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Towards a Grand Unified Theory of sports performance

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ABSTRACT

Sports performance is generally considered to be governed by a range of interacting physiological, biomechanical, and psychological variables, amongst others. Despite sports performance being multi-factorial, however, the majority of performance-oriented sports science research has predominantly been monodisciplinary in nature, presumably due, at least in part, to the lack of a unifying theoretical framework required to integrate the various subdisciplines of sports science. In this target article, I propose a Grand Unified Theory (GUT) of sports performance—and, by elaboration, sports science—based around the constraints framework introduced originally by Newell (1986). A central tenet of this GUT is that, at both the intra- and inter-individual levels of analysis, patterns of coordination and control, which directly determine the performance outcome, emerge from the confluence of interacting organismic, environmental, and task constraints via the formation and self-organisation of coordinative structures. It is suggested that this GUT could be used to: foster interdisciplinary research collaborations; break down the silos that have developed in sports science and restore greater disciplinary balance to the field; promote a more holistic understanding of sports performance across all levels of analysis; increase explanatory power of applied research work; provide stronger rationale for data collection and variable selection; and direct the development of integrated performance monitoring technologies. This GUT could also provide a scientifically rigorous basis for integrating the subdisciplines of sports science in applied sports science support programmes adopted by high-performance agencies and national governing bodies for various individual and team sports.

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1. Introduction

It is generally accepted that sports performance is governed by a complex interaction of variables, such as physiological fitness, psychological preparedness, physical development, biomechanical proficiency, and tactical awareness, amongst others (e.g., nutrition, genetics, general health and wellbeing, sociocultural factors, etc.). Despite sports performance being multi-factorial, however, the overwhelming trend historically has been for sports performance research to be monodisciplinary in nature—that is, it has tended to be conducted within the confines of one of the subdisciplines of sports science, usually either sports physiology, sports biomechanics, or sports psychology (e.g., [Abernethy et al., 2013](#); [Burwitz, Moore, & Wilkinson, 1994](#)). The lack of genuine interdisciplinary collaborative research, where sports scientists operate in *symbiosis* to fully *integrate* principles, concepts, methods, and data from their respective fields to solve applied research problems and enhance knowledge of sports performance ([Freedson, 2009](#)), has been a perennial issue over the years despite repeated calls

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for sports scientists to engage in such agendas. For example, [Dillman \(1985\)](#) argued: “It is my opinion that there is a major weakness in sports science, and this deficiency stems from the lack of integration of ideas and problem solving both within various disciplines and among areas. Thus, I believe that until a concerted effort is made to form interdisciplinary teams, the field of sports science will stagnate and not produce effective solutions to many problems” (p. 107). In a forthright and provocative essay, [Morgan \(1989\)](#) also claimed: “It is not possible for a given individual, operating from the perspective of a given discipline (e.g., psychology or physiology) or subdiscipline (e.g., sport psychology and exercise physiology), even to raise the right questions much less to answer the right questions. It is possible for the unique individual to become a true hybrid (e.g., bioengineer, exercise physiologist, engineering psychologist, or sport psychologist), but it is more efficient for competent, well-trained individuals from two or more disciplines to join forces as an interdisciplinary or multidisciplinary team” (p. 106). More recently, [Elliott \(1999\)](#) further endorsed the need for more interdisciplinary research and highlighted the importance of uniting sports scientists by stating: “Seldom is a complex question answered by research based in a single science discipline. Hence, the biomechanist must combine with the exercise physiologist and biochemist, the sport psychologist and the motor development specialist to structure appropriate research design” (p. 307). Similar recommendations have also been made by [Shephard \(1984\)](#), [Cavanagh \(1990\)](#), [Davids, Handford, and Williams \(1994\)](#), [Franks and McGarry \(1996\)](#), [Gregor \(2008\)](#), [Buttfield, Ball, and MacMahon \(2009\)](#), and [Davids and Glazier \(2010\)](#), amongst others.

One of the reasons for this fragmented approach and the general paucity of interdisciplinary research might be that a unifying theoretical framework capable of integrating the various subdisciplines of sports science has, to date, been lacking. Indeed, [Sands and McNeal \(2000\)](#) cited the absence of a unifying theoretical framework as one of the main reasons why sports science has generally been poor at predicting sports performance. In this target article, I propose a Grand Unified Theory (GUT)¹ of sports performance, based on the conceptual model introduced originally by [Newell \(1986\)](#), which could provide the platform for much-needed interdisciplinary work in sports science and better explain, and possibly predict, sports performance at both the intra- and inter-individual levels of analysis. Although Newell’s constraints model is nearly 30 years old, and despite it receiving exposure in the sports medicine (e.g., [Davids, Glazier, Araújo, & Bartlett, 2003](#); [McKeon & Hertel, 2006](#)), physical therapy and rehabilitation (e.g., [Holt, Wagenaar, & Saltzman, 2010](#); [Newell & Valvano, 1998](#); [Wikstrom, Hubbard-Turner, & McKeon, 2013](#)), talent development (e.g., [Phillips, Davids, Renshaw, & Portus, 2010](#)), skill acquisition (e.g., [Araújo, Davids, Bennett, Button, & Chapman, 2004](#); [Davids, Button, & Bennett, 2008](#); [Renshaw, Davids, & Savelsbergh, 2010](#)), motor development (e.g., [Haywood & Getchell, 2014](#); [Piek, 2002](#)), physical education (e.g., [Chow et al., 2006, 2007](#)), strength and conditioning (e.g., [Holmberg, 2009](#); [Ives & Shelley, 2003](#); [Jeffreys, 2011](#)), sports biomechanics (e.g., [Caldwell, van Emmerik, & Hamill, 2000](#); [Glazier & Davids, 2009a](#); [Seifert & Chollet, 2008](#)), and sports performance analysis (e.g., [Glazier, 2010](#); [Glazier & Robins, 2013](#); [Vilar, Araújo, Davids, & Button, 2012](#)) literatures recently, I believe that its scope and potential contribution to applied sports science research and support work has generally been overlooked by the sports science community at large. Moreover, I suggest that, not only can this constraints-based GUT offer greater explanatory power and versatility than some other prevailing paradigms in sports science (e.g., deterministic modelling – [Glazier & Robins, 2012](#); information processing theory – [Zelaznik, 2014](#)), and provide a more holistic understanding of sports performance, it could help break down some of the silos that have developed over recent years (see [Gregor, 2008](#); [Kretchmar, 2008](#)) and restore greater disciplinary balance to the field (see [Ives & Knudson, 2007](#)), as well as provide stronger rationale for data collection and variable selection, and direct the development of integrated performance monitoring technologies.

In the following sections, I provide an introduction to the concept of constraints and outline the basic tenets of [Newell’s \(1986\)](#) constraints model (Section 2). I make the distinction between organismic, environmental, and task constraints, and provide examples from sports of these three categories of constraints. Despite its deceptively simple appearance—which can be considered a virtue given my intention to apply it to sports performance and the need for it to be accessible to athletes and coaching practitioners ([Meyers, 2006](#))—this framework has deep theoretical roots that can be traced back to the pioneering work of [Kugler, Kelso, and Turvey \(1980, 1982\)](#) on the application of principles and concepts of non-equilibrium thermodynamics ([Nicolis & Prigogine, 1977](#)), homeokinetics ([Soodak & Iberall, 1978](#)), and synergetics ([Haken, 1977](#)) to the study of human movement. I then discuss how the different types of constraints shape emergent patterns of coordination and control at both the intra- and inter-individual levels of analysis by providing ‘equations of constraint’ that metaphorically get ‘written over’ multiple independent component parts or degrees of freedom (DOF) to functionally combine them into task-specific structural units known as coordinative structures (Section 2.1). Once formed, these special-purpose devices are able to operate relatively autonomously by exploiting ubiquitous processes of self-organisation that are inherent to many natural physical and biological systems ([Camazine et al., 2001](#); [Kelso, 1995](#); [Yates, 1987](#)). Next, I outline the implications of the proposed GUT for the various subdisciplines of sports science, particularly how it can provide the conduit for the interdisciplinary integration of principles, concepts, methods, and data from motor control and development, skill acquisition, sports performance analysis, sports biomechanics, sports physiology, sports psychology and sports technology (Section 3). Because of their often significant impact on sports performance, special consideration is then given to how key physiological

