4

SELF-ORGANISATION AND CONSTRAINTS IN SPORTS PERFORMANCE

Paul S. Glazier[1] *and Matthew T. Robins*[2]

[1]INSTITUTE OF SPORT, EXERCISE AND ACTIVE LIVING, FOOTSCRAY PARK CAMPUS,
VICTORIA UNIVERSITY, MELBOURNE, AUSTRALIA
[2]CHICHESTER CENTRE OF APPLIED SPORT AND EXERCISE SCIENCE,
UNIVERSITY OF CHICHESTER, UK

Summary

A criticism often directed at sports performance analysis is that it is too focused on performance outcomes rather than the underlying processes and mechanisms that produce those outcomes. In recognition of these and other issues, dynamical systems theory has been promoted as a viable multidisciplinary theoretical framework for sports performance analysis because: (i) it has the potential to more effectively link behaviours to outcomes due to its process-oriented, rather than product-oriented, focus; (ii) the same principles and concepts govern pattern formation at all levels (i.e. intra- and inter-individual) of sports performance; and (iii) it provides an opportunity for sport physiologists and sport psychologists to play a more prominent role in sports performance analysis. In this chapter, we provide an overview of two of the main concepts of dynamical systems theory, namely self-organisation and constraints, and consider how these constructs might be applied to the analysis and explanation of sport performance at the individual and team levels.

Introduction

Over the last decade, sports performance analysis has emerged as an independent sub-discipline of sport science and an integral part of many applied sport science support programmes. In addition to using various information and communications technologies (e.g. video) to provide augmented information (e.g. visual feedback) about sports performance during competition and practice, a significant task for sports performance analysts has been to identify and measure key performance variables that are statistically associated with successful sports performance outcomes. However, these metrics, known variously in the literature as performance indicators or performance parameters (Hughes and Bartlett, 2002), have been criticised for promoting only a rudimentary understanding of sports performance and providing little information about the underlying techniques and behaviours that produce performance outcomes (McGarry, 2009; Glazier, 2010).

In recognition of these and other issues, Glazier (2010) outlined an alternative process-oriented approach to sports performance analysis based on the principles and concepts of dynamical systems theory. It was argued that the constraints-based framework advocated in that paper, which has previously been applied to other areas of sport and human movement science, such as strength and conditioning (e.g. Ives and Shelley, 2003), skill acquisition (e.g. Araújo *et al.*, 2004; Davids *et al.*, 2008), sport biomechanics (e.g. Glazier and Davids, 2009; Seifert and Chollet, 2008) and motor development (e.g. Heywood and Getchell, 2009), provides a suitable platform on which to base applied sports performance research and support work.

Glazier (2010) argued that this alternative approach to sports performance analysis offers the following benefits to researchers and practitioners: (i) it has the potential to more effectively link behaviours to outcomes due to its process-oriented, rather than product-oriented, focus (i.e. rather than simply *describing* performance outcomes in terms of key performance indicators and performance parameters, it seeks to *explain* the underlying mechanisms and processes causing those outcomes; see also Vilar *et al.*, 2012); (ii) the same principles and concepts (i.e. self-organisation and constraints) govern pattern formation at all levels of sports performance (i.e. they are equally applicable to the analysis of coordination and control within a single sports performer or among a group of sports performers); and (iii) it provides an opportunity for sport physiologists and sport psychologists to play a more prominent role in the performance analysis of sport, therefore, providing a more holistic understanding of sports performance.

In this chapter, we provide an overview of two of the main concepts of dynamical systems theory, namely self-organisation and constraints. Some consideration is then given to how these constructs might be applied to the analysis and explanation of sport performance at the individual and team levels. Further information regarding the application of dynamical systems theory to sports performance analysis, more generally, can be found in Chapters 5 and 6 of this book. Interested readers are also encouraged to consult the excellent monographs by Kugler and Turvey (1987), Thelen and Smith (1994), Kelso (1995) and Williams *et al.* (1999) for comprehensive overviews of dynamical systems theory as applied to the sport and human movement sciences.

