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Game, Set and Match? Substantive Issues and Future Directions in Performance Analysis

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Abstract

This article discusses the main substantive issues surrounding performance analysis and considers future directions in this recently formed sub-discipline of sport science. It is argued that it is insufficient to bring together sport biomechanics and notational analysis on the basis that they share a number of commonalities, such as they both aim to enhance performance, they both make extensive use of information and communications technology, and both are concerned with producing valid and reliable data. Rather, it is suggested that the common factor linking sport biomechanics and notational analysis is that they can both be used to measure and describe the same phenomenon (i.e. emergent pattern formation) at different scales of analysis (e.g. intra-limb, inter-limb and torso, and inter-personal). Key concepts from dynamical system theory, such as self-organization and constraints, can then be used to explain stability, variability and transitions among coordinative states. By adopting a constraints-based approach, performance analysis could be effectively opened up to sport scientists from other sub-disciplines of sport science, such as sport physiology and psychology, rather than solely being the preserve of sport biomechanists and notational analysts. To conclude, consideration is given to how a more unified approach, based on the tenets of dynamical systems theory, could impact on the future of performance analysis.

The emergence of performance analysis as an independent sub-discipline of sport science in the last decade has provoked some debate among academics from the more established sub-disciplines of sport physiology, sport psychology and sport biomechanics. The generally accepted conceptualization of performance analysis – that is, the bringing together of sport biomechanics and notational analysis[1-3] – has attracted frequent criticism from sceptics who have condemned it as a ‘marriage of convenience’ contrived to produce vocational pathways for applied sport biomechanists and notational analysts. Much of the controversy appears to be centered on the rationale for combining sport biomechanics and notational analysis, the apparent ‘dumbing down’ of the theory and methods of biomechanics, and the fact that the current conceptualization of performance analysis offers limited scope and opportunity for other applied sport scientists, such as sport physiologists and psychologists, who would argue that they, too, are performance analysts.

This article outlines the main substantive issues currently inhibiting progress in performance analysis. It should become clear that what is required is a unified multidisciplinary theoretical framework that not only brings together sport biomechanics and notational analysis more effectively, but one that also provides the scope and opportunity for the integration of ideas and theoretical concepts from other sub-disciplines of sport science, such as sport physiology and psychology. As it has already been proposed as a viable theoretical framework for both applied sport biomechanics[4,5] and notational analysis,[6,7] it can be argued that dynamical systems theory may offer even greater scope and potential for scientific endeavour in performance analysis. The common factor linking sport biomechanics and notational analysis is that they both can be used to measure and describe the same phenomenon (i.e. emergent pattern formation) at different scales of analysis (e.g. intra-limb, inter-limb and torso, and inter-personal) and that key concepts from dynamical system theory, such as self-organization and constraints, can be used to help explain stability, variability and transitions among coordinative states. To conclude, consideration is given to how a more unified approach, based on dynamical systems theory, could impact on the future of performance analysis.

1. Current Status and Substantive Issues in Performance Analysis

Although a conclusive definition of performance analysis has yet to be formalized (see Hughes[8] for a commentary), it is generally regarded to be the symbiosis of sport biomechanics and notational analysis. Motor control has featured in more recent schematics of performance analysis (see figures 2 and 3 of Hughes[8]) but the rationale for doing so was not provided and the prevalence of its application in the extant literature since has been extremely limited. According to Bartlett[2,3] and Hughes and Bartlett,[1,9,10] the bringing together of sport biomechanics and notational analysis is predicated on a number of commonalities that the two sub-disciplines apparently share including (i) the aim of enhancing performance; (ii) the analysis of movements of sport performers; (iii) the extensive use of information technology and communications equipment; (iv) the provision of objective feedback to sport performers and their coaches; (v) the importance of producing valid and reliable data; (vi) the need to normalize, scale or non-dimensionalize data; (vii) the use of 'performance parameters' or 'performance indicators' that are derived from theoretical models of performance; and (viii) the opportunity to exploit and apply more fully recent developments in artificial intelligence. Although Hughes and Bartlett should be applauded for attempting to conjoin notational analysis, which has traditionally been viewed as a methodology rather than a science, with the more traditional sub-discipline of sport biomechanics, it could be argued that the existence of these proposed commonalities, on their own, do not justify the formation of a new sub-discipline of sport science.