¹ Grand Theories represent the broadest form of theory within a discipline ([Ayres, 2008](#)) and are prevalent in a variety of diverse fields from quantum mechanics to sociology and nursing. They attempt to explain the inter-relationships amongst numerous concepts and are designed to be universally applicable over all scales of space and time. Grand Theories can be useful as organising frameworks for knowledge development or as foundations for mid-range theory development ([Ayres, 2008](#)). They have often been described as being ‘normative’—that is, they are prospective in their outlook and describe not the way a discipline is, but the way that discipline should be. The GUT for sports performance—and, by elaboration, sports science—proposed in this target article fulfils many of the qualifying criteria for a Grand Theory.

(Section 3.1) and psychological (Section 3.2) constraints impact on emergent patterns of coordination and control at both the intra- and inter-individual levels of analysis, which ultimately determine the performance outcome. The proposed GUT presents applied sports scientists, most notably those from the subdisciplines of sports biomechanics and sports performance analysis, with a number of challenges from a measurement and analysis perspective, which are then discussed (Sections 4.1 and 4.2, respectively). The opportunities afforded by this GUT for sports scientists to engage in interdisciplinary research and integrated applied sports science support programmes—and the benefits of doing so for all stakeholders—are then considered (Section 5).

2. Constraints on sports performance

The concept of constraints has rich tradition in theoretical physics, evolutionary and theoretical biology, and mathematics. In movement science, constraints have emerged as a central construct in the dynamical systems theoretical approach to motor control and learning, which has evolved over the past three decades in response to perceived inadequacies with the traditional information processing theoretical approach derived from cognitive psychology and computational neuroscience (see Abernethy & Sparrow, 1992; Schmidt & Fitzpatrick, 1996; Summers, 2004). Broadly defined, constraints are internal or external boundaries, limitations, or design features that restrict the number of possible configurations that the many DOF of a complex system can adopt (Sparrow & Newell, 1998). Constraints can have spatial or temporal components or both, they reside at all levels of analysis from microscopic to macroscopic (e.g., biochemical, neurological, behavioural, morphological, etc.), and they operate over a multitude of different timescales, from milliseconds to years (Newell, Liu, & Mayer-Kress, 2009; Newell, Mayer-Kress, & Liu, 2001). Kugler, Kelso, and Turvey (1980) underscored the importance of constraints in emergent, rather than prescriptive, explanations of human movement by stating: “... 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” (p. 9). Newell (1986) extended this initial theorising and outlined a model in which three categories of constraint—organismic, environmental, and task—coalesce to channel and guide emergent patterns of coordination² and control³ that ultimately determine performance outcome⁴ (see Fig. 1).

Organismic constraints are those constraints that reside within the boundaries of individual movement systems. Broadly defined, organismic constraints are those constraints imposed physically, physiologically, morphologically, or psychologically (McGinnis & Newell, 1982). To account for the diverse nature of organismic constraints, they have been partitioned into either structural or functional constraints to reflect the time dependent nature by which this specific type of constraint manifests (Newell & Valvano, 1998). Structural organismic constraints tend to be physical or morphological and remain relatively constant over time, and include: stature, body mass and composition; genetic make-up; the anthropometric and inertial characteristics, and resonant frequencies, of the torso and limbs; the number of anatomical DOF and ranges of motion of articulating structures; 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., Carson & Riek, 1998; Jensen, 1993; Newell, 1984; Shemmell, Tresilian, Riek, & Carson, 2004; Wagenaar & van Emmerik, 2000). Some of these structural constraints, specifically those relating to muscle architecture, location of muscle origin and insertion, and fibre composition, have also been referred to in the literature as neuromuscular-skeletal constraints (e.g., Carson, 1996; Carson & Riek, 1998; Shemmell et al., 2006) or neuroanatomical constraints (e.g., Riek & Woolley, 2005). Functional organismic constraints have a relatively faster rate of change and tend to vary quite considerably over time. They are typically either physiological or psychological and account for much of the variation in sports performance over the duration of an event, match, or contest. Important functional organismic constraints include: heart rate; lactate concentrations; glucocorticoid release; synaptic connections; emotions; (focus of) attention; sensory perception; motivation; and so on. Perhaps the most prominent and influential functional organismic constraint that can shape movement coordination is the intentions of the performer (Kelso, 1995).

Environmental constraints are those constraints that are external to the movement system. They tend to be 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, ubiquitous gravitational forces, and the reaction forces exerted by the ground and other contact surfaces and apparatus. Sociocultural constraints, encompassing factors such as peer groups and societal expectations (Chow et al., 2006; McGinnis & Newell, 1982), can also be classified as environmental constraints (Clark, 1995, 1997). Even the location of a competitive sporting event, such as playing at home or away (e.g., Nevill & Holder, 1999), can be considered an important environmental constraint. Newell (1986) originally made the distinction between environmental constraints that are general

² Coordination is the function that constrains DOF into a behavioural unit (Newell, 1985). Intra-individual coordination refers to the coupling relationship between body segments, limbs, or limbs and torso. Inter-individual or inter-personal coordination refers to the coupling relationship between athletes or players in the context of sport (see also Sparrow, 1992). Bernstein (1967) succinctly described coordination as the “... organisation of the control of the motor apparatus” (p. 127). Coordination, therefore, precedes control (Meijer, 2001).

³ Control is the process of parameterising, scaling, or tuning of the coordination function (Newell, 1985). Typical measures of control include amplitude, velocity, acceleration, and force (see also Sparrow, 1992).

⁴ Performance outcome is the product or result of an action. Success or failure in a particular task is dependent on whether the performance outcome satisfies the task goal or criterion. The outcome of action is, therefore, usually expressed in the same terms as the goal of the action (Newell, 1996).

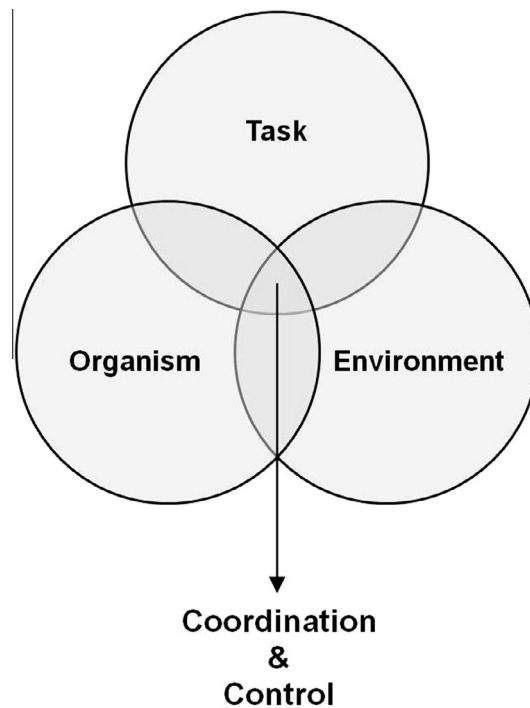


Fig. 1. Newell's (1986) constraints model was originally drawn as a triangle with one of the three categories of constraint listed on each of its three corners. I prefer, as others have (e.g., Holt et al., 2010), to draw the model as a Venn diagram as it better illustrates how behaviour (i.e., patterns of coordination and control) emerge from the confluence of interacting constraints (depicted by the dark grey area of intersection or overlap). Furthermore, as the relative position and, therefore, the extent of overlap of the three circles is free to change, this format nicely captures the dynamic nature of constraints and their respective contribution to performance at any given time.

