencing in fast bowling. However, even with the inclusion of corresponding time histories as reported, for example, by Stockill and Bartlett (1994), identical peak segment endpoint velocities may be generated by completely different acceleration profiles, providing little information about segmental interactions and energy transfer.

To gain a better understanding of how body segments are coordinated in fast bowling, sports biomechanists should refrain from habitually reducing time-series data to discrete kinematic measurements and their corresponding time histories, as this procedure fails to capture the dynamic nature of the movement (e.g. Baumann, 1992). Instead, as a precursor to more sophisticated kinetic analyses, segmental interactions could be examined by analyzing sets of time series data obtained from adjacent body segments or joints with the following qualitative and quantitative analysis techniques commonly used by dynamical systems theorists in motor control research (see Sparrow, 1992; Hamill et al., 2000; Mullineaux et al., 2001 for comprehensive reviews)…

- **Variable-variable plots** (Grieve, 1968; Schmidt and Lee, 1999) have been used extensively to analyze the motion of one joint relative to the motion of another joint (angle-angle plot) and the angle of one joint relative to the angular velocity of that joint (phase-plane plot). These techniques would be useful, for example, for describing the coupling between the bowling arm and non-bowling arm in fast bowling since this aspect of bowling technique has been proposed as an important determinant of ball release speed (Davis and Blanksby, 1976). Variable-variable plots are classified as qualitative analysis tools, as they do not formally quantify coordination. Coordination can only be quantified by the subsequent implementation of other analysis techniques such as continuous relative phase analysis, cross-correlation and vector coding.

- **Continuous relative phase analysis** (Kelso, 1995; Hamill et al., 1999; Kurz and Stergiou, 2002) produces the relative phase angle (the spatial and temporal coupling) of a pair of joints throughout the entire movement cycle. This angle can be obtained by calculating the four-quadrant arctangent phase angle from a phase-plane plot of each joint (see Hamill et al., 2000). Having normalized the time histories of the displacement and velocity data obtained from each joint, continuous relative phase can be calculated by subtracting the phase angle of one joint from that of the other joint at corresponding time intervals throughout the entire cycle. Providing that all the underlying assumptions are satisfied (see Hamill et al., 2000; Kurz and Stergiou, 2002), continuous relative phase can provide an indication of the type of relationship (in-phase or anti-phase) between the pair of joints and the relative amount of in-phase and anti-phase.
- **Cross-correlations** (Amblard et al., 1994) are based on the assumption that linear relationships exist between two sets of kinematic time series data (e.g. pairs of joints) but do not assume that these variables change in synchrony during the movement (Mullineaux et al., 2001). By introducing time lags between data sets and calculating the corresponding correlation coefficients, researchers can obtain an indication of the type of relationship between body segments (in-phase or anti-phase), the degree of linkage between body segments, and the stability of coordination patterns when applied to repeated trials (Temprado et al., 1997). Similar cross-correlation coefficients can result from pairs of time series that have quite different relationships, so it is prudent to interpret a cross-correlation coefficient in conjunction with its time lag and qualitative measures such as angle-angle plots. Also, because cross-correlations measure linearity between time series, they are not particularly useful in determining the degree of linkage between body segments that have a non-linear relationship (Sidaway et al. 1995). In such circumstances, alternative techniques such as vector coding may be more informative.
- **Vector coding** (Whiting and Zernicke, 1982; Sparrow et al., 1987; Tepavac and Field-Fote, 2001; Heiderscheit et al., 2002) is based on the chain-encoding technique devised originally by Freeman (1961). This procedure involves using a superimposed grid to transform the data curve from an angle-angle plot or a position-time plot into a chain of digital elements (see also Whiting and Zernicke, 1982; Tepavac and Field-Fote, 2001). Each of the digital elements that comprise the chain is given a weighting based on the direction of the line formed by the frame-to-frame interval between two successive data points. The chain of digital elements can then be cross-correlated with a chain of digital elements obtained from another angle-angle plot or position-time plot to obtain a recognition coefficient, which is the peak value of the cross-correlation function. The recognition coefficient can then be interpreted in much the same way as the cross-correlation coefficient outlined previously. A limitation of Freeman's (1961) chain-encoding technique is that it requires the data points to be equally spaced (Sparrow et al., 1987). Moreover, this technique converts ratio scale data to a nominal scale, which limits the type of statistical analyses that can be applied and,

> therefore, may mask important information (Tepavac and Field-Fote, 2001). However, the recent introduction of a revised ratio-scale vector-based coding scheme to quantify relative motion data (see Tepavac and Field-Fote, 2001) appears to provide a satisfactory solution to these problems.

A proficient fast bowler must achieve high accuracy as well as a fast ball speed. In the only published study to measure fast bowling accuracy, Portus et al. (2000) examined the interrelations between selected physical capacities, technique, ball release speed and accuracy of 14 A-grade or higher fast bowlers. An image-based motion analysis system was used to obtain kinematic data describing the alignment of the back foot at back foot impact, the alignment of the shoulder axis throughout the delivery stride, and the angle of the front knee between front foot impact and ball release. To obtain an objective measure of bowling accuracy, a cotton sheet marked with three rectangular scoring zones of various dimensions was suspended immediately in front of the batsman's stumps at the other end of the pitch. Finally a radar gun provided a measure of ball speed. Mean bowling accuracy changed little during the 48 balls (deliveries). However, there was a substantial increase in the amount of counter-rotation of the shoulder axis for the group of five fast bowlers who adopted a front-on technique, and counter rotation showed a moderate inverse linear relationship with accuracy. From these results, one may speculate that front-on fast bowlers become less accurate during a prolonged bowling spell because of their tendency to increase the amount of counter-rotation of the shoulder axis when fatigued.