There appears to be a number of problems related to the current conceptualization of performance analysis. First, the commonalities apparently shared by sport biomechanics and notational analysis are not unique to those sub-disciplines. Academics from every sub-discipline of sport science are concerned with enhancing performance and producing valid and reliable data, and data normalization is commonplace, particularly in sport physiology (e.g. maximal oxygen uptake [$\dot{V}O_{2max}$] per unit bodyweight, percentage of age-related maximum heart rate, percentage of one repetition maximum). The performance parameter or performance indicator concept also features strongly in both sport physiology and psychology research. For example, $\dot{V}O_{2max}$ and lactate threshold have both been shown to be key variables underpinning endurance performance[11,12] and a certain level of arousal has been shown to be necessary for optimal perceptuo-motor performance.[13,14] However, as discussed further and in more detail within this section, despite the widespread use of performance parameters or performance indicators in sport science, these variables do not significantly enhance our understanding and could be considered a concept of limited application.

Second, although one can tentatively appreciate how sharing knowledge and experience may enrich the respective skills and enhance the career prospects of applied sport biomechanists and notational analysts, it is less clear how doing so will actually help athletes and coaches to enhance performance. Bartlett[2] makes reference to a number of examples where sport biomechanics and notational analysis have been used successfully by various organizations and national governing bodies, as part of their sports science support programmes. Although it is not possible to comment on how effective this sport biomechanics and notational analysis support has been, it is debatable whether an increased knowledge and understanding of the theory and methods of notational analysis can actually help applied sport biomechanists, or vice versa, to provide more effective scientific support and, ultimately, to enhance performance. Of course, what this extra knowledge and experience does provide is the opportunity for sport biomechanists and notational analysts to service a much wider range of sports and clientele in a greater variety of contexts. The benefits to athletes and coaches, in contrast, are far less tangible.

One practical outcome of performance analysis identified by Bartlett,[2,3] is that well chosen performance parameters can highlight good and bad sport techniques. However, as Lees[15] pointed out, performance parameters are derived from deterministic or hierarchical models of *performance*, not models of *technique*. The emphasis in these performance models is very much on the outcome rather than the causative mechanisms and processes underpinning the outcome. For example, in the hierarchical model of javelin throwing outlined by Morriss and Bartlett,[16] one of the most important performance parameters is release speed (see figure 1). Although some information regarding isolated aspects of technique believed to be mechanically related to this important performance parameter are provided, the model does not specify what movement patterns should be used to produce a high javelin speed at the moment of release. In addition, as elaborated further in this section, the efficacy of such models is challenged by evidence indicating that individual athletes scale and parameterize aspects of technique according to interacting constraints impinging on performance.[18] In principle, many different movement patterns or more precisely coordination patterns, could be used to generate the same set of performance parameter values for any given motor skill (a phenomenon known as motor equivalence[19]). It could be suggested, therefore, that rather than adopting this type of reductionist, nomothetic (inter-individual) product-oriented approach, a more holistic, idiographic (intra-individual), process-oriented approach emphasizing the analysis of emergent patterns of coordination and control underpinning performance in specific individuals, might be more profitable (see McGarry[20] for a similar discussion of the need to link sports behaviours to outcomes). Indeed, Davids

