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Ludovic Seifert, Chris Button & Keith Davids

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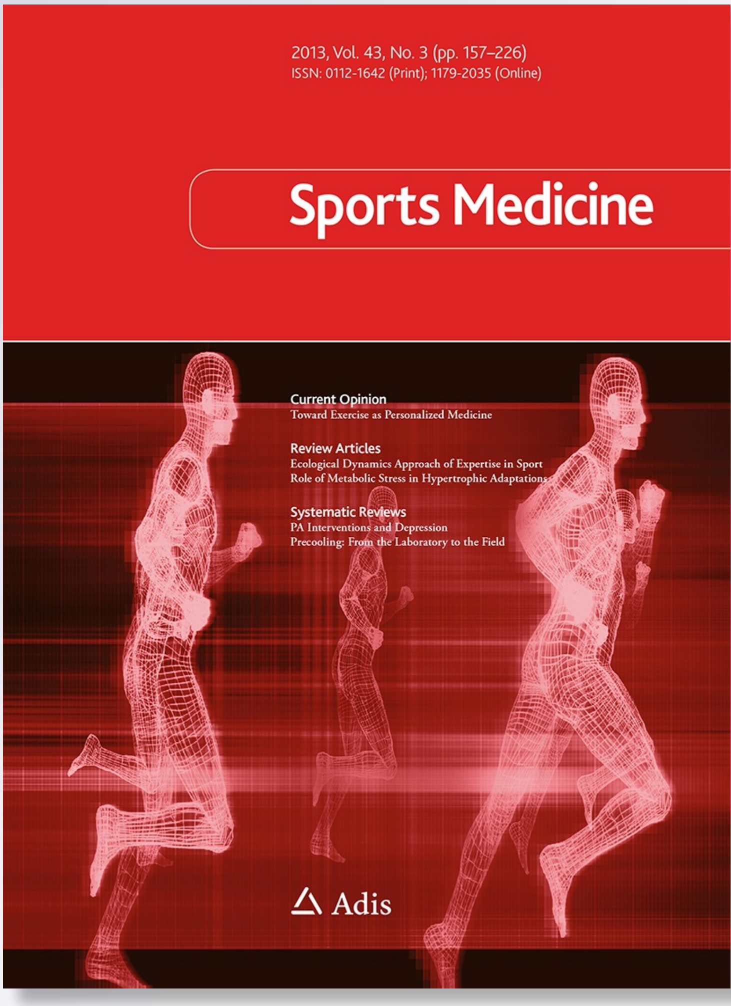

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REVIEW ARTICLE

Key Properties of Expert Movement Systems in Sport

An Ecological Dynamics Perspective

Ludovic Seifert · Chris Button · Keith Davids

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Abstract This paper identifies key properties of expertise in sport predicated on the performer-environment relationship. Weaknesses of traditional approaches to expert performance, which uniquely focus on the performer and the environment separately, are highlighted by an ecological dynamics perspective. Key properties of expert movement systems include 'multi- and meta-stability', 'adaptive variability', 'redundancy', 'degeneracy' and the 'attunement to affordances'. Empirical research on these expert system properties indicates that skill acquisition does not emerge from the internal representation of declarative and procedural knowledge, or the imitation of expert behaviours to linearly reduce a perceived 'gap' separating movements of beginners and a putative expert model. Rather, expert performance corresponds with the ongoing co-adaptation of an individual's behaviours to dynamically changing, interacting constraints, individually perceived and encountered. The functional role of adaptive movement variability is essential to expert performance in many different sports (involving individuals and teams; ball games and outdoor activities; land and aquatic environments). These key properties signify that, in sport performance, although basic movement patterns need to be acquired by developing athletes, there exists no ideal movement template towards which all learners should aspire, since relatively unique functional movement solutions emerge from the interaction of key constraints.

L. Seifert (✉)
Centre d'Etude des Transformations des Activités Physiques et Sportives (CETAPS)-EA 3832, Faculty of Sport Sciences, University of Rouen, Bld Siegfried, 76821 Mount Saint Aignan Cedex, Mont Saint Aignan, France
e-mail: ludovic.seifert@univ-rouen.fr