Self-organisation

Despite being intuitively simple, the concept of self-organisation has proven to be notoriously difficult to define. A number of definitions have appeared in the literature over the years (see Anderson, 2002, for a summary) but one of the most popular was provided by Camazine *et al.* (2001). They defined self-organisation as:

> a process in which pattern at the global level of a system emerges solely from numerous interactions among the lower-level components of the system. Moreover, the rules specifying interactions among the system's components are executed using only local information, without reference to the global pattern.
>
> *(p. 8)*

In other words, self-organisation is a process whereby structure or pattern emerges in an open system (i.e. those systems that are capable of engaging in energy and matter transactions with the environment) without specification from an intelligent executive or external regulating agent. Camazine *et al.* (2001) provided a number of fascinating examples of self-organisation in nature, from the synchronised flashing of fireflies to the spiralling patterns of an aggregating slime mould.

The construct of self-organisation was first introduced to movement science during the 1980s in a series of landmark publications by Kugler, Kelso and Turvey (Kugler *et al.* 1980, 1982; Kugler, 1986; Kugler and Turvey, 1987). Kugler also edited a special issue of *Human Movement Science* in 1988 entitled 'Self-Organisation in Biological Work Spaces' (Vol. 7, Issue 2–4, pp. 91–407), which was dedicated to theoretical topics related to the then-new paradigm of self-organisation. In the early years, the concept of self-organisation was poorly understood and often misconstrued. Indeed, as Beek *et al.* (1995: 577) observed: '. . . the notion of self-organization is interpreted by some movement scientists as a kind of mystical ability, according to which movements come out of the blue. This is giving an incorrect ontological twist to the concept.' Readers are referred to Chapter 7 of Camazine *et al.* (2001) for a more extensive examination of some of the common misconceptions, in science and beyond, surrounding self-organisation. More recently, however, self-organisation has become firmly established as an overarching or guiding metaphor for investigating coordinated behaviours, although there is still much work to be done to develop it as a valid theoretical concept in the human movement domain (Robertson *et al.*, 1993; Newell and Jordan, 2007).

Self-organisation was originally introduced by Kugler *et al.* (1980, 1982) as part of a 'natural-physical' alternative to cognitive theories of motor behaviour following rejection of the symbol-based computer metaphor that had prevailed in movement science since the 1960s. According to Kugler *et al.* (1980, 1982), this recipient paradigm, which they borrowed from the theoretical subfields of homeokinetics (Soodak and Iberall, 1978), non-equilibrium thermodynamics (Nicolis and Prigogine, 1977) and synergetics (Haken, 1977), offered a principled solution to the problem originally formulated by Bernstein (1967) of how the many degrees of freedom residing at different levels of the movement system are harnessed during goal-directed action (see also Turvey, 1990). Instead of relying on anthropomorphic concepts such as programmes, plans and schemas to resolve this issue, Kugler *et al.* (1980: 6) argued that order and regularity in the human movement system emerge from 'the free interplay of forces and mutual influences among components tending toward equilibrium or steady states' – that is, they self-organise.

Although self-organisation occupies a central role in the evolution of physiological and biomechanical processes, it alone is insufficient. To guide and shape emergent pattern formation among degrees of freedom of the system, self-organising processes need to be juxtaposed with competing and cooperating internal and external constraints that pressurise the system into changes of organisational state (Kugler, 1986; Newell, 1986). This process is commonly referred to in the literature as 'self-organisation under constraint' (e.g. Williams *et al.* 1999; Araújo *et al.* 2004; Davids *et al.* 2008). In the next section, we provide an overview of the concept of constraints.

Constraints

The concept of constraints is central to many branches of science, including mathematics, physics and biology. Kugler *et al.* (1980: 9) highlighted the primacy of constraints in the human movement system by stating that:

> the order in biological and physiological processes is primarily owing to dynamics and that the constraints that arise, both anatomical and functional, serve only to channel and guide dynamics; it is not that actions are caused by constraints; it is, rather, that some actions are excluded by them.

Constraints can, therefore, be viewed as boundaries, limitations or design features that apply restrictions to the organisation of the degrees of freedom residing at the different levels of the movement system (Sparrow and Newell, 1998). Indeed, as Kugler (1986: 471) argued:

> the only sensible interpretation of a constraint is that it is an alternative description of the behaviour of the individual degrees of freedom [...] It is a reduced, less detailed description [...] Being less detailed it is less complex and therein lies its utility: in terms of control a constraint is simple and efficient because it makes the fullest use of the dynamical context without being a description of that context.