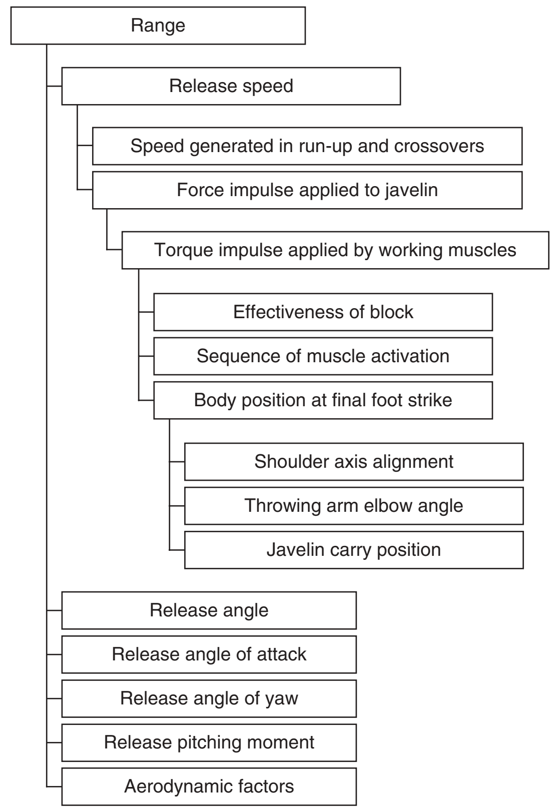

Fig. 1. A deterministic or hierarchical model of javelin throwing (reproduced from Morriss and Bartlett,[16] with permission from Adis, a Wolters Kluwer business © Adis Data Information BV, 1996. All rights reserved). Although this model does not strictly conform to the criteria set out by Hay and Reid[17] for constructing these performance models, it does provide a useful indication of what mechanical factors might be most related to performance.

et al.[21] argued that this type of analytical approach could form a significant component of scientific programmes for talent identification and skill development in soccer. However, as discussed further in this section, due to the limitations of the video analysis technology habitually used by performance analysts, this strategy may be difficult to implement.

Another more general problem with the performance parameter or performance indicator concept is that it promotes only a very rudimentary understanding of human motor performance. For example, it is somewhat self-evident that a high release speed is a prerequisite for proficient javelin throwing performance. Likewise, a large $\dot{V}O_{2max}$ is a prerequisite for adept performance in endurance athletic events. However, reducing human motor performance to a small number of measurable outcome variables belies the enormous complexity of the biomechanical, physiological and psychological processes underlying performance. Accurate prediction of human motor performance for a given task at a given time is far from straightforward because of the existence of complex, non-linear interactions between the many independent component parts of the human movement system at different levels of the system. In principle, small-scale changes at a more microscopic level of the system (e.g. molecular, cellular, neuromuscular) can have a large-scale impact at a more macroscopic level (e.g. behavioural, biomechanical, psychological).[22-24] Furthermore, not only is the current state of the human movement system important, environmental conditions and the specific requirements of the task being undertaken are also influential in shaping and guiding the ensuing patterns of coordination and control.[18]

Third, there appears to be increasing concern, particularly amongst more traditional sport biomechanists, regarding the apparent 'dumbing down' of the theory and methods of biomechanics. Perhaps the most contentious issue is that 'coach-friendly' video analysis packages habitually used by performance analysts, are being used in a capacity far beyond for which they were designed. Software applications, such as Quintic® (Quintic Consultancy Ltd, Coventry, UK; www.quintic.com) and siliconCOACH® (siliconCOACH, Dunedin, New Zealand; www.siliconcoach.com) are useful for planar semi-quantitative analyses and frame-by-frame or split-screen video playback, but they are no substitute for purpose-built, image-based or marker-based motion capture systems. As recommended above in this section, performance analysts need to dedicate much greater attention to measuring and analysing patterns of intra-limb and inter-limb coordination and control rather than just focusing on the time-discrete performance parameters most related to the performance outcome. However, only the most sophisticated automated motion capture systems can produce sufficiently large and accurate time-continuous datasets to construct variable-variable plots (e.g. angle-angle plots, phase-plane portraits) and apply various coordination (e.g. continuous relative phase, cross-correlations, vector coding) and variability measures (e.g. standard deviation, coefficient of variation, normalized root-mean-square, trans-entropy).[25-30]