C. Button
School of Physical Education, University of Otago, Dunedin, New Zealand

K. Davids
School of Human Movement Studies, Queensland University of Technology, Brisbane, QLD, Australia

1 Introduction

Expertise in sport has been traditionally explained with reference to cognitivist, computational and hierarchical models of motor behaviour [1–4] and of performance [5–9]. From this overarching perspective, achieving expert levels of performance requires the acquisition of representations for the execution, monitoring and planning of performance [9]. Perceptual, cognitive and motor skills provide the capacity, acquired through learning and experience, to achieve performance outcomes prescribed in advance, with maximal probabilities of success, and often with minimal time, energy or both [10]. Some have argued that expertise can only be achieved by undertaking an extended period of deliberate practice, which is not particularly enjoyable and results from repeated, intense engagement in a task, requiring effortful concentration [7]. Based on these ideas, Ericsson et al. [6] operationally described an expert as an individual that has accrued at least 10 years or 10,000 h of deliberate, high-level practice. They proposed that learners exposed to this period of intense, repetitive practice will gain the capacity to both reproduce the same behaviour and increase the automatic control of a movement. The main goal of deliberate practice is to reduce deviations of performance from an internalized expert model or template, requiring problem-solving, trial-and-error corrections to produce better methods for task performance, with help from coaches and teachers [6]. The skill acquisition process traditionally involves much logical reasoning, verbalization, imitation and internalization of declarative and procedural knowledge using explicit teaching methods and frequent verbal instructions on how to achieve a task goal [11–13]. Widespread acceptance of these ideas about expertise is reflected by numerous references to Ericsson and colleagues' work in popular science books, such as *Outliers* [14], *The Talent Code* [15] and *Bounce* [16].

This conception of sport expertise is, however, not without its critics in academia. The traditional approach predicated on deliberate practice, has been questioned with regard to effects of age, sociocultural context, genetics and talent, degree of specificity of the activity, motivation and an overemphasis on 'time' spent practising as a key constraint [17]. In a nutshell, this conception of the acquisition of expertise fails to consider a wide range of interacting constraints on each individual, the ongoing coupling of an athlete with the performance environment and the functional role (i.e. adaptive) of movement variability between and within individuals [18, 19]. For example, Tucker and Collins [20] observed that Ericsson and colleagues [6] failed to provide measures of variability (standard deviations (SDs) of data on hours spent in deliberate practice) for the 10,000 h hypothesis in their study of violinists [6]. This is a crucial omission, since in a study of chess masters, an astonishing range of 3,016–23,608 h was observed in the achievement of that level of expertise [20]. Variability in achieving expert performance is important to investigate and, here, we highlight the contribution of an 'ecological dynamics' framework for understanding skill acquisition [21–23]. We build on previous dynamical systems' theoretical descriptions of the study of movement coordination and its acquisition [18, 21–30]. In previous work, only Phillips et al. [29] have focused on sport expertise examining its relationship with talent. Here we review empirical evidence for key properties of expertise espoused by a mix of theoretical ideas from dynamical systems theory and ecological psychology including: system 'multi- and 'metastability', 'adaptive variability', 'redundancy', 'degeneracy' and the 'attunement to affordances'. The final section of this paper explores the adaptive and functional role of 'movement pattern variability' between and within individuals in relation to expert performance in different sports (involving individuals and teams; ball games and outdoor activities; land and aquatic environments).

2 An Ecological Dynamics Approach to Sport Performance and Expertise

Traditional approaches to the study of sport performance and expertise have been criticized in ecological dynamics because of (i) the common misconception that expertise is only achieved through acquiring knowledge about the environment in internal representations. In these traditional explanations the role of cognition information processing and attentional processes in the control of voluntary behaviours, although important, are typically over-emphasized [11, 12]. Standard accounts of expertise focus on how expert behaviours are almost exclusively predicated on knowledge about the environment (perception of which is indirect and mediated by language, symbols, pictures and instructions) [31]. In contrast, Gibson [31] reconceived expertise in terms of 'knowledge' of the environment, which is embedded in knowing how to realize an action. It involves perception of affordances (information-based opportunities for action) used to regulate behaviour directly without reliance on symbol mediation and the internalization of knowledge about the environment [32–37]; (ii) genetic constraints and innate characteristics that support the emergence of individual and adaptive behaviours and are typically not taken into account [18, 20, 29]; and (iii) standardized performance evaluation tests used that include a reduced range of task constraints, restricting possibilities for the emergence of spontaneous behaviours in athletes by incorporating a static environmental design in performance assessment [37–40]. Standardized evaluation tests often reduce a simulated performance context to static situations in a controlled setting instead of considering the dynamics of skill acquisition as a perpetually changing non-linear process.