Although a number of different constraint models have been postulated in the literature over the years (see van der Kamp *et al.*, 1996), the most widely cited model was introduced by Newell (1986) and updated, more recently, by Newell and Jordan (2007). Inspired by the work of Kugler *et al.* (1980, 1982), Newell (1986) proposed that three types of constraints act to channel and shape emergent patterns of coordination and control underpinning human movement:

1. **Organismic constraints** are those constraints that reside within the boundaries of individual movement systems. They can be subdivided into structural and functional constraints. Structural constraints tend to be physical constraints that remain relatively constant over time and include: height, body mass and composition; genetic make-up; the anthropometric and inertial characteristics of the torso and limbs; the number of mechanical degrees of freedom and ranges of motion of articulating structures; the fast- and slow-twitch fibre composition; angle of pennation, cross-sectional area, and the activation and fatigue characteristics of skeletal muscle; and so on (e.g. Newell, 1984; Jensen, 1993; Carson and Riek, 1998; Shemmell *et al.*, 2004). Functional constraints that have a relatively faster rate of change, on the other hand, tend to vary quite considerably over time and are typically either physiological or psychological. Important functional constraints include: heart rate; lactate concentrations; glucocorticoid release; synaptic connections; anxiety; perception; motivation; and so on. Perhaps the most prominent and influential organismic constraint that can shape movement coordination is the intentions of the performer (Kelso, 1995).
2. **Environmental constraints** are those constraints that are external to the movement system. They tend to be global, non-specific constraints that pertain to the spatial and temporal layout of the surrounding world or the field of external forces that are continually acting on the movement system. Examples of environmental constraints include ambient light and temperature, altitude, acoustic information, ubiquitous gravitational forces and the reaction forces exerted by *terra firma* and other contact surfaces and apparatus. Sociocultural constraints, such as family support, peer pressure, societal expectations and cultural norms, can also be classified as environmental constraints (Clark, 1995). Newell (1986) originally made the distinction between environmental constraints that are general or ambient and those that are task specific. However, Newell and Jordan (2007) argued that it is much cleaner, in a definitional sense, not to force this distinction and they modified the definition of an environmental constraint to encompass any physical constraint beyond the boundaries of the organism. Any implements, tools or apparatus, which were originally categorised by Newell (1986) as being tasks constraints, are now classified as environmental constraints.
3. **Task constraints** are those constraints that are specific to the task being performed and are related to the goal of the task and the rules governing the task. McGinnis and Newell

> (1982: 299) proposed that task constraints 'are not physical, rather they are implied constraints or requirements which must be met within some tolerance range in order for the movement to produce a successful action'. In sport, task constraints that explicitly specify limb and torso segment movements, or restrict them to within certain boundaries, are commonplace. For example, the successful performance or otherwise of many gymnastics skills is determined by whether or not a certain movement pattern can be executed, and in cricket, a bowler can use any action providing the elbow of the bowling arm is not extended beyond a pre-defined limit. Instructions issued by a coach or practitioner may also be viewed as a type, or subset, of task constraint (Davids *et al.*, 2008; Newell and Ranganathan, 2010).

A number of important points should be noted when attempting to apply Newell's model of constraints to analyses of human movement. First, the three categories of constraints only identify the source and not the actual nature of the constraints impinging on performance (Newell *et al.*, 1989). Second, as constraints can be interpreted differently by different performers, they need to be considered from the perspective of the performer rather than at a level of description that is external or independent of the performer (Newell, 1989). Third, although some constraints are clearly more influential than others in certain performance contexts, it is the *confluence* of *interacting* organismic, environmental and task constraints that channel and shape patterns of coordination, control and, ultimately, performance outcomes (Newell and Jordan, 2007). Fourth, small-scale changes in one of the three categories of constraints can have a large-scale impact on the ensuing pattern of coordination and control. By the same token, variations in two or three of the constraint categories can, in effect, cancel each other out and have very little impact on the resulting pattern of coordination and control (Newell, 1986). Fifth, the ensuing patterns of coordination and control that emerge from the confluence of constraints are putatively a reflection of 'self-organising optimality' (Newell, 1986) or 'constrained optimisation' (Maynard Smith, 1978), so even though the performance outcome might be suboptimal or unsuccessful with regard to some externally defined criterion, the pattern of coordination and control produced could be considered optimal in relation to the immediately imposed constraints. The concepts of self-organising optimality or constrained optimisation state that the behaviour of a system at any point in time will always be optimal for the specific confluence of constraints acting on the system. Some (e.g. Mazur, 1983) have argued that the usefulness of these explanatory concepts are limited, whereas others (e.g. Staddon and Hinson, 1983) have suggested that they allow a better understanding of the constraints within which optimisation occurs.