Another concern that has been aired frequently by sceptics is that much of the work being conducted in performance analysis lacks sound theoretical rationale and, consequently, is descriptive rather than explanatory. Over the years a similar criticism has been directed, with some justification, at applied sport biomechanics research.[31-34] One of the main problems has been that empirical studies in sport biomechanics have seldom moved beyond the kinematic level of analysis. However, to fully understand the causative mechanisms underpinning performance, sport biomechanists need to focus much more on the kinetic level of analysis.[35] As it is virtually impossible to make inferences about the underlying kinetics from the kinematics, complex inverse dynamics analyses have been used to examine net joint torques and reaction forces, and mechanical work and power transfers among joints.[36] Although inverse dynamics analyses are still comparatively rare and somewhat hypothetical in nature,[37] they at least enable sport biomechanists to explore the causative mechanisms that underpin performance and explain them using the fundamental theoretical laws and principles of Newtonian and Euler mechanics.

Due to the complexity of inverse dynamics analyses, combined with the need to use sophisticated force measuring equipment (usually in a controlled environment) and the need to acquire athlete-specific anthropometric (geometric and inertia) data, it is unlikely that performance analysts will be able to implement this type of analysis. Furthermore, it is unlikely whether athletes and coaches will be able to relate well to concepts such as 'net joint torques' and 'mechanical power transfers'. Perhaps a more effective approach would be to analyse and explain the underlying processes of coordination and control at the kinematic level of analysis using the analytical tools and theoretical concepts of dynamical systems theory, respectively, particularly given that athletes and coaches use relative motion information about the limbs and the torso when making judgements about sports techniques.[38] As discussed in more detail in section 2, one of the advantages of adopting a dynamical systems framework is that it can be used to explain stability, variability and transitions between coordinative states in any complex system irrespective of the material composition of that system – that is, the same theoretical concepts governing intra-limb and inter-limb coordination also govern inter-personal coordination.[39,40] For this reason, combined with the fact that it has been closely linked already with applied sport biomechanics[4,5] and notational analysis,[6,7] dynamical systems theory would appear to be an ideal theoretical framework for performance analysis.

Fourth, performance analysis appears to be almost exclusively the preserve of sport biomechanists and notational analysts with very limited scope and opportunity for sport physiologists and psychologists. This state of affairs appears to have been perpetuated by remarks that sport physiologists and psychologists are only really concerned with the preparation of sport performers for competition.[1] However, given the fact that sport physiologists and psychologists must analyse and evaluate performance to establish the effectiveness of, and make subsequent modifications to, any strength and conditioning programmes, psychological interventions or coping strategies that they might have administered, it could be argued that they too must also be performance analysts. However, one of the problems preventing sport physiologists and psychologists from becoming more involved in performance analysis is that the affect of key physiological and psychological factors, such as fatigue and anxiety, on the processes underpinning performance, is not well understood.[41,42] Of course, anyone who has been involved in sport knows that fatigue and anxiety tend to cause decrements or errors in performance outcome (e.g. speed and accuracy), but how do these decrements come about? How does fatigue and anxiety impact on patterns of intra-limb and inter-limb coordination and control when executing kicking, throwing or striking actions? Furthermore, how does fatigue and anxiety affect patterns of inter-personal coordination in a game, match or contest?