Ecological dynamics offers an alternative view that combines concepts from ecological psychology with dynamical systems theory. In ecological psychology the perception-action cyclical relationship emphasizes the role of information that emerges from the performer-environment system to regulate action directly [31, 42]. In that respect, the concept of affordance was introduced by Gibson [31, 42] to capture the possibilities for action offered by perception of key properties of the environment. This information-based approach provides a compelling analysis of action-relevant informational variables, but did not explain how information is cyclically related to the dynamics of action. Dynamical systems theory provides an elegant conceptual framework for understanding neurobiological coordination at multiple levels (i.e. from behaviour to brain) [43–45] with roots in thermodynamics [46] and synergetics [47, 48]. Physical principles and concepts from nonlinear, dissipative, self-organizing systems explain coordination dynamics as a natural process of pattern formation in neurobiological systems [28, 49]. Coordination dynamics explains and predicts how patterns of coordination emerge, adapt, persist and change in integrated complex systems [28, 49]. These ideas have been instrumental in explaining the dynamics of perception and action in the individual-environment system [21–24, 50–52], providing an ecological physics and a physical psychology [53]. Such a 'behavioral dynamics' approach captures the emergence of adaptive functional behaviours by an individual in a performance environment, coupled by perceptual information [24, 50, 51]. An ecological dynamics approach uses the concepts and tools of dynamical systems to understand phenomena that occur at an ecological scale (i.e. considering the relationships between individuals and their environments) [21–23]. Thus, perception and action are viewed as emerging from the interactions of individuals with environmental constraints over time towards specific behavioural goals. This ecological dynamics framework provides a substantial epistemological approach to studying and understanding expertise and skill acquisition in sport. Within this framework, there is no ideal template for expert behaviour in an absolutist sense [54]; rather, it is considered that expert performance is achieved as each individual satisfies the unique set of interacting constraints impinging on him/her [55]. Functional movement behaviours emerge from the interaction of task, environmental and organismic constraints [23, 27, 56, 57]. The unpredictable nature of the environment and the indeterminate solutions for many tasks in human behaviour emphasizes the circular causality of the relationship between each individual and the performance environment, brain and behaviour and perception and action [24, 28, 58–60]. Ecological dynamics emphasizes the performer-environment relationship as the basis for understanding expert performance and it is a misconception to propose that this approach is environmentalist ([61] exemplifies this misconception). The causality between brain and behaviour, and between processes of perception and action, is not linear but cyclical, as the individual continuously constructs goal-directed interactions with the performance environment. From this perspective, expertise is the continuous functional adaptation of behaviours to a set of interacting constraints in order to exploit them to the fullest in achieving specific intended performance goals [23, 62]. In this adaptive behaviour, it is important to understand the role of key neurobiological system properties in driving the acquisition of expertise in sport.

3 Key Properties of Complex Neurobiological Systems Functioning in Performance Environments

According to Kelso [28, 63, 64], coordination dynamics is an attempt to understand the laws that govern spatial-temporal pattern formation in complex systems. Within this framework 'coordination' relies on collective variables that specify the spatial-temporal ordering between system elements [28, 63, 64]. Coordination dynamics capture the time evolution of a system according to laws of motion, exploring how these patterns become stable and attractive, or unstable and changing in response to environmental or task demands [28, 63, 64]. These continuous system changes could merely result in an adaptive pattern refinement or the adoption of new form through a non-linear phase transition. In humans, key properties of complex and dynamical systems concern the formation of behavioural patterns (i.e. stable states of organisation or 'attractors'); 'non-linear transitions' from one attractor to another attractor (e.g. system transitions or bifurcations, hysteresis, critical slowing down); 'multi-stability' (i.e. ability to transit between multiple states of organization under given constraints); 'meta-stability' (i.e. ability to exploit co-existing coordination tendencies in a transition or unstable region); and 'variability' (exploiting critical fluctuations to enable adaptive behavioural transitions). An important concern is the information that guides complex system behaviours and here Gibson [31, 42] emphasized the role of 'affordances' as a key property of performer-environment interactions, which skilled individuals become progressively attuned to as their expertise levels increase [32].

During sport performance, the degrees of freedom of human movement systems can become temporarily coordinated to achieve task goals. Spontaneously and through extensive practice, movement systems converge toward stable states of coordination (attractors), towards which coaches can guide learners. Performance changes can often emerge without involving any intermediate states, as abrupt transitions or after an intermittent period of bi-stability is observed during learning (known as a saddle-node bifurcation; for further details, see [65–67]). In nonlinear systems, a microscopic input change can lead to a qualitative macroscopic output change [28, 68, 69].