Implications for sports performance analysis

So far in this chapter, we have outlined how self-organising processes and constraints combine to channel and shape emergent pattern formation in single-agent neurobiological systems. In principle, these concepts also govern pattern formation in multi-agent neurobiological systems, although Newell's (1986) constraints model, to our knowledge, has yet to be applied formally in this context.

To date, most studies that have considered pattern formation in sports performance analysis have, following the recommendation of McGarry *et al.* (2002), applied concepts and tools of coordination dynamics, which have been derived from Haken's (1977) theory of synergetics. Briefly, this approach involves the identification of collective variables or '*order parameters*' that define stable and reproducible relationships among degrees of freedom and '*control parameters*' that move the system through its many different coordinative states or attractor states in dynamical systems parlance (see Jeka and Kelso, 1989, and Kelso *et al.*, 1993, for tutorial reviews). Although a number of order parameters have been proposed in the literature, such as linear and angular displacement and their derivatives, either between players or with respect to a specific location or object (e.g. target or obstacle) in the performance environment (e.g. Araújo, *et al.*, 2006; Hristovski *et al.*, 2006), relative phase has typically been promoted as the order parameter that best characterises coordination in a sports contest (e.g. Palut and Zanone, 2005; Lames, 2006; Walter *et al.*, 2007). Several control parameters have also been postulated in the literature, including oscillatory frequency, interpersonal distance and relative velocity (e.g. McGarry *et al.*, 1999; Passos *et al.*, 2008; Duarte *et al.*, 2010). Interestingly, control parameters may have no obvious informational link to the resultant movement pattern (i.e. they do not prescribe or specify movement patterns but rather usher the system through its organisational states).

A research strategy that has typically been invoked by investigators adopting a dynamical systems approach in sports performance analysis is the '*synergetic strategy*' (Kelso and Schöner, 1988). In this approach, the control parameter is allowed to vary, or is experimentally manipulated, through a broad range, and concurrent changes in the order parameter are monitored. At low control parameter values, order parameter dynamics typically remain consistent and stable, reflecting the adoption of an attractor state. As the control parameter is increased, order parameter dynamics can become unstable, leading to a non-equilibrium phase transition or bifurcation and the adoption of a new attractor state. This phenomena was first demonstrated in the now-classic experiments on bimanual rhythmic coordination by Kelso and colleagues in the 1980s (e.g. Kelso, 1984; Haken *et al.*, 1985) and have since been reported widely in studies of intra-limb, inter-limb and inter-individual coordination (e.g. Schmidt *et al.*, 1990; Kelso *et al.*, 1991; Kelso and Jeka, 1992). A number of studies examining symmetry-breaking behaviour in sub-phases (e.g. 1 v. 1 dyads) of sports contests have also reported similar results (e.g. Palut and Zanone, 2005; Bourbousson *et al.*, 2010).

However, there are a number of issues surrounding the application of the synergetic strategy and coordination dynamics, more generally, to sports performance analysis. First, as noted in the previous section, although control parameters might be considered the main constraint on performance, it is the *confluence* of *interacting* organismic, environmental and task constraints that ultimately determines pattern formation (Newell, 1986; Newell *et al.*, 1989; Newell and Jordan, 2007). Second, relative phase assumes that the movements of each degree of freedom are approximately sinusoidal and that they have a one-to-one frequency ratio. Although the effects of violating these assumptions have not been assessed in multi-agent systems, they have in single-agent systems, where it has been shown that anomalous results may be found where these conditions are not met (Peters *et al.*, 2003). To overcome this issue, additional processing using Hilbert Transforms have been recommended (e.g. Lames, 2006) but even this procedure has been shown to overestimate continuous relative phase (Varlet and Richardson, 2011). Third, the systematic scaling of control parameters has been a useful paradigm in research agendas attempting to empirically verify the existence of non-linearities in human movement but its application in sport is limited to a very narrow set of performance contexts, such as when an attacker and defender converge. Moreover, key issues that are of great important to practitioners, such as how collective behaviour changes with match location, environmental conditions, quality of opposition and match status, for example, cannot readily be accounted for using the synergetics approach. Fourth, some of the specialist terminology associated with the synergetic approach (e.g. order parameters, control parameters, non-equilibrium phase transition, bifurcation, critical fluctuations, hysteresis, etc.) is not readily comprehensible to the sports practitioner and, therefore, may limit its practical contribution to sport. The inability to effectively communicate research findings in an appropriate language has recently been identified as one of the reasons why sport science, to date, has only had a limited impact on practice (e.g. Bishop *et al.*, 2006; Meyers, 2006; Williams and Kendall, 2007). Owing to the highly applied nature of sports performance analysis, it is our opinion that a clear, concise and 'user-friendly' set of terms and definitions needs to be developed. We propose that the constraints-based framework advocated in this chapter could contribute to achieving this aim.