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 task constraints, are now classified as environmental constraints under the revised framework.

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) 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" (p. 299). Examples of task constraints include shooting distance during a basketball match or imposing a one-touch rule within a simulated football match during a training session. Task constraints that explicitly specify limb and torso movements, or restrict them to within certain boundaries, are commonplace in sport. 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 during the delivery stride (see Sparrow, Shemmell, & Shinkfield, 2001). Instructions issued by a coach or practitioner may also be viewed as a type of task constraint (Newell & Ranganathan, 2010). Thus, the manipulation of task constraints is considered to be important for motor skill acquisition because augmented feedback, in the form of verbal instruction or visual demonstration, for example, is also viewed as a type of task constraint. Within this coaching-related context, task constraints have been referred to as instructional constraints (e.g., Al-Abood, Bennett, Hernandez, Ashford, & Davids, 2002; Lopes, Araújo, Duarte, Davids, & Fernandes, 2012) or informational constraints⁵ (e.g., Al-Abood, Davids, Bennett, Ashford, & Marin, 2001; Pinder, Davids, Renshaw, & Araújo, 2011).

Although Newell, van Emmerik, and McDonald (1989) emphasised that it is the organismic, environmental, and task constraints acting in concert that ultimately determines the pattern of coordination and control produced, the relative contribution of these three categories of constraint on sports performance is dependent on the specific requirements of the performance context and the task being performed (see caption for Fig. 1). Moreover, their impact on coordination

⁵ More generally, the term 'informational constraints' refers to visual, acoustic, and haptic information that can be directly perceived by the performer (i.e., affordances) and used to shape and guide behavioural output. This type of constraint represents an important component of the 'behavioural dynamics' (Warren, 2006) or 'ecological dynamics' (Araújo, Davids, & Hristovski, 2006) approach to perception and action, which integrates principles and concepts from ecological psychology and dynamical systems theory.

and control is dependent, not only on the performer's perception of the constraint and the action it affords, but also the state of the organism–environment system at that specific moment in time (Newell, 1989). In principle, 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 (Newell, 1996). Also, it is possible that changes 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).

Whilst other constraint classifications have been proposed in the literature before by Pattee (1972; non-holonomic vs. holonomic) and Higgins (1977; environmental vs. biomechanical vs. morphological), and since by Warren (1990; physical vs. informational), Carson, Byblow, Abernethy, and Summers (1996; inherent vs. incidental), and Swinnen, Jardin, Meulenbroek, Dounskaia, and Hofkens-Van Den Brandt (1997; egocentric vs. allocentric), Newell's (1986) model has been the most widely cited (1163 times as of 15 June 2015 according to Google Scholar™) and was the first to make explicit reference to the formation and dissolution of what Turvey (1990) described as the "... most primitive independently governable actuators of movement" (p. 940)—the functional motor synergy or coordinative structure.^{6,7}

2.1. Role of constraints in the formation of coordinative structures

So far, I have established *what* constraints impact on sports performance but an important question is: *how* do organisational, environmental, and task constraints shape the patterns of coordination and control that determine performance outcomes in sport? In dynamical systems accounts of human movement, internal and external constraints provide 'equations of constraints' that get metaphorically 'written over' DOF to functionally combine or 'softly assemble' them into task-specific structural units known as coordinative structures (Goldfield, 1995; Kugler & Turvey, 1987; Saltzman, 1979; Schmidt & Fitzpatrick, 1996; Tuller, Turvey, & Fitch, 1982). Following Easton (1972), Turvey (1977) proposed that coordinative structures may provide a solution to Bernstein's (1967) famous 'degrees of freedom problem'—that is, how the large number of independent, but often functionally redundant, component parts of the movement system can be regulated without ascribing excessive responsibility to a higher-order executive or external regulating agent (Turvey, 1990). Kugler et al. (1980) defined a coordinative structure as "... a group of muscles often spanning several joints that is constrained to act as a single functional unit" (p. 17). However, Kay (1988) subsequently defined them, more generally, as "... an assemblage of many micro-components ... assembled temporarily and flexibly, so that a single micro-component may participate in many coordinative structures on different occasions" (p. 344). This latter definition perhaps better reflects the ubiquity of these special-purpose devices at different levels of analysis (e.g., molecular, cellular, neuronal, muscular, etc.) and more effectively captures the concept of degeneracy⁸ in single-agent neurobiological systems. More recently—and importantly given the focus of this target article and my desire to develop a GUT that is universally applicable across all levels of analysis of sports performance—the coordinative structure concept has been extended and applied to multi-agent neurobiological systems to help explain the emergence of interpersonal coordination and control (e.g., Dale, Fusaroli, Duran, & Richardson, 2014; Riley, Richardson, Shockley, & Ramenzoni, 2011; Schmidt, Fitzpatrick, Caron, & Mergeche, 2011; Schmidt & Richardson, 2008; Shockley, Richardson, & Dale, 2009).

Two defining operational characteristics of a coordinative structure are dimensional compression and reciprocal compensation (Latash, 2008; Riley et al., 2011). Dimensional compression refers to the conversion of a high-dimensional system comprising of very many independent DOF to a low-dimensional system consisting of comparatively few sets of interdependent DOF, which yield relatively stable and well-defined behavioural patterns or attractor states (Kay, 1988). This feature, in effect, simplifies the problem of regulating movement since the central nervous system only has to macromanage the collective, not micromanage its constituents. Reciprocal compensation refers to the capacity of mutually dependent DOF to make compensatory adjustments or covariations, thus ensuring the functional integrity and common output of the coordinative structure are preserved should an error be introduced or perturbation occur (Latash, Scholz, & Schöner, 2002). These task-specific structural units are able to operate relatively autonomously with minimal intervention from a higher-order executive or external regulating agent because they are able to exploit the "... free interplay of forces and mutual influences among components tending toward equilibrium or steady states" (Kugler et al., 1980, p. 6)—that is, they are able to self-organise (see Kelso, 1995).⁹ So, just as the coach or manager of a football team does not specify the exact motion of each of his or her

⁶ The terms 'synergy' and 'coordinative structure' have often been used synonymously in the literature. Other labels, such as special-purpose device (e.g., Fowler & Turvey, 1978), task-specific device (e.g., Bingham, 1988), uncontrolled manifold (e.g., Scholz & Schöner, 1999), and coordination mode (e.g., Balasubramaniam & Turvey, 2004), have also been used to denote these temporary assemblages of micro-components.

⁷ Interestingly, Nitsch (1985) emphasised unique 'person–environment–task constellations' in his action-theoretical approach to human performance (see also Schack & Hackfort, 2007).

⁸ Edelman and Gally (2001) defined degeneracy as "... the ability of elements that are structurally different to perform the same function or yield the same output" (p. 13763). They argued that degeneracy is a more appropriate term than redundancy when referring to neurobiological systems since the latter occurs only when "... the same function is performed by identical elements" (p. 13763) and, therefore, is perhaps best reserved for electronic or mechanical systems where duplication or repetition is an inherent design feature that provides a safeguard against component failure (see also Tononi, Sporns, & Edelman, 1999). The term degeneracy has had a somewhat chequered history in neurobiology (see Mason, 2010, 2015, and Mason, Domínguez, Winter, & Grignolio, 2015, for reviews) and some researchers (e.g., Mayr, 1994) have questioned whether it is justifiable given it has negative connotations—meaning deterioration or degradation of structure and function—in common usage. Nevertheless, it is a concept that has a substantial theoretical and empirical basis and is increasingly being used by a number of influential researchers in sport and human movement science (e.g., Davids, Araújo, Button, & Renshaw, 2007; Kelso, 2012; Newell & Liu, 2012).