In experts, preferred organization tendencies form basins of attraction that reveal an individual's 'intrinsic dynamics' (i.e. inherent coordination dispositions) in specific performance contexts [70]. Expertise is predicated on adapting one's intrinsic dynamics to cooperate with a task's dynamics, and the transfer of expertise is defined by the amount of cooperation or competition between each individual's intrinsic dynamics and the task dynamics. When the gap existing between the intrinsic dynamics of an individual and the task demands is low, and/or when the tasks demands are weak, a convergence between the two might be expected (facilitating transfer of skill). Previously, Kelso [71] demonstrated the presence of multi-stability in performance of a bi-manual coordination task. Specifically, bi-stability (i.e. inphase and antiphase coordination patterns co-existing) was observed when participant index fingers were flexed and extended at low frequencies of oscillation. Conversely, a change in task constraints (e.g. higher frequency of oscillation) led to only an inphase coordination pattern sustained [71]. However, multi-stability is not only observed under low levels of task constraint and could also be a signature of expertise in relation to performance creativity. Multi-stable movement patterns can reflect behavioural creativity since it can result in the emergence of distinct functional (i.e. those which can specify actions) motor solutions in satisfying interacting constraints that were not imposed by an external source [72]. As explained in Sect. 4.3, the co-existence of various adaptive motor solutions, with the inherent degeneracy of neurobiological systems, can be exploited to enable different system components to achieve the same performance outcomes [25, 26, 37].

Expert performers are able to transit functionally between distinct motor solutions by exploiting system multi-stability and picking up affordances, which they have the capacity to functionally exploit during performance. With increasing levels of expertise, individuals exploit system degeneracy to focus on different perceptual variables that are more effective under a variety of different performance circumstances. In contrast, novices tend to pick up and use sources of information that may be only partially functional in particular performance situations because they do not specify actions effectively. For instance, in rock climbing, Boschker et al. [73] demonstrated how experts recalled more information specifying the 'functional' properties of a climbing wall, neglecting to perceive its 'structural' features. Conversely, novices were not able to recall such functional properties of the wall to support their actions and they tended to report almost exclusively the structural (less functional) features of the holds [73]. For instance, if a rock climber grasps a surface hold because of its large size instead of its shape or its orientation, she/he may be using the wrong structural feature (e.g. hold size instead of hold shape or hold orientation) to decide which hold to grasp and how to grasp it. Indeed, a large hold is not always easy to grasp, because the hold could be rounded, smooth and lacking in friction. An affordance in rock climbing specifies what a hold is and what a hold means, not separately but unified in one perceiving-acting process. This simple practical example exemplifies the mutuality and reciprocity of the coupling of perception and action systems in the climber-environment relationships [58–60]. The increasing attunement of a performer to affordances can be understood by examining how an individual's intentions converge with that of the task, then how such individuals improve his/her attunement to the relevant informational variables and, finally, how she/he constantly adjusts his/her calibration by scaling movement to the information. Seifert et al. [74] reported how expert ice climbers showed a greater attunement to environment constraints (notably by exhibiting multi-stable movement patterns) than novices during performance as they exploited the properties of frozen water falls for climbing. Expert ice climbers were attuned to functional holes in an ice fall, which could facilitate multi-stable movement patterns (different climbing actions), by perceiving stochastic variations in key properties such as ice-fall shape and steepness, temperature, thickness and density of ice. Expert climbers exhibited upper and lower inter-limb coordination tendencies that varied in horizontal, oblique, vertical and crossed-angular locations, by swinging their ice tools to create different anchorages and by hooking existing holes in the ice fall [74]. Conversely, novices only tended to use horizontal and oblique angles of upper and lower limb organization, with their ascent resembling climbing up a ladder. For novices, a functional anchorage was most often synonymous with a deep anchorage, which they tended to create by swinging their ice tools and kicking with their crampons more frequently than experts, instead of exploiting existing holes in the ice fall [74]. In summary, the multi-stability of limb-angular positioning and movement patterning observed in expert climbers highlighted their ability to perceive ice-fall properties as affordances (i.e. possibilities for action called 'climbing opportunities' by Boschker et al. [73]). In contrast, the reduced number of limb angular coordination tendencies exhibited by novices showed that they are less attuned to the relevant informational variables from environmental properties, as they mostly focused on maintaining their body equilibrium under control (in accordance with the findings of Bourdin et al. [75] in rock climbing). These findings highlight the acute perception-action coupling of the expert performers and the undeveloped perception-action coupling of the novice climbers.