The constraints-based approach, originally outlined by Newell (1986) and advocated as a theoretical framework for sports performance analysis by Glazier (2010), may provide a less restrictive alternative to the synergetic approach. A key aspect of this approach is the monitoring of qualitative and quantitative changes in pattern formation among degrees of freedom with changing constraints. McGinnis and Newell (1982) outlined a framework based on '*topological dynamics*' that uses biomechanical measurements and control spaces for mapping movement to constraints (see also Newell and Jordan, 2007). Each control space frame of reference (i.e. configuration space, event space, state space and state–time space) describes different spatio-temporal properties of movement and provides a useful insight into the restrictive nature of the constraints impinging on the system. One of the virtues of this approach is that it describes both movement and imposing constraints in common terms. The graphical mapping of attractor states can also help visualise how intra- and inter-individual coordination patterns change under varying constraints, which is likely to be a useful tool for sports performance analysts when communicating with athletes and coaches.

Although this framework is presently difficult to implement at the within-individual level, particularly during competition, because markerless motion capture is still in its infancy and not widely available (see Mündermann *et al.*, 2006, for a recent review), recent advances in player tracking technology may make it a feasible proposition at the between-individual level in the near future. The increasing capacity of GPS and image-based systems (see recent reviews by Aughey, 2011, and Barris and Button, 2008, respectively) to generate the time-continuous kinematic datasets necessary to map movement trajectories and attractor states in different control spaces has great potential for enhancing understanding of how patterns of inter-personal coordination are shaped by changing constraints, particularly if physiological and psychological data can be collected concurrently using other interfaced biofeedback technologies (see Blumenstein *et al.*, 2002, and Edmonds and Tenenbaum, 2012, for reviews). We propose that the information yielded by this approach could be used to inform tactical decision making, direct technical development strategies and prescribe modifications to strength and conditioning programmes.

Concluding remarks

In this chapter, we have provided an overview of the self-organising processes and constraints that shape and guide pattern formation at both the within- and the between-individual levels of sports performance. In order to move self-organisation beyond a metaphor and further develop it as a valid theoretical concept in the area of sports performance analysis, more empirical research is required. Indeed, Newell and Jordan (2007) suggested that empirical examinations of the self-organisation metaphor in the human movement domain could be addressed, in part, by manipulating key constraints impinging on the system and examining any concomitant changes that may ensue in the qualitative and quantitative properties of movement. As discussed in this chapter, this approach may also prove to be a more accessible framework on which to base sports performance analysis. Although conceptually similar to the synergetic approach, this approach is mathematically less formal, is arguably more versatile in terms of the range of situations it can be applied to and uses terminology that is more understandable to athletes and coaches. Further developments in motion capture, player tracking and biofeedback technologies will greatly facilitate the application of this framework in both research and applied settings in the near future. This approach could also be instrumental in helping to establish firmer links between sport behaviour and performance outcome, as identified as a research priority by McGarry (2009) and Glazier (2010).

Acknowledgment

We thank Karl Newell for his feedback on an earlier version of this chapter.

References

Anderson, C. (2002) 'Self-organization in relation to several similar concepts: Are the boundaries to self-organization indistinct?', *Biological Bulletin*, 202: 247–55.

Araújo, D., Davids, K., Bennett, S.J., Button, C. and Chapman, G. (2004) 'Emergence of sport skills under constraints', in A.M. Williams and N.J. Hodges (eds), *Skill Acquisition in Sport Research, Theory and Practice* (pp. 409–33). London: Routledge.

Araújo, D., Davids, K. and Hristovski, R. (2006) 'The ecological dynamics of decision making in sport', *Psychology of Sport and Exercise*, 7: 653–76.

Aughey, R.J. (2011) 'Applications of GPS technologies to field sports', *International Journal of Sports Physiology and Performance*, 6: 295–310.