⁹ A special issue of *Human Movement Science* entitled 'Self-Organization in Biological Works Spaces' was also dedicated to the then-new paradigm of self-organisation in 1988 (Volume 7, Issue 2–4, pp. 91–407).

players during a particular passage of play, each player's central nervous system does not prescribe the exact sequence and duration of muscle activation required to produce a particular series of limb and torso movements for a given action (e.g., running or kicking). In both instances, the organisation and interaction of DOF are governed only by locally created information against the backdrop of interacting organismic, environmental, and task constraints (e.g., [Davids et al., 2003](#); [Passos, Araújo, & Davids, 2013](#)). Furthermore, the number of active or dynamic DOF¹⁰ involved in the production of a particular pattern of coordination and control has also been suggested to be influenced by the confluence of constraints. Indeed, [Newell and Vaillancourt \(2001\)](#) concluded that the "... change in both the organization of the mechanical degrees of freedom and the dimension of the attractor dynamic organizing motor output can either increase or decrease according to the confluence of constraints imposed on action" (p. 695).

A schematic summarising the role of self-organisation and constraints in the formation of coordinative structures and the assembly of emergent patterns of coordination and control at both the intra- and inter-individual levels of analysis, can be found in [Fig. 2](#).

3. The GUT as a conduit for integrating the subdisciplines of sports science

In [Section 2](#), I proposed that, at both the intra- and inter-individual levels of analysis, patterns of coordination and control, which directly determine the performance outcome, emerge from the confluence of interacting organismic, environmental, and task constraints via the formation and self-organisation of coordinative structures. If this theoretical perspective is accepted,¹¹ the proposed GUT could provide a scientifically rigorous basis for the interdisciplinary integration of the various subdisciplines of sports science to better explain, and gain a more holistic understanding of, sports performance. A schematic summarising how the main subdisciplines of sports science, including motor control and development, skill acquisition, sports biomechanics, sports performance analysis, strength and conditioning, sports physiology, sports psychology, and sports technology, could coalesce is shown in [Fig. 3](#).

To elaborate briefly the proposed roles and contributions of the respective subdisciplines within the framework provided by this GUT: sports biomechanics, sports performance analysis, and sports technology can provide the methods and tools for measuring and analysing patterns of coordination and control at the intra- and inter-individual levels of analysis (see [Glazier, 2010](#); [Glazier & Robins, 2013](#)); skill acquisition and motor control can enhance understanding of how coordinative structures at both the intra- and inter-individual levels of analysis are formed and how their morphology changes during skill acquisition (e.g., [Vereijken, van Emmerik, Bongaardt, Beek, & Newell, 1997](#); [Vereijken, van Emmerik, Whiting, & Newell, 1992](#)), how practice design and training environments can be manipulated to accelerate their assembly and optimisation (e.g., [Chow, Davids, Hristovski, Araújo, & Passos, 2011](#)), and how their constituent DOF re-organise as internal and external constraints change; motor development can provide insights into how 'complexity' (i.e., flexibility and adaptability) of physiological and biomechanical processes change across the lifespan of an athlete and how they impact on sports performance (e.g., [Deutsch & Newell, 2005](#); [Morrison & Newell, 2012](#); [Newell, Vaillancourt, & Sosnoff, 2006](#); [Vaillancourt & Newell, 2002](#)); sports physiology and sports psychology, in addition to providing insights into fundamental biophysical, biochemical, and cognitive mechanisms, can provide the methods and tools for measuring and analysing key functional organismic constraints, such as fatigue and anxiety, which have both been shown to have a substantial impact on the organisation and interaction of DOF (e.g., [Bonnard, Sirin, Oddsson, & Thorstensson, 1994](#); [Collins, Jones, Fairweather, Doolan, & Priestley, 2001](#); [Forestier & Nougier, 1998](#); [Higuchi, Imanaka, & Hatayama, 2002](#)); and strength and conditioning can contribute to the development of structural organismic constraints through carefully devised and implemented training interventions (e.g., [Ives & Shelley, 2003](#); [Jeffreys, 2011](#)). The contribution of this latter subdiscipline is important during performance preparation since any physical and physiological deficiencies or weaknesses in individual DOF may compromise the structural and functional integrity of its constituent coordinative structure, thereby potentially jeopardising its collective output, whether that be at the intra- or inter-individual level of analysis.

The aforementioned list of roles and contributions of the various subdisciplines of sports science is not intended to be exhaustive or definitive. Instead, it should be viewed more as a guide—and possibly a goad—as to how the subdisciplines and their respective scientists could operate more symbiotically, using the GUT as a conduit, to gain a deeper, more complete, understanding of sports performance. Of course, the adoption of the GUT does not preclude sports scientists from working in isolation or in parallel with other sports scientists—as would be the case in monodisciplinary and multidisciplinary research, respectively (see [Abernethy et al., 2013](#); [Burwitz et al., 1994](#))—but clearly, to fully understand sports performance, an interdisciplinary approach is required. For example, to understand how a full-back missed a crucial penalty kick in the closing moments of an important rugby union match, it is necessary to examine not only the magnitude and

¹⁰ The number of active or dynamic DOF involved in the production of a particular behavioural pattern or attractor state is largely determined by the strength or rigidity of the coupling amongst physical or mechanical DOF. If physical or mechanical DOF are strongly coupled, the number of active or dynamic DOF, and the dimension of the corresponding attractor, is likely to be low. Conversely, if physical or mechanical DOF are loosely coupled, the number of active or dynamic DOF, and the dimension of the corresponding attractor, is likely to be high. The dimension of an attractor is, therefore, an index of the number of independent DOF that are required to reconstruct the time-evolutionary properties (i.e., geometric organisation) of movement trajectories. There need not be any direct relation between the number of physical or mechanical DOF and the dimension of the attractor output ([Newell & Vaillancourt, 2001](#)).

¹¹ Other unifying frameworks, based on computational theories, have been proposed to explain motor control and social interaction (e.g., see [Wolpert, Doya, & Kawato, 2003](#)) and could, in principle, be applied to sports performance.