Meta-stability represents a fruitful property of complex, dynamical movement systems that coaches and teachers can exploit to support the emergence of rich and creative motor behaviours that characterize expertise in sports. Meta-stability has been defined as a transient or semi-transient behaviour or a 'dynamically stable' state of system organization [28, 63, 64]. According to Kelso [63], meta-stability is the "simultaneous realisation of two competing tendencies: the tendency of the components to couple together and the tendency for the components to express their intrinsic independent behavior" (p. 186). In a meta-stable performance region, component tendencies of independence coexist, explaining how rich and varied movement patterns can spontaneously emerge in dynamic sport environments as an individual adapts his/her motor behaviours to achieve particular performance goals [68, 76–78]. In a meta-stable performance region one or several movement patterns are weakly stable (when there are multiple attractors) or weakly unstable (when there are only attractor remnants), and switching between two or more movement patterns occurs under interacting constraints. Kelso [28] noted that, in a meta-stable region, there is attractiveness but, strictly speaking, no attractors.

There exists some evidence of meta-stability in skilled sport performance. For example, Hristovski et al. [76, 77] investigated how boxers' striking patterns were adapted when they punched a heavy bag at various scaled distances to the target (i.e. a ratio of physical distance/arm length). At greater distances from the boxing bag (e.g. 1–1.2 of each boxer's arm length scaled to target distance 'jab' movement pattern emerged, whereas at closer distances (e.g. 0.3) 'uppercuts' or 'hooks' patterns were observed. No specific instructions were provided to participants on which strokes to use. A critical value of 0.6 scaled distance to target seemed to lie within the meta-stable performance region as the novice boxers explored a rich, varied and creative range of movement patterns involving 'uppercuts', 'hooks' and 'jabs' [77]. The boxing striking patterns transitioned according to the perception of a 'strikeability' affordance (i.e. the perception of the scaled distance to a target) [76]. These findings are important in understanding the acquisition of expertise in sport, since they exemplified how placing a performer's perceptual, cognitive and action systems in a meta-stable region of performance enhanced their exploratory behaviours.

Pinder et al. [78] postulated the emergence of a meta-stable region where two cricket batting patterns (i.e. involving backward and forward strokes) dwelt at a critical body-scaled ball-landing location against medium fast bowlers. Mono-stable forward movement patterns were observed when the ball was bowled close to a batter (2.5–3.5 m from the stumps), at a location 5–6 m away (that corresponded to ball bouncing to the height of the top of the stumps). A transition towards mono-stable backward strokes also occurred with a ball bowled to land 8–9 m away from the stumps. This location corresponded to the ball bouncing higher, typically requiring a batter to move on to the back foot to play a stroke [78]. When the bowler delivered the ball to a region of 6.5–7.5 m away from the stumps, a meta-stable region emerged where batters demonstrated 48% forward strokes and 52% backward strokes [78]. Skilled batters were able to functionally transit between forward and back foot strokes in the meta-stable region, exhibiting a relative blend of dependence/independence of environmental information sources during performance, which allows them to regulate functional behaviours by perceiving environmental properties to achieve initial planned intentions (to hit the ball rather than let it go past). In the case of cricket batting, due to the disguise used by a skilled bowler, sometimes waiting to perceive the relevant properties of a fast bowling delivery may not provide enough time for a batter to functionally organize the appropriate (back-foot or front-foot) stroke. In this performance context, skilled cricketers harness emergence by deciding an initial response that can be modified by information from the actual delivery. In summary, a meta-stable region represents a performance region, characterized by indeterminacy and emergent motor responses, which corresponds to adaptability, i.e. a subtle blend between behavioural stability and flexibility that, as we suggest in the next section, represents a promising way to develop expertise in sport.

4 Movement Variability as Adaptive Skilled Behaviour

4.1 Variability, Stability, Flexibility and Adaptability

Traditional approaches to the study of sport performance and expertise have typically focused on performance outputs and their consistent achievement. Ecological dynamics and its emphasis on emergent behaviours under interacting constraints signals the need to carefully distinguish variability in movement organization, a healthy sign of adaptive behaviour in indeterminate biological movement systems, from variability in performance outputs that is synonymous with performance inconsistency and, therefore, less functional [19]. This idea has significant implications for interpreting the quality of movement patterns that may deviate from a putative expert model of performance.