Barris, S. and Button, C. (2008) 'A review of vision-based motion analysis in sport', *Sports Medicine*, 38: 1025–43.

Beek, P.J., Peper, C.E. and Stegeman, D.F. (1995) 'Dynamical models of movement coordination', *Human Movement Science*, 14: 573–608.

Bernstein, N.A. (1967) *The Coordination and Regulation of Movements*, Oxford: Pergamon Press.

Bishop, D., Burnett, A., Farrow, D., Gabbett, T.W. and Newton, R. (2006) 'Sports-science roundtable: Does sports-science research influence practice?', *International Journal of Sports Physiology and Performance*, 1: 161–8.

Blumenstein, B., Bar-Eli, M. and Tenenbaum, G. (eds) (2002) *Brain and Body in Sport and Exercise: Biofeedback Applications in Performance Enhancement*, Chichester, East Sussex: Wiley.

Bourbousson, J., Sève, C. and McGarry, T. (2010) 'Space-time coordination dynamics in basketball: Part 1. Intra- and inter-couplings among dyads', *Journal of Sports Sciences*, 28: 339–47.

Camazine, S., Deneubourg, J.-L., Franks, N.R., Sneyd, J., Theraulaz, G. and Bonabeau, E. (2001) *Self-Organization in Biological Systems*, Princeton, NJ: Princeton University Press.

Carson, R.G. and Riek, S. (1998) 'Moving beyond phenomenology: Neuromuscular-skeletal constraints upon coordination dynamics', in J.P. Piek (ed.), *Motor Behavior and Human Skill: A Multidisciplinary Approach* (pp. 209–30). Champaign, IL: Human Kinetics.

Clark, J.E. (1995). 'On becoming skillful: patterns and constraints', *Research Quarterly for Exercise and Sport*, 66: 173–83.

Davids, K., Button, C. and Bennett, S. (2008) *Dynamics of Skill Acquisition: A Constraints-Led Approach*, Champaign, IL: Human Kinetics.

Duarte, R., Araújo, D., Gazimba, V., Fernandes, O., Folgado, H., Marmeleira, J. and Davids, K. (2010) 'The ecological dynamics of 1v1 sub-phases in association football', *The Open Sports Sciences Journal*, 3: 16–18.

Edmonds, W.A. and Tenenbaum, G. (eds) (2012) *Case Studies in Applied Psychophysiology: Neurofeedback and Biofeedback Treatments for Advances in Human Performance*, Chichester, East Sussex: Wiley.

Glazier, P.S. (2010) 'Game, set and match? Substantive issues and future directions in performance analysis', *Sports Medicine*, 40: 625–34.

Glazier, P.S. and Davids, K. (2009) 'Constraints on the complete optimization of human motion', *Sports Medicine*, 39: 15–28.

Haken, H. (1977) *Synergetics: An Introduction. Non-equilibrium Phase Transitions and Self-Organization in Physics, Chemistry and Biology*, New York: Springer Verlag.

Haken, H., Kelso, J.A.S. and Bunz, H. (1985) 'A theoretical model of phase transitions in human hand movements', *Biological Cybernetics*, 51: 347–56.

Heywood, K.M., and Getchell, N. (2009). *Life Span Motor Development* (5th ed.), Champaign, IL: Human Kinetics.

Hristovski, R., Davids, K., Araújo, D. and Button, C. (2006) 'How boxers decide to punch a target: Emergent behaviour in nonlinear dynamical movement systems', *Journal of Sports Science and Medicine*, 5: 60–73.

Hughes, M.D. and Bartlett, R.M. (2002) 'The use of performance indicators in performance analysis', *Journal of Sports Sciences*, 20: 739–54.

Ives, J.C. and Shelley, G.A. (2003) 'Psychophysics in functional strength and power training: Review and implementation framework', *Journal of Strength and Conditioning Research*, 17: 177–86.

Jeka, J.J. and Kelso, J.A.S. (1989) 'The dynamic pattern approach to coordinated behaviour: A tutorial review', in S.A. Wallace (ed.), *Perspectives on the Coordination of Movement* (pp. 3–45). Amsterdam: North-Holland.

Jensen, R.K. (1993) 'Human morphology: Its role in the mechanics of movement', *Journal of Biomechanics*, 26: 81–94.

Kelso, J.A.S. (1984) 'Phase transitions and critical behavior in human bimanual coordination', *American Journal of Physiology: Regulatory, Integrative and Comparative Physiology*, 246: R1000–4.