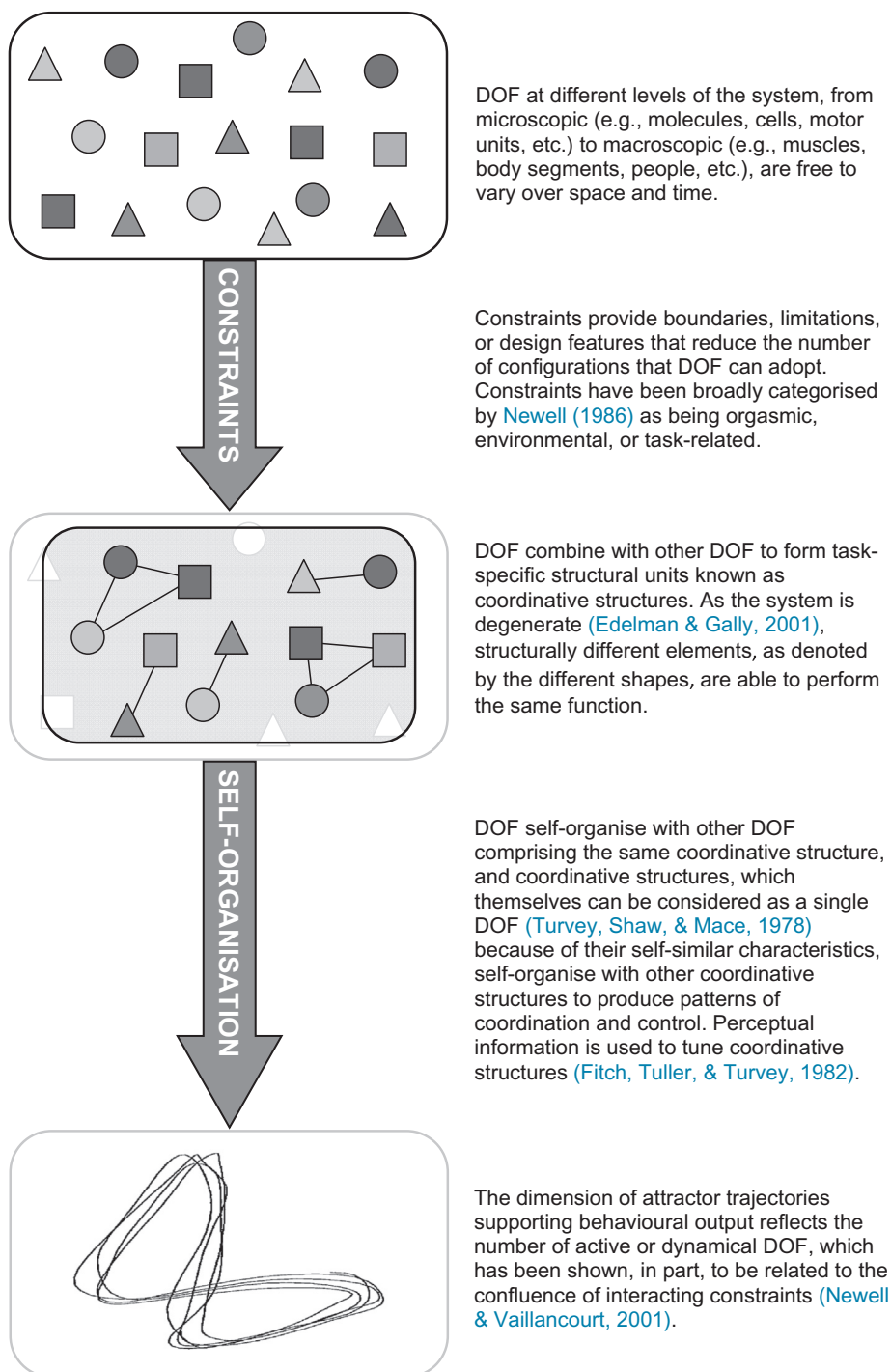


Fig. 2. The role of constraints and self-organisation in the formation of coordinative structures at the intra- and inter-individual levels of analysis (adapted from [Riley et al., 2011](#)).

direction of the force applied to the ball by the kicking foot during the impact phase and its relation to key task (e.g., required distance) and environmental (e.g., wind direction) constraints, but also how the DOF (e.g., muscles, joints, and segments) of the kicking leg were organised and how they interacted to produce that force, and how psychological constraints, such as anxiety, may have disrupted the organisation and interaction of these DOF. Similarly, to understand how a successful rugby union team performed better than a less successful rugby union team over the duration of a match or season, it is necessary

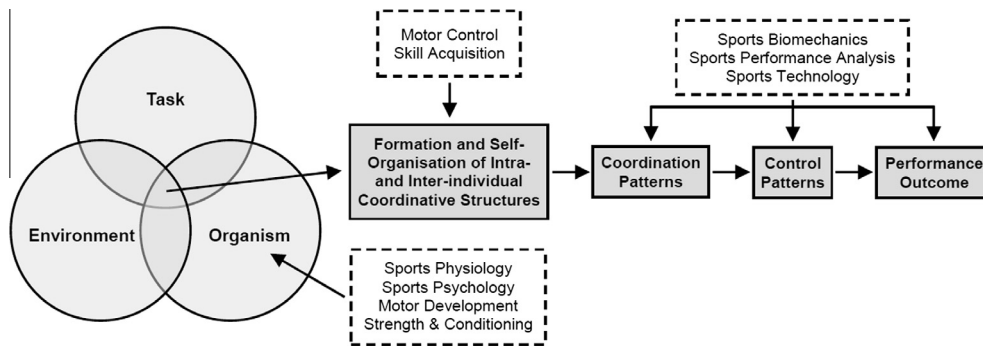


Fig. 3. A schematic summarising how the GUT (shaded areas) can be used as a basis for the interdisciplinary integration of the main subdisciplines of sports science (unshaded areas) to gain a more comprehensive and holistic understanding of sports performance (see text for further elaboration).

to examine not only how DOF (i.e., players) were organised and how they interacted with each other during attacking and defensive plays, but also how the organisation and interaction of DOF varied according to changes in task (e.g., tactics) and environmental (e.g., weather conditions) constraints, as well as how key physiological constraints, such as fatigue, impacted on this organisation and interaction of DOF. In both of the aforementioned examples, it would appear that the integration of principles, concepts, methods, and data from at least two subdisciplines of sports science is necessary to gain a more complete understanding of sports performance.

As physiological and psychological constraints occupy such important roles in sports performance, and because they have rarely been stated in these terms or within a unified framework previously, further consideration is given in Sections 3.1 and 3.1, respectively, to how these key functional organismic constraints impact on emergent patterns of coordination and control at the intra- and inter-individual levels of analysis, and, in particular, the organisation and interaction of DOF.

3.1. Physiological constraints

The physiological constraint that perhaps impacts directly on sports performance more than any other is fatigue. Fatigue develops when the substrates from which energy is derived for muscle contraction become depleted or when the by-products of metabolism accumulate in the active muscle. Many definitions of fatigue can be found in the extant literature (see Williams & Ratel, 2009, for a review) but one of the most widely-cited was provided by Bigland-Ritchie and Woods (1984) who defined it as "... any reduction in the force generating capacity of the total neuromuscular system regardless of the force required in any given situation" (p. 691). Most empirical investigations examining the effects of fatigue on sports performance have typically reported that it leads to decreases in the magnitude, and increases in the variability, of various indices of control (e.g., force, amplitude, velocity, acceleration, power, range of motion, etc.), which, in turn, lead to reductions in the speed, accuracy, and consistency of performance outcomes (e.g., Apriantono, Nunome, Ikegami, & Sano, 2006; Davey, Thorpe, & Williams, 2002; Higham, Pyne, Anson, & Eddy, 2012; Kellis, Katis, & Vrabas, 2006; Murray, Cook, Werner, Schlegel, & Hawkins, 2001; Rampinini, Impellizzeri, Castagna, Coutts, & Wisløff, 2009; Rota, Morel, Saboul, Rogowski, & Hautier, 2014; Russell, Benton, & Kingsley, 2011).

Fewer studies have considered how fatigue affects the organisation and interaction (i.e., the coordination) of DOF underlying movement control (e.g., Aune, Ingvaldsen, & Ettema, 2008; Bonnard et al., 1994; Dorel, Drouet, Couturier, Champoux, & Hug, 2009; Forestier & Nougier, 1998; Rodacki, Fowler, & Bennett, 2001; Trezise, Bartlett, & Bussey, 2011) and the vast majority of extant investigations have only considered changes in coordination at the intra-individual level of analysis. A common finding of many of these studies, however, is that, during prolonged sub-maximal physical activity, DOF at various levels of analysis are able to adjust their contribution to minimise the global impact of fatigue, thereby allowing the same level of intensity to be maintained for longer (see also Patla, 1987). For example, Bonnard et al. (1994) reported that, when hopping for an extended period, some participants were able to maintain power output and compensate for fatigue-induced impairment of force production in ankle extensor muscles by proportionally increasing force production in the knee extensors. Dorel et al. (2009) also reported large increases in muscle activity in hip extensors to compensate for reduced muscle activity in knee extensors when under fatigue during cycling. The existence of similar compensatory muscle and joint actions have also been reported in investigations into the effects of fatigue in hand-held industrial tool usage (e.g., Côté, Feldman, Mathieu, & Levin, 2008; Côté, Mathieu, Levin, & Feldman, 2002) and repetitive occupational load lifting (e.g., Sparto, Parnianpour, Reinsel, & Simon, 1997). These collective findings tentatively confirm the existence of coordinative structures and the important role that reciprocal compensation amongst their constituent DOF may play in prolonging sports performance.