During the past decades a number of studies have focused on the functional and adaptive role of movement variability, whereas it has traditionally been conceptualized as error or system noise to be reduced [79–81]. Movement variability should not be misconceived as a deviation from a putative expert performance model that should be constantly corrected in beginners [23]. Considering the functional role of movement variability leads to an exploration of what adaptive behaviour means, so that it could be more appropriate to consider the term 'adaptability' rather than variability. Adaptability relates to an appropriate ratio between 'stability' (i.e. persistent behaviours) and 'flexibility' (i.e. variable behaviours) [18, 24, 82, 83], and is essential to skilled performance in many different sports. Expert behaviour is characterized by stable movement patterns that are consistent over time, resistant to perturbations and reproducible in that a similar movement pattern may recur under different task and environmental constraints. Experts are capable of subtly nuanced behaviour that is not stereotyped and rigid but flexible and adaptive. Even if movement patterns show regularities and similarities within their structural components, they are not fixed into a rigidly stable solution, but can be adapted in a functional way, since neurobiological complex systems can exploit inherent degeneracy [84].

An ecological dynamics model of expertise promotes the performance value of both stability and flexibility: experts and non-experts each have their stable states and sometimes share the same coordination modes; however, a particularity of expert performance is the capacity for adaptability, i.e. to produce behaviour that is stable when needed and flexible when needed. In fact, although human movement systems naturally tend to move toward stable states with experience, as more economical organization modes [85–87], stability and flexibility should not be construed as opposites. Flexibility should not be interpreted as a loss of stability but, conversely, as a sign of adaptability [24, 83].

4.2 Movement Variability is an Adaptive Response to Interacting Constraints

Movement system variability can be functional when athletes need to respond to changes in dynamic performance constraints [18, 19, 27, 62, 79]. Within the ecological dynamics framework, there is no one ideal motor coordination solution towards which all learners should aspire, but rather functional patterns of coordination that emerge from the interaction of constraints (task, environmental and organismic) [23, 27, 56, 57, 88]. In this sense, constraints are resources that limit or set the boundaries for the emergence of form in human movement systems.

'Environmental' constraints are external to the individual and can be physical, reflecting the environmental conditions of the task (light, temperature, altitude, gravity, buoyancy). In swimming, in response to changing environmental constraints (e.g. variation of aquatic resistance and swim speed: drag relates to speed square), experts were observed to exhibit three distinct coordination patterns [89–92]. Typically in breaststroke, at slow active drag and speed, experts use a 'glide' pattern of coordination as they can insert a glide time of varying length, while a 'continuous' pattern of coordination is used at medium drag and speed ('continuous' signifying that arm propulsion follows leg propulsion, i.e. no glide phase). At sprint speed where active drag is high, expert breaststrokers use a 'superposition' coordination pattern where the beginning of the leg propulsion overlaps the end of the arm recovery in order to maintain high average swim speed [90, 92, 93]. Conversely, changes in environmental constraints do not lead to the emergence of qualitatively different modes of coordination in novices, since they only tend to exhibit an 'accordion' coordination pattern, regardless of speed range. Moving as an 'accordion' signifies the synchronization of flexion movements of both arms and legs (i.e. inphase mode of arms to legs coordination), with the same for extension movements [94, 95]. The only kinematic change observed in novice behaviours concerns the variation of the stroke rate [93].

'Task' constraints include the goal of the task, the rules, boundary locations, instructions or equipment specifying a response. For instance, in a kicking task in soccer (chipping a ball over a barrier to reach a target), the changing task constraints (barrier height and position of the target) caused experts and intermediate-level players to vary their kicks by varying speed, thus sending the ball higher or lower in the air. In contrast, novices tended to drive the ball in the same way in all situations, suggesting less flexibility and adaptation to the task constraints [96]. The 'organismic' or personal constraints are structural or functional and refer to characteristics of an individual such as genes, anthropometric properties, cognition, motivation and emotions. For instance, a gender effect was found to explain differences in terms of inter-limb coordination in swimming [97]. Indeed, females typically exhibit a higher frequency of 'glide' coordination tendencies (less propulsive continuity between the propulsion of the two arms) than males in relation to their greater fat mass, a different distribution of this mass, lower arm strength and greater difficulty in overcoming forward resistance [97].