In summary, it can be argued that the current formulation of performance analysis is rather ill-conceived and that much stronger rationale for linking sport biomechanics and notational analysis is necessary if performance analysis is to survive and prosper as an independent academic sub-discipline of sport science. The real link between sport biomechanics and notational analysis is not, or should not be, the fact that they share a number of rather tenuous commonalities, but because they both can be used to measure and describe the same phenomenon (i.e. emergent pattern formation) at different scales of analysis (e.g. intra-limb, inter-limb and torso, and interpersonal). Performance analysts must focus much more on the processes of coordination and control underpinning the performance outcome and not just the performance outcome itself. However, merely describing patterns of coordination and control is unlikely to make a significant impact on performance analysis. What is required is a multidisciplinary theoretical framework that explains stability, variability and transitions among coordinative states, and one such candidate with an excellent pedigree in science is dynamical systems theory. Section 2 provides a brief overview of the basic tenets of dynamical systems theory and outlines how key concepts, such as self-organization and constraints, can be applied to performance analysis.

2. Modelling Emergent Pattern Formation in Sport at the Individual and Team Level: Applications of Dynamical Systems Theory

What do individual sports performers executing goal-directed movements and a team of sports performers participating in a game, match or contest have in common? The answer is that they both can be conceptualized as complex non-linear dynamical systems.

In general, non-linear dynamical systems are those physical, chemical, biological or social systems that exhibit many independent component parts or degrees of freedom that are free to vary over space and time. These complex systems are typically open systems that operate under conditions that are said to be far from thermodynamic equilibrium; that is, they are capable of interacting with the environment and are in a constant state of flux due to changes in internal and external energy flows.[43-45] Despite the enormous potential for disorder, complex non-equilibrium dynamical systems are able to exploit these energy flows and the surrounding constraints to form orderly and stable relationships among the many degrees of freedom at different levels of the system.[46-48] However, rather than being pre-planned or prescribed by an intelligent executive or external regulating agent, these functional coordinative states, or attractor states in dynamical systems language, emerge spontaneously through ubiquitous processes of physical self-organization.[49-51] Once assembled into an attractor state, degrees of freedom operate autonomously and in self-regulatory fashion due to being functionally, rather than mechanically, coupled together. The 'soft assembly' of system degrees of freedom means that if any of the many individual degrees of freedom are perturbed by internal or external influences, the other degrees of freedom adjust their relative contribution, thus preserving system output.[52,53]

A research strategy commonly adopted by human movement scientists studying pattern formation in complex neurobiological systems is the 'synergetic strategy'.[49,54,55] This approach, based on the pioneering work of Haken[56] in the field of synergetics, 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. As Kelso[51] noted, order parameters and control parameters are the "yin and yang" of the synergetic approach – they are "separate but intimately related" (page 45). In neurobiological systems, relative phase has been the primary, if not the only, order parameter identified to date[57,58] and oscillatory frequency has typically been considered to be an important control parameter.[51,59,60] When an attractor state is adopted, order parameter dynamics have been shown to be highly ordered and stable, reflecting the capacity of the system to produce consistent and reproducible patterns of coordination.[59,60] As control parameters increase towards a critical value, variability of order parameter dynamics typically increases until stability is lost, leading to a non-equilibrium phase transition and the adoption of a new attractor state. The main emphasis of the synergetic strategy has been to identify candidate control parameters and systematically manipulate or scale them through their full range and observe concomitant changes in order parameter dynamics and other related non-linear phenomena. The synergetic strategy has been successfully applied to empirical analyses of within-individual coordination[61,62] and between-individual coordination.[63,64]

2.1 The Role of a Constraints-Based Approach and the Future of Performance Analysis

As outlined in section 2, the synergetic strategy has been integral to many experimental investigations into pattern formation both within and between individuals.[61-64] However, just as coaches and athletes might struggle to comprehend complex biomechanical concepts like 'net joint torques' and 'mechanical power transfers', specialist terminology from the field of synergetics such as 'control parameters', 'order parameters', 'bifurcations' and 'non-equilibrium phase transitions' could be equally baffling. Indeed, it would appear that even some academics have had difficulty understanding the technical jargon and are sceptical about whether this approach is ready to make a practical contribution to sport.[65]