Another finding to emerge from these studies is that segmental interactions tend to become increasingly more rigid with fatigue. For example, Forestier and Nougier (1998) showed that, in a throwing task, the peak velocities of the elbow, wrist, and hand followed a progressive proximal to distal sequence in the no fatigue condition but, in the fatigue condition, the

temporal delay between peak velocities of these anatomical landmarks largely disappeared indicating that the arm moved more as a single unit. [Martin and Brown \(2009\)](#) also reported that joint power and range of motion decreased more in the ankle compared to the knee and hip during maximal cycling. The authors of both studies suggested that, by increasing the stiffness of upper and lower extremity joints, the tasks of throwing and pedalling would, in effect, be simplified. This strategy is harmonious with the ‘freezing’ of DOF strategy proposed by [Bernstein \(1967\)](#) and empirically verified by [Vereijken et al. \(1992\)](#) during early stages of skill acquisition in which learners attempt to reduce the abundance of peripheral DOF to a more manageable number by rigidly fixing joints. Interestingly, similar findings have also been reported at the inter-individual level of analysis by [Duarte et al. \(2013\)](#). They showed that the organisation and interaction of football players on the same team tended to become more regular and predictable during the course of a match as fatigue collectively accumulated. Again, these findings are consistent with the theoretical predictions of [Bernstein \(1967\)](#) and the inflexible collective behaviour exhibited by inexperienced young junior footballers in a recent preliminary empirical study by [Button, Chow, Dutt Mazumder, and Vilar \(2011\)](#).

Some, albeit very limited, research has shown that more skilled performers may be more adept at delaying the deleterious effects of fatigue than less skilled performers. [Aune et al. \(2008\)](#) compared the techniques and performances of expert and recreational table tennis players and found that more skilled players were able to adjust their forehand drive techniques to maintain performance outcomes whereas less skilled players were less able to adapt and consequently performance outcomes deteriorated. These findings can be explained by more expert performers having increased flexibility in couplings amongst DOF comprising coordinative structures integral to the production of the forehand table tennis stroke, thus allowing a wider repertoire of coordination solutions to emerge under fatigue constraints. [Royal et al. \(2006\)](#) also showed how the throwing techniques of elite water polo players changed with different levels of fatigue and perceived exertion but performance level (i.e., speed and accuracy of ball release) was maintained. However, since no other expertise group was included in that study, no skill level comparisons could be made.

3.2. Psychological constraints

The psychological constraint that perhaps impacts directly on sports performance more than any other is anxiety. At any level of sports competition, anxiety can often have a profound—sometimes catastrophic—affect on performance. Anxiety has been classically defined by [Spielberger \(1966\)](#) as: “... subjective, consciously perceived feelings of apprehension and tension, accompanied by or associated with activation or arousal of the autonomic nervous system” (p. 17). A commonly-identified antecedent of anxiety is performance pressure created from the desire to perform at the highest possible level in situations that are perceived to be very important by the individual or team ([Baumeister, 1984](#)). Moderately to severe pressure-induced anxiety can lead to acute and dramatic declines in performance—a phenomenon colloquially known as ‘choking’ (e.g., [Hill, Hanton, Fleming, & Matthews, 2009](#)). A variety of theories have been proposed to explain how sports performance can, and often is, affected by anxiety (see [Beilock & Gray 2007](#)) but, given most of these hypotheses (e.g., reinvestment theory – [Masters, 1992](#); processing efficiency theory – [Eysenck & Calvo, 1992](#)) have origins in information processing theory, the focus of most research has predominantly been on establishing cognitive mechanisms (e.g., attentional processes, memory structures, etc.) with relatively little consideration given to how anxiety physically manifests in terms of its impact on the processes of coordination and control that ultimately determine sports performance (see [Weinberg, 1990](#)).

A feature of early research examining the relationship between anxiety and sports performance was the use of a diverse array of somewhat crude and insensitive parameters pertaining, often directly, to the successful attainment or otherwise of the performance outcome (see [Gould, Greenleaf, & Krane, 2002](#)). There have, however, been some more recent attempts to monitor changes in various indices of control with anxiety during the performance of sports skills. For example, in studies of golf putting, it has been demonstrated that pressure and anxiety increases the time to peak speed ([Mullen & Hardy, 2000](#)) and lateral acceleration ([Cooke, Kavussanu, McIntyre, & Ring, 2010](#)) of the putter head during the downswing as well as decreases in the velocity of the putter head at impact under intermediate levels of pressure ([Cooke, Kavussanu, McIntyre, Boardley, & Ring, 2011](#)). [Tanaka and Sekiya \(2010\)](#) found that the amplitude of the backswing and downswing were significantly smaller, and the velocity of the downswing significantly slower, for both expert and novice putters under pressure, although no significant changes in anxiety amongst pressure conditions were reported. [Gray, Allsop, and Williams \(2013\)](#) also reported a smaller range of downswing amplitudes when putting under pressure over different distances. For full swings, [De Ste Croix and Nute \(2008\)](#) reported significantly shorter downswing durations performed under high anxiety competition conditions compared to low anxiety practice conditions by amateur club golfers of varying expertise. In another biphasic hitting action from sport, [Gray \(2004\)](#) found that the temporal ratio of the wind-up and swing phase durations in baseball batting was more variable under pressure compared to baseline conditions. A common, but far from universal (e.g., [Mullen & Hardy, 2000](#); [Tanaka & Sekiya, 2010](#)), artefact of the aforementioned changes in indices of control was reduced accuracy and consistency of impact conditions leading to an increased frequency of unsuccessful performance outcomes.

The number of studies that have investigated the effect of anxiety on the organisation and interaction (i.e., the coordination) of DOF underlying movement control has been more limited. Similar to research on the effects of fatigue on sports performance, a common finding to emerge from the few extant studies focusing on this issue is that anxiety tends to increase the rigidity or stiffness of joints, indicating a temporary regression to an earlier stage of skill learning ([Bernstein, 1967](#)). Early research by [Weinberg and Hunt \(1976\)](#) found elongated periods of co-contraction of the biceps and triceps of the throwing arm during a throwing task for participants experiencing high anxiety under high pressure conditions, whereas participants

experiencing low anxiety displayed more sequential muscle action under the same conditions. Although no kinematic measurements were taken, it is likely that the prolonged period of co-contraction increased the stiffness and reduced the range of motion at the elbow joint. More recently, [Higuchi et al. \(2002\)](#) showed that, in a computer-simulated batting task, the amplitude of arm movements reduced, and kinematic variability decreased, when anxiety was induced by administering mild electric shocks. Furthermore, higher correlations between movement onset and various kinematic events were reported under the anxiety condition. Taken together, these findings were interpreted as evidence of freezing DOF, although segmental interactions were not formally analysed. [Pijpers, Oudejans, Holsheimer, and Bakker \(2003\)](#) also showed that novice rock climbers displayed greater rigidity and less fluency of movements when climbing at higher, compared to lower, heights. Further evidence of increased joint stiffness and reduced movement variability with stress and anxiety has been provided by [Collins et al. \(2001\)](#) and [van Loon, Masters, Ring, and McIntyre \(2001\)](#).