4.3 Redundancy and Degeneracy

Bernstein [98] emphasized that motor system degrees of freedom are temporarily coordinated together according to the performance environment and task requirements. It has been well documented that novices typically freeze their motor system degrees of freedom, while experts release the degrees of freedom not useful in task performance (observed for an example in a ski simulator task [99], swimming [92, 94, 95], the volleyball serve [100] and in ice climbing [74]). Freezing system degrees of freedom corresponds to rigidly fixing the joints to reduce the control problem for a performer. This control strategy has been observed in an inphase coordination pattern (reflecting an isodirection or isocontraction of two limbs together [101]) in rhythmic movements such as a ski simulator task [99]. In this task, releasing degrees of freedom corresponds to an out-of-phase strategy (in particular, antiphase coupling of homologous muscles [99]). These distinctive patterns were exemplified by the antiphase coordination (accordion) pattern in breaststroke swimming of novices [94, 95]. This strategy of freezing the degrees of freedom was used by the novices to maintain the body at the water surface by continuous and synchronous limbs movements. However, this coordination mode is not mechanically effective and does not provide high swim speeds because leg propulsive action is thwarted by arm recovery action and arm propulsion is thwarted by leg recovery action [94, 95]. Conversely, intentions and actions of experts are mostly dedicated to swimming fast with the lowest active drag, so that elite swimmers need to organize different coordination patterns within the cycle, requiring the release of system degrees of freedom. Expert swimmers display an out-of-phase pattern of coordination of their arms and legs during propulsion (i.e. flexion or extension of a pair of limbs while the other pair of limbs is fixed in extension), an inphase coordination pattern during the glide (i.e. extension of the arms and legs) and an antiphase coordination pattern during recoveries (i.e. extension of the arms during leg flexion) [90, 94].

The varying role of these motor system degrees of freedom in assembling actions is essential, and is exemplified by the degenerate networks existing at different levels of human movement systems, including molecular, genetic and musculoskeletal [26, 27]. Neurobiological system 'degeneracy' is technically defined as "the ability of elements that are structurally different to perform the same function or yield the same output" [84] (p. 13763). Thus, behavioural adaptability could reflect the modification of one component of the system and/or a whole modification of coordination realised by 'redundant' elements (i.e. the presence of isomorphic and isofunctional components) or by 'degenerate' elements (i.e. the presence of heteromorphic variants that are isofunctional) [102]. Degeneracy in complex biological systems provides the neurophysiological basis for the diversity of actions required to negotiate information-rich, dynamic environments from moment to moment, as well as providing a huge evolutionary fitness advantage. Degeneracy signifies that an individual can vary motor behaviour (structurally) without compromising function, providing evidence for the adaptive and functional role of movement pattern variability in order to satisfy task constraints. The presence of degeneracy in a biological system increases its complexity and robustness against perturbation and underlies 'pluripotentiality', a property that ensures an organism's functional ongoing engagement with the dynamic performance environment [102–104]. Mason [102] proposed four avenues for degeneracy in biological systems that advances understanding of how experts functionally adapt their motor behaviours to exhibit consistently high levels of performance in dynamic sport contexts. First, "redundancy can create the opportunity for degeneracy to arise as the function of the original structure is maintained by one copy, while any other copy is free to diverge functionally" [102] (p. 282). Second, degeneracy can occur through 'parcellation', when an initial structure is subdivided into smaller units that can still perform the initial function and can also be functionally redeployed" [102] (p. 282). Third, degeneracy may emerge through a coordinative structure that realizes a function in combination. It means that whether a structure is able to perform an initial function independently, another one is available for modification. Last, degeneracy may exist when two or more independent structures converge upon the same function. These four avenues for degeneracy emphasize the potential adaptation in human movement systems that coaches and teachers could encourage to emerge in various individual motor responses to satisfy task constraints. Degeneracy of neurobiological systems provides the capacity for sport performers to exploit multi- or meta-stability of actions under dynamic task constraints.

A substantial body of literature has highlighted the functional role of multi-articular movement variability in sport performance environment and exemplifies how degeneracy emerges at an 'intra-individual' (i.e. inter-trial and intra-trial) and 'inter-individual' level in soccer kicking [96], basketball shooting [105, 106], the volleyball serve [100], the handball shot [107–109], the field hockey drive [110–112], the table tennis forehand drive [113], swimming [95–97], climbing [74], and long and triple jumping [114, 115]. Concerning intra-individual movement variability, Fradet et al. [107] and Schorer et al. [108] showed that having the highest and most stable speed/accuracy ratio during the shooting phase in handball, was not the only characteristic of expertise. For example, the ability to vary the shot from one trial to another in order to deceive a goalkeeper is a more important reflection of expertise because it better assures achievement of the task goal. Analysis of the basketball shot has indicated that inter-trial coordination variability between the elbow and wrist joints became more variable toward the end of the action than at the beginning, to ensure better accuracy [105]. Expert shooters compensated the values of ball release speed and release angle against each other to achieve a consistent performance outcome. In field hockey shooting, Burgess-Limerick et al. [111] and Franks et al. [112] showed that the movement was more variable in the backswing phase, to maintain consistency in the downswing and particularly at impact with the ball. When analysing the volleyball serve, Davids et al. [88] showed that variability (between the start of the serve, the peak of ball toss height and contact) in the ball location, at the time of contact with the hand, decreased in the vertical axis, but increased in the sagittal and lateral axes. The authors noted more variability at the point of ball-hand contact in order to adjust the direction of the ball in real time. Similar results were observed for the table tennis forehand. Bootsma and van Wieringen [113] showed that trial to trial, expert players varied the time between the initiation of movement and ball/racket contact, providing a model based on continuous perception-action coupling for this type of task.