Although the study by Portus et al. (2000) provided a useful insight into fast bowling accuracy, it did not contribute substantially to our understanding of the biomechanical and motor-control mechanisms that underpin control in fast bowling. A major limitation of the research design was that only the last delivery of each of the second, fifth and eighth "overs" (sets of six deliveries) was selected for kinematic analysis–a total of only three out of the 48 deliveries. The rationale for using this design was based on a similar study by Burnett et al. (1995), who examined the effects of a 12-over bowling spell on selected physiological and biomechanical variables in a group of nine potentially elite fast bowlers. These authors reported no significant difference between selected kinematic variables of the fifth and sixth deliveries bowled by each fast bowler during overs one, six, ten and twelve, thus suggesting that the use of a single trial to represent technique at each of these intervals during the spell of bowling was acceptable. However, considering the amount of variability in the accuracy scores reported by Portus et al. (2000), and the assumed causal relationship between technique and accuracy score, Burnett et al. may have failed to detect an effect because of inadequate sampling of deliveries and/or inadequate sample size.

As noted above, the use of a single performance trial to represent generalized performance outcomes is a common practice in performance-oriented sports biomechanics research. An implicit assumption of many sports biomechanists is that skilled motor performance is characterized by little variability between trials. This notion has led sports biomechanists to establish normative values for key performance variables that characterize a hypothetical ideal movement template or common optimal motor pattern that should be considered as the criterion for all performers (Brisson and Alain, 1996). Dynamical systems theorists, on the other hand, argue that the existence of a common optimal motor pattern is a fallacy, owing to the intra- and inter-individual variability typically observed in human motor performance. Movement variability has traditionally been viewed as dysfunctional and a reflection of noise in the central nervous system (Newell and Corcos, 1993). Dynamical systems theorists, however, suggest that movement variability is an intrinsic feature of skilled motor performance, as the variability provides the flexibility required to adapt to complex dynamic sport environments (Williams et al., 1999). Future research on the accuracy of fast bowling and on the performance of other skilled movements should therefore include multiple-individual analyses to better characterize the role of intra- and inter-individual variability of movement in relation to the purpose of the movement (Newell and Slifkin, 1998). Two new tools will enhance these analyses...

- **Coordination profiling** (Button and Davids, 1999) refers to the use of individualized, in-depth analyses to examine how each individual performer uniquely satisfies specific task constraints during goal-directed behavior. In contrast to the traditional approach of pooling group outcome data or error scores to examine central tendencies and dispersion, coordination profiling requires a small number of subjects to perform multiple trials in a repeated measures design. The implementation of various analysis of variance techniques to kinematic data obtained from each subject over repeated trials can establish a generalizable response for each subject, thus helping to identify commonalities and differences between subjects. Although single-subject methodologies have been criticized because of their lack of generalizability (see Bates, 1996 and Reboussin and Morgan, 1996 for a debate), dynamical systems theorists argue that they are appropriate for the purposes of studying the unique ways in which individuals satisfy specific task constraints according to the intrinsic dynamics of their movement systems. Coordination profiling provides a satisfactory compromise to these conflicting viewpoints.
- **Self-organizing neural networks** (Kohonen, 1995) have emerged in the movement sciences as a method for analyzing the global nature of movement patterns. Kohonen's networks effectively compress high dimensional input data, such as three-dimensional kinematic data, on to neurons located on a low dimensional topological self-organizing map, using a series of non-linear weighting vectors. Instead of measuring the "distance" between performances in the high dimensional input space, the neighborhood preservation properties of self-organizing maps enable the investigator to measure more effectively the distance between performances in the low dimensional output space. A cluster analysis algorithm can then be used to categorize performances in terms of their topology, which can be determined by the amount of distance between trials, where less distance is thought to represent greater similarity (stability) and therefore less variability. Kohonen's networks have already been applied successfully to analyses of javelin throwing (Bauer and Schöllhorn, 1997) and discus throwing (Schöllhorn and Bauer, 1998). They have also been used in gait analysis to evaluate walking patterns (Barton, 1999; Barton et al. 2000; Schöllhorn et al. 2002).

In conclusion, we have argued that dynamical systems theory applied to motor control is a relevant framework for performance-oriented sports biomechanics research. We have proposed that dynamical systems theory provides a unique opportunity for motor control theorists and biomechanists to work together to explore alternative research designs and analysis techniques that will ultimately enhance our understanding of the processes of coordination and control in human movement system, leading to improved motor performance. Finally, we have discussed potentially useful analysis techniques to support such an interdisciplinary approach to investigating coordination and control of dynamic actions in sport.

Reviewers' Comments

Alan Gibson. I understand the authors' viewpoint and I think they have put it across well in this revised article. I cannot add anything to it.

Simon Bennett. Link to comment.

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