Although the aforementioned empirical studies clearly demonstrate that pressure and anxiety can lead to the freezing of DOF, it has been suggested that it is not pressure and anxiety *per se* that is responsible for the change in the organisation and interaction of DOF, but, rather, it is the shift to a more internal focus of attention caused by pressure and anxiety (e.g., [Gray, 2011](#)). To support this supposition, not only have participants reported greater self-consciousness and self-awareness under pressure (e.g., [Gray, 2004](#)), recent focus of attention research by [Lohse, Sherwood, and Healy \(2010\)](#) and [Lohse, Jones, Healy, and Sherwood \(2014\)](#) has shown that participants who were instructed to focus on movement execution (internal focus of attention) exhibited less variability in shoulder and elbow joint motions and performed worse than participants who focused on the task outcome or goal of the movement (external focus of attention). These findings are supported by earlier work indicating that a more internal focus of attention increases activity in agonist and antagonist muscles ([Zachry, Wulf, Mercer, & Bezodis, 2005](#)), which has been associated with more rigid joint action. Although most prevailing explanations of the effect of focus of attention on motor behaviour and performance have been based on information processing theory (e.g., constrained action hypothesis – [Wulf, McNevin, & Shea, 2001](#)), it may be posited that attention represents another psychological constraint that acts to rigidly couple DOF and disrupt inherent self-organising processes (e.g., [Davids, 2007](#)).

4. Measurement and analysis issues posed by the GUT

Many of the empirical studies examining the effect of key physiological and psychological constraints on emergent patterns of coordination and control in Sections 3.1 and 3.2, respectively, were conducted within the confines of the laboratory or a similar tightly controlled environment using comparatively simple motor tasks. Furthermore, it is evident that there is a clear bias in the number of studies investigating the effects of these functional organismic constraints on emergent patterns of coordination and control at the intra-individual, as opposed to inter-individual, level of analysis. A significant challenge for applied sports scientists adopting the GUT advocated here, however, is the task of measuring and analysing the effects of different constraints on emergent patterns of coordination and control at both the intra- and inter-individual levels of analysis in real-time during competition. The development of ‘integrated technology’—the conjoining of wireless performance monitoring technologies with emerging motion capture and analysis systems ([Dellaserra, Gao, & Ransdell, 2014](#))—in sports biomechanics and sports performance analysis promises to be an important step in meeting this challenge. The main measurement and analysis issues related to the implementation of this GUT are discussed in Sections 4.1 and 4.2, respectively.

4.1. Measurement issues

A significant issue posed by the GUT is the measurement of individual DOF at different levels of analysis. At the intra-individual level of analysis, it is not currently possible to accurately measure the output of individual DOF (e.g., motor units, muscles, etc.) beyond the kinematic level of analysis in the field during competition.¹² At the kinematic level of analysis, manual coordinate digitising techniques are labour-intensive, time-consuming, and measurement error tends to mask movement variability when no superficial skin markers are used ([Bartlett, Bussey, & Flyger, 2006](#)). Recent developments in automated markerless motion capture technology (see [Mündermann, Corazza, & Andriacchi, 2006](#)) indicate that accurate measurement of three-dimensional limb and torso kinematics in real-time during sports competition may soon become reality. Indeed, a recent study by [Corazza, Mündermann, Gambaretto, Ferrigno, and Andriacchi \(2010\)](#) has shown that average differences between joint centre locations using automated marker and markerless motion capture systems during walking trials were between 9 and 19 mm. The application and utility of this technology has since been further demonstrated by [Sheets, Abrams, Corazza, Safran, and Andriacchi \(2011\)](#) and [Abrams, Harris, Andriacchi, and Safran \(2014\)](#) who used it to examine differences in the kinematics and kinetics of three types of tennis serve. The emergence of new motion sensing technology in the gaming and entertainment industries may also help accelerate the development of automated markerless motion capture technology in sport (e.g., see [Choppin & Wheat, 2013](#), for a summary of recent research exploring the potential use of Microsoft Kinect™ in the analysis of human movement).

¹² Even under laboratory conditions, there is some debate as to whether it is possible to accurately measure the output of individual muscles or motor units ([Glazier & Davids, 2009b](#)). The measurement of muscle force is particularly problematic and is often inferred from surface electromyography. However, owing to the well-documented non-linear relationship between electromyographic signals and muscle force (e.g., [De Luca, 1997](#); [Hug, Hodges, & Tucker, 2015](#)), values obtained for the latter can only be considered approximations. This anomaly may have ramifications for the interpretation of findings relating to the organisation and interaction of DOF under physiological and psychological constraints summarised in Sections 3.1 and 3.2, respectively.

At the inter-individual level of analysis, player tracking systems based on global positioning system (GPS) technology (see Aughey, 2011 and Cummins, Orr, O'Connor, & West, 2013, for recent reviews) and local positioning system (LPS) technology (see Leser, Baca, & Orgis, 2011, for a recent review) have great potential but owing to regulations imposed by some governing bodies precluding tagging of players with tracking sensors during competitive matches (e.g., soccer), the use of these systems is generally limited to practice environments. Other image-based player tracking systems, such as Prozone[®] (Prozone Sports Ltd., Leeds, UK) and SportVU[®] (STATS Corp., Chicago, USA), do not have this limitation but they have typically required significant amounts of manual intervention to accurately track individual players (see Barris & Button, 2008 and Castellano, Alvarez-Pastor, & Bradley, 2014, for recent reviews). As GPS, LPS, and image-based player tracking technologies mature and regulations are relaxed, applied sports scientists will be able to more accurately measure the motion of individual DOF (i.e., players) in a competitive match environment. Given the current state of the art, the measurement of emergent patterns of coordination and control at the inter-individual level seems far more feasible than at the intra-individual level, at least in the immediate future.

Another significant issue posed by the GUT is the measurement of different physiological and psychological constraints during sports performance. The use of heart rate monitors (Achten & Jeukendrup, 2003) to measure *in situ* changes in heart rate and heart rate variability is both straightforward and convenient, although the measurement of single physiological variables in isolation provides only an incomplete picture of physical activity. Other technologies capable of capturing different variables simultaneously are being developed for sports application. For example, the BioHarness[™] 3 (Zephyr Technology Corporation, Annapolis, MD) is a wearable Bluetooth[®]-enabled device that allows valid and reliable heart rate, breathing rate, accelerometer data, skin temperature, and postural information to be collected both in the laboratory (Johnstone, Ford, Hughes, Watson, & Garrett, 2012a,b) and in the field (Johnstone et al., 2012c). In terms of measuring psychological constraints, various scales, questionnaires, and inventories have typically been used to evaluate stress, pressure, and anxiety in sport (see Ostrow, 1996, for a review). An emerging technology in sports science, which could be useful for gaining further insight into psychological constraints, is electroencephalography (EEG) (Schneider & Strüder, 2012; Thompson, Steffert, Ros, Leach, & Gruzelier, 2008). Indeed, EEG has recently been used to study brain dynamics both within and between individuals of a team under different task constraints (Dodel, Tognoli, & Kelso, 2013; Dodel et al., 2011). Although methodological issues have generally meant that EEG has been limited to indoor use, a recent pilot study by Reinecke et al. (2011) showed that it may be a viable tool in the near future for analysing brain dynamics whilst performing sports actions in the field.