Kelso, J.A.S. (1995) *Dynamic Patterns: The Self-Organisation of Brain and Behavior*, Cambridge, MA: MIT Press.

Kelso, J.A.S. and Schöner, G. (1988) 'Self-organization of coordinative movement patterns', *Human Movement Science*, 7: 27–46.

Kelso, J.A.S. and Jeka, J. J. (1992) 'Symmetry breaking dynamics of human multilimb coordination', *Journal of Experimental Psychology: Human Perception and Performance*, 18: 645–68.

Kelso, J.A.S., Buchanan, J.J. and Wallace, S.A. (1991) 'Order parameters for the neural organization of single, multijoint limb movement patterns', *Experimental Brain Research*, 85: 432–44.

Kelso, J.A.S., Ding, M. and Schöner, G. (1993) 'Dynamic pattern formation: A primer', in L.B. Smith and E. Thelen (eds), *A Dynamic Systems Approach to Development: Application* (pp. 13–50). Cambridge, MA: MIT Press.

Kugler, P.N. (1986) 'A morphological perspective on the origin and evolution of movement patterns', in M.G. Wade and H.T.A. Whiting (eds), *Motor Development in Children: Aspects of Coordination and Control* (pp. 459–525). Dordrecht: Martinus Nijhoff.

Kugler, P.N. and Turvey, M.T. (1987) *Information, Natural Law, and the Self-Assembly of Rhythmic Movement*, Hillsdale, NJ: Erlbaum.

Kugler, P.N., Kelso, J.A.S. and Turvey, M.T. (1980) 'On the concept of coordinative structures as dissipative structures: I. Theoretical lines of convergence', in G.E. Stelmach and J. Requin (eds), *Tutorials in Motor Behavior* (pp. 3–47). Amsterdam: North-Holland.

Kugler, P.N., Kelso, J.A.S. and Turvey, M.T. (1982) 'On the control and coordination of naturally developing systems', in J.A.S. Kelso and J.E. Clark (eds), *The Development of Movement Control and Coordination* (pp. 5–78). New York: Wiley.

Lames, M. (2006) 'Modelling the interaction in game sports – Relative phase and moving correlations', *Journal of Sports Science and Medicine*, 5: 556–60.

Maynard Smith, J. (1978) 'Optimization theory in evolution', *Annual Review of Ecology and Systematics*, 9: 31–56.

Mazur, J.E. (1983) 'Optimization: A result or a mechanism?', *Science*, 221: 977.

McGarry, T. (2009) 'Applied and theoretical perspectives of performance analysis in sport: Scientific issues and challenges', *International Journal of Performance Analysis in Sport*, 9: 128–40.

McGarry, T., Khan, M.A. and Franks, I.M. (1999) 'On the presence and absence of behavioural traits in sport: An example from championship squash match-play', *Journal of Sports Sciences*, 17: 297–311.

McGarry, T., Anderson, D.I., Wallace, S.A., Hughes, M.D. and Franks, I.M. (2002) 'Sport competition as a dynamical self-organizing system', *Journal of Sports Sciences*, 20: 771–81.

McGinnis, P.M. and Newell, K.M. (1982) 'Topological dynamics: A framework for describing movement and its constraints', *Human Movement Science*, 1: 289–305.

Meyers, M.C. (2006) 'Enhancing sport performance: Merging sports science with coaching', *International Journal of Sports Science & Coaching*, 1: 89–100.

Mündermann, L., Corazza, S. and Andriacchi, T.P. (2006) 'The evolution of methods for the capture of human movement leading to markerless motion capture for biomechanical applications', *Journal of NeuroEngineering and Rehabilitation*, 3: 6.

Newell, K.M. (1984) 'Physical constraints to development of motor skills', in J.R. Thomas (ed.), *Motor Development During Childhood and Adolescence* (pp. 105–20). Minneapolis, MN: Burgess.

Newell, K.M. (1986) 'Constraints on the development of coordination', in M.G. Wade and H.T.A. Whiting (eds), *Motor Development in Children: Aspects of Coordination and Control* (pp. 341–60). Dordrecht: Martinus Nijhoff.

Newell, K.M. (1989) 'On task and theory specificity', *Journal of Motor Behavior*, 21: 92–6.