A possible alternative approach that has received some exposure in the sport and human movement science literature, which could be useful in performance analysis, is the 'constraints-based' approach. This approach, based on the widely cited constraints framework introduced by Newell[18] and championed largely by Davids and colleagues,[66-69] was originally conceived to help explain emergent pattern formation in single-agent neurobiological systems (i.e. intra-personal coordination) but could, in principle, be useful in helping to provide important insights into emergent pattern formation in multi-agent neurobiological systems (i.e. inter-personal coordination). This approach proposes that pattern formation in neurobiological systems emerges from the confluence of competing and cooperating physical and informational constraints impinging on the system. These constraints coalesce to shape coordinative states not by prescribing them but by channelling the search towards optimal movement solutions.

According to Newell,[18] the constraints on performance originate from one of three sources: the organism, environment or task. Organismic constraints are those that are internal to the neurobiological system and can be classified as being either structural or functional. Structural organismic constraints tend to change very slowly over time and include factors such as age, height, body mass, muscle fibre composition and genetic make-up, among others. Functional organismic constraints, in contrast, have a more rapid rate of change and include factors such as the onset of fatigue, anxiety levels and emotional state. The intentions of individual athletes are also an important functional organismic constraint on performance.[51] Environmental constraints are those that are external to the neurobiological system. Examples of important environmental constraints in sport are weather conditions, ambient light and temperature, altitude, crowd influence, the frictional and stiffness characteristics of playing surfaces and the dimensions of the playing area. The relative positioning of defenders to one another and their proximity to the target area (e.g. goal, try-line or basket) have been shown to be important environmental constraints in the symmetry-breaking behaviour of attackers in team sports.[70] Task constraints are more specific to the task at hand and are related to the goal of the task and the rules that govern the task.[22] The need to score goals or points or defend a lead are key task constraints in sport. Instructions and tactics issued by the coaching staff or team captain can also be considered as major task constraints.

Recent advances in player tracking technology could help establish the affect of different constraints on pattern formation among individuals in a game, match or contest. Although player tracking systems such as Prozone™ (Prozone Sports Ltd, Leeds, UK; www.prozonesports.com) and TRAKUS® (TKS Inc., MA, USA; www.trakus.com) are still relatively new and not without limitation (see Barris and Button[71] for a state of the art review), they do have enormous potential, especially if interfaced or synchronized with other performance-monitoring technologies (e.g. heart rate monitors), for mapping spatio-temporal relationships among individuals under different organismic, environmental and task constraints. For example, in rugby union, it would be informative for coaches to establish how attacking and defensive formations change during the course of a match as specific individuals get fatigued, if weather conditions deteriorate or if the specific requirements of the game change as the final whistle nears. The data produced by these player tracking systems could be used to inform tactical decision making, direct technical development strategies and prescribe modifications to strength and conditioning programmes. Although less formal and not as mathematically rigorous as the synergetic approach, the constraints-based approach is arguably more versatile and likely to be more comprehensible to athletes and coaches seeking to understand pattern formation within and between individuals in a sporting contest.

3. Conclusion

The common factor linking sport biomechanics and notational analysis is that they can both be used to measure and describe the same phenomenon (i.e. emergent pattern formation) at different scales of analysis (e.g. intra-limb, inter-limb and torso, and inter-personal) and that key concepts from dynamical system theory, such as self-organization and constraints, can be used to help explain stability, variability and transitions between coordinative states. The adoption of dynamical systems theory as the basis of performance analysis is a logical progression given that it has previously been suggested to be a viable theoretical framework for both applied sport biomechanics[4,5] and notational analysis.[6,7] However, rather than adopting a research approach based on the 'synergetic strategy'[49,54,55] as has typically been the case in empirical analyses of pattern formation both within and between individuals, a constraints-based approach[18] might be more appropriate, particularly in an applied context, given that it is likely to be more comprehensible by athletes and coaches. The utility of this approach has already been demonstrated in applied sports biomechanics[72] and motor control and learning[73] research, but further research is necessary to establish its utility in notational analysis.

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