4.2. Analysis issues

Another key aspect of implementing the GUT advocated in this target article is being able to analyse and evaluate the effects of different constraints on emergent patterns of coordination and control at the intra- and inter-individual levels of analysis, especially how they impact on the organisation and interaction of DOF. To date, however, most empirical investigations in applied sports biomechanics and sports performance analysis have predominantly focused on the analysis of 'performance parameters' or 'performance indicators' (Hughes & Bartlett, 2002) thought to be related to successful performance. These variables are putatively derived from theoretical models of performance (e.g., hierarchical flow charts – Hughes & Franks, 2004; deterministic models – Chow & Knudson, 2011) and are usually classified as being either technical (e.g., number of completed passes, shots on goal, possession duration, etc.), tactical (e.g., length and distribution of passes, tackles won and lost, attacking and defending duration, etc.), or physical/biomechanical (e.g., distances covered at various speeds, peak velocity and acceleration, number of changes of direction, etc.). Although considered useful for informing the coaching process, formulating tactical strategies, and designing physical conditioning programmes, these measures have a tendency to be studied in isolation of each other, often lack context, have questionable reliability, and promote only a rudimentary understanding of sports performance (e.g., Glazier, 2010; Lames & McGarry, 2007; McGarry, 2009; Vilar et al., 2012). Importantly, these variables are typically outcome- rather than process-focused and, consequently, have a tendency to describe *what* happens without explaining *how* or *why* it happens (Glazier & Robins, 2012; McGarry, 2009; Vilar et al., 2012). For example, research suggests that more successful football teams may complete a greater number of passes than less successful football teams (e.g., Oberstone, 2009) but this apparently important performance indicator provides no information about how players on the same team interact either with one another, or in relation to their opponents, to enable a higher number of passes to be completed. Similarly, when shooting at goal, a high foot velocity has been shown to be an important prerequisite for generating a high ball velocity (e.g., Dörge, Bull Andersen, Sørensen, & Simonsen, 2002), which is important as it reduces the amount of time available for the goalkeeper to react and intercept the ball's trajectory, thus preventing a goal from being scored, but this performance parameter does not specify how the thigh, shank, and foot segments should interact to produce a high foot velocity.

There is a need for sports biomechanists and sports performance analysts to move beyond reductionist paradigms, such as analysing relationships between discrete performance parameters and/or performance indicators and performance outcomes, and focus more on the analysis of continuous movement-related variables to establish firmer links between sports behaviours and performance outcomes (Glazier, 2010; McGarry, 2009), and the impact of different constraints (e.g., fatigue, anxiety, match status, playing environment, etc.) on the organisation and interaction of DOF integral to those behaviours. Although techniques such as dimensionality analysis (e.g., Kay, 1988), principal component analysis (e.g., Daffertshofer, Lamoth, Meijer, & Beek, 2004; Federolf, Reid, Gilgien, Haugen, & Smith, 2014; Wang, O'Dwyer, & Halaki, 2013), and uncontrolled manifold analysis (e.g., Scholz & Schöner, 1999), may be required to formally examine the hallmark features

of coordinative structures (i.e., dimensional compression and reciprocal compensation), other methods have been developed that could be used for analysing the attractor dynamics supporting sports performance. For example, McGinnis and Newell (1982), Newell and McGinnis (1985), and Newell and Jordan (2007) outlined a framework based on topological dynamics for the graphical mapping of movement trajectories and constraints in different control spaces (i.e., configuration space, event space, state space, and state-time space). The construction of relative motion plots and phase-plane portraits based on these trajectory mappings, and the subsequent application of analytical and statistical techniques, such as vector coding (e.g., Tepavac & Field-Fote, 2001), continuous relative phase (e.g., Lamb & Stöckl, 2014), and cross-correlations (e.g., Amblard, Assaiante, Lekhel, & Marchand, 1994), have been used to examine qualitative and quantitative changes in patterns of coordination and control (see Wheat & Glazier, 2006, for a review). These techniques, however, can only be used to analyse the interaction of a very limited number of DOF and have generally been applied to investigations of intra- and inter-limb coordination. To analyse whole-body and inter-personal coordination, which involve the interaction of a much larger number of DOF, unsupervised or self-organising artificial neural networks have generally been used. Two of the most popular have been the Kohonen Feature Map (Kohonen, 2001) and the Dynamically Controlled Network (Perl, 2002). These closely-related approaches involve the compression of high-dimensional input data (e.g., three-dimensional kinematic data) onto a low-dimensional map whilst preserving the topological characteristics of the original data. Both methods have been successfully used, for example, to analyse differences in technique amongst elite and sub-elite sports performers (see Schöllhorn, Chow, Glazier, & Button, 2014, for a review) and to identify playing patterns within and between teams in sports matches (see Perl, Tilp, Baca, & Memmert, 2013, for a review).

5. Summary and concluding remarks

The GUT of sports performance proposed in this target article, which is based on the conceptual model introduced originally by Newell (1986), asserts that, at both the intra- and inter-individual levels of analysis, patterns of coordination and control, which directly determine the performance outcome, emerge from the confluence of interacting organismic, environmental, and task constraints via the formation and self-organisation of coordinative structures. Although many of the principles and concepts of the proposed GUT are not new, it appears they have been overlooked by many applied sports scientists who have seldom used them, for example, to gain a greater understanding of how various physiological and psychological variables impact on sports performance. As I have discussed in this target article, the GUT has the potential to help explain how these, and other, variables act as key constraints on sports performance by impacting on the organisation and interaction of DOF at different levels of analysis.¹³ Although there are measurement and analysis issues that need to be resolved, the GUT advanced here could provide a platform on which applied sports scientists can integrate their respective skills and knowledge, provide a more holistic understanding of sports performance, increase explanatory power of applied research work, and guide applied research programmes and support work. The realisation of this GUT, which, to my knowledge, is the first to be postulated in the sports performance literature, is timely given that sports science is currently searching for a unifying theoretical framework (it was the theme of the 18th Annual Congress of the European College of Sport Science, 26–29 June 2013, Barcelona, Spain) and there is a need to explore alternative paradigms in applied sports science following a recent independent report in the UK by the House of Lords Select Committee on Science and Technology (2012), which stated “... research on elite athletes is generally observational and anecdotal; at best it describes what, but does not explain why” and that there is “... little evidence to suggest that the enhancement of performance of elite athletes is generally based on strong biomedical science, nor that the latest advances in relevant areas of biomedical research are consistently applied to this work” (p. 4). I believe that the GUT outlined here could provide much-needed impetus and help to reinvigorate the field of sports science, which has apparently been on the decline in some parts of the world (Stone, Sands, & Stone, 2004).

In addition to the potential benefits to sports performers, coaching practitioners, and the productivity of applied sports scientists themselves, it is likely that the GUT outlined in this target article may afford other benefits to higher education institutions and aspiring academics researching in the field. For example, in the ‘Unit of Assessment Report for Sports-Related Studies’ published by Higher Education Funding Council for England (2009) following the UK’s Research Assessment Exercise in 2008, it was suggested that “... one strategy for achieving international research excellence is through collaboration, internally and with other groups, regionally, nationally and internationally. Such cooperation may entail increased use of interdisciplinary approaches, especially in light of the relative scarcity of interdisciplinary models in this multidisciplinary subject” (p. 4).¹⁴ Furthermore, one of the key components of the UK’s recent Research Excellence Framework 2014 was ‘impact’, which the Higher Education Funding Council for England (2011) defined as the “... effect on, change or benefit to the economy, society, culture, public policy or services, health, the environment or quality of life, beyond academia” (p. 26). I suggest that the GUT proposed in this target article not only affords one of the apparently few opportunities for sports scientists to develop robust

¹³ The proposed GUT may also have further application in the sister discipline of sports medicine. For example, it has been shown that pathology and pain can not only cause a redistribution of activity within (e.g., Tucker, Butler, Graven-Nielsen, Riek, & Hodges, 2009) and between (e.g., Ervilha, Farina, Arendt-Nielsen, & Graven-Nielsen, 2005) individual muscles, but also reduce variability in joint and segment couplings (e.g., Hamill, van Emmerik, Heiderscheit, & Li, 1999). The principles and concepts of the proposed GUT may help to explain these empirical findings and increase understanding of motor adaptation to pain, more generally, especially in light of the inadequacies of existing theories (see Hodges, 2011; Hodges & Tucker, 2011).

¹⁴ The promotion and fostering of interdisciplinary research is also recognised as being strategically important by the National Institutes of Health in the US (see Freedson, 2009).

interdisciplinary research collaborations, but it also provides a scientifically rigorous rationale for the formation of such collaborative partnerships, and has the potential to increase the reach and significance of applied sports science research in a practical context. I hope that more sports scientists will be inspired to adopt this previously unheralded approach and explore the exciting opportunities for interdisciplinary research that it presents in the coming years.

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