Newell, K.M. and Jordan, K. (2007) 'Task constraints and movement organization: A common language', in W.E. Davis and G.D. Broadhead (eds), *Ecological Task Analysis and Movement* (pp. 5–23). Champaign, IL: Human Kinetics.

Newell, K.M. and Ranganathan, R. (2010) 'Instructions as constraints in motor skill acquisition', in I. Renshaw, K. Davids and G.J.P. Savelsbergh (eds), *Motor Learning in Practice: A Constraints-Led Approach* (pp. 17–32). London: Routledge.

Newell, K.M., van Emmerik, R.E.A. and McDonald, P.V. (1989) 'Biomechanical constraints and action theory: Reaction to G.J. van Ingen Schenau (1989)', *Human Movement Science*, 8: 403–9.

Nicolis, G. and Prigogine, I. (1977) *Self-Organization and Nonequilibrium Systems: From Dissipative Structures to Order through Fluctuation*, New York: Wiley.

Palut, Y. and Zanone, P.-G. (2005) 'A dynamical analysis of tennis: Concepts and data', *Journal of Sports Sciences*, 23: 1021–32.

Passos, P., Araújo, D., Davids, K., Gouveia, L., Milho, J. and Serpa, S. (2008) 'Information-governing dynamics of attacker-defender interactions in youth rugby union', *Journal of Sports Sciences*, 26: 1421–9.

Peters, B.T., Haddad, J.M., Heiderscheit, B.C., van Emmerik, R.E.A. and Hamill, J. (2003) 'Limitations in the use and interpretation of continuous relative phase', *Journal of Biomechanics*, 36: 271–4.

Robertson, S.S., Cohen, A.H. and Mayer-Kress, G. (1993) 'Behavioral chaos: Beyond the metaphor', in L.B. Smith and E. Thelen (eds), *A Dynamic Systems Approach to Development: Applications* (pp. 119–50). Cambridge, MA: MIT Press.

Schmidt, R.C., Carello, C. and Turvey, M.T. (1990) 'Phase transitions and critical fluctuations in the visual coordination of rhythmic movements between people', *Journal of Experimental Psychology: Human Perception and Performance*, 16: 227–47.

Seifert, L. and Chollet, D. (2008) 'Inter-limb coordination and constraints in swimming: A review', in N.P. Beaulieu (ed.), *Physical Activity and Children: New Research* (pp. 65–93). New York: Nova Science Publishers.

Shemmell, J., Tresilian, J.R., Riek, S. and Carson, R.G. (2004) 'Musculoskeletal constraints on the acquisition of motor skills', in A.M. Williams and N.J. Hodges (eds), *Skill Acquisition in Sport Research, Theory and Practice* (pp. 390–408). London: Routledge.

Soodak, H. and Iberall, A. (1978) 'Homeokinetics: A physical science for complex systems', *Science*, 201: 579–582.

Sparrow, W.A. and Newell, K.M. (1998) 'Metabolic energy expenditure and regulation of movement economy'., *Psychonomic Bulletin and Review*, 5(2): 173–96.

Staddon, J.E.R. and Hinson, J.M. (1983) 'Optimization: A result or a mechanism?', *Science*, 221: 976–7.

Thelen, E. and Smith, L.B. (1994) *A Dynamic Systems Approach to the Development of Cognition and Action*, Cambridge, MA: MIT Press.

Turvey, M.T. (1990). 'Coordination', *American Psychologist*, 45: 938–53.

van der Kamp, J., Vereijken, B. and Savelsbergh, G. (1996) 'Physical and informational constraints in the coordination and control of human movement', *Corpus, Psyche et Societas*, 3: 102–18.

Varlet, M. and Richardson, M.J. (2011) 'Computation of continuous relative phase and modulation of frequency of human movement', *Journal of Biomechanics*, 44: 1200–4.

Vilar, L., Araújo, D., Davids, K. and Button, C. (2012) 'The role of ecological dynamics in analysing performance in team sports', *Sports Medicine*, 42: 1–10.

Walter, F., Lames, M. and McGarry, T. (2007) 'Analysis of sports performance as a dynamical system by means of the relative phase', *International Journal of Computer Science in Sport*, 6: 35–41.

Williams, S.J. and Kendall, L. (2007) 'Perceptions of elite coaches and sports scientists of the research needs for elite coaching practice', *Journal of Sports Sciences*, 25: 1577–86.

Williams, A.M., Davids, K. and Williams, J.G. (1999) *Visual Perception and Action in Sport*, London: E & FN Spon.