At an inter-individual level, movement pattern variability has been observed both at novice and expert level, suggesting that neurobiological degeneracy is a common property in human motor behaviour. However, degeneracy is instrumental in different ways with regards to expertise level. Due to extensive experience in various performance contexts, experts exploit to the fullest their individual properties according to the task demands and the environmental constraints. For instance, research has shown that expert players in field hockey reached the same performance outcomes (e.g. ball velocity) with different movement patterns. In particular, they exhibited kinematic differences in relation to their role on the field (defenders vs. midfielders and forwards) [110]. The backswing was found to be not universal but, conversely, a foundation for varied technical profiles. Players achieved a compromise between (i) a long backswing duration that permits adaptations to task constraints and increased drive amplitude to provide great velocity to the ball, but which also increases the risk of opponents' interceptions; and (ii), a short backswing duration that is a real advantage in contexts of temporal pressure as movement preparation time is shortened, but which can be detrimental in terms of adaptation and ball velocity [110]. During competitive performance, defenders, midfielders and forwards in hockey do not typically encounter the same task constraints (such as proximity to goal, temporal pressure, player density levels, team-mates and opponent positioning, ball location) and, consequently, they do not have the same performance role. For this reason, in the study of Bretigny et al. [110], defenders tended to exhibit longer backswings than midfielders and forwards.

As stated in section 3, when the gap existing between the intrinsic dynamics of an individual and the task demands are low and/or weak, multi-stability of movement patterns can emerge, providing a platform for exploitation of neurobiological system degeneracy. For instance, Seifert et al. [95] suggested that the higher inter-individual coordination variability observed in novice swimmers than in experts related to an exploratory phase with regard to environmental constraints (relationship between gravity and buoyancy = Archimedes principle; Newton's third law, i.e. producing an action to get a reaction in the opposite direction). In relation to their lower experience levels with the aquatic environment, novices may also individually interpret the instructional constraint (i.e. propel the body forward) imposed by a teacher or coach that leads them to use different motor solutions to satisfy task constraints [95]. Notably, the priority of novice swimmers may be to not only advance in the water but also to balance (e.g. to stay in a ventral position), float (e.g. to stay at the water surface) and breathe (e.g. to avoid bringing hands to the chest in order to keep the head above water) and perceive in the aquatic environment (Newton's law and Archimedes principle) [81]. These needs may explain the great inter-individual coordination pattern variability in novice swimmers without a direct link to performance outcomes, predicated on neurobiological system degeneracy. More broadly, these examples all indicate that the intra- and inter-individual movement variability for fixed or temporary constraints can be considered to emerge as the result of functional adjustments, and not as the result of fluctuations due to chance that should be minimized.

5 Conclusions and Implications

Within a traditional cognitivist framework, expertise acquisition usually relates to the capacity of imitating, reproducing and automating a putative expert behaviour, and of correcting any deviation and error from this model. Although this approach has led to a popular theoretical framework to understand expertise and skill acquisition in sport during the last five decades, the ecological dynamics framework brings a fruitful basis for a richer interpretation of motor expertise and movement pattern variability within and between individuals. In this position paper we have highlighted how dynamical systems theory and ecological psychology, in combination, enable (i) a new understanding of expertise by considering performer-environment couplings through emergent and self-organizing behaviours in relation to interacting constraints; (ii) an explanation of how experts as complex, dynamical systems pick up affordances to regulate adaptive transitions between functional movement behaviours. We showed how movement pattern variability could play a functional role as individuals adapt their behaviours to ecological constraints of performance by exhibiting multi-stability and metastability; (iii) understanding that one main trait of expertise relates to adaptability, a subtle blend between stability and flexibility as expert performance can be stable and variable when needed; and (iv) a new emphasis on how novices and experts individually manage motor system degrees of freedom in coordination through redundancy or degeneracy as they structurally adapt system and subsystem organization in order to achieve functional goals.

The main implications for sport clinicians and practitioners are to identify and manipulate key constraints to perturb and create emergence of appropriate behaviours rather than to encourage the imitation of a single response in reference to a putative ideal expert model. Indeed, asking novices to imitate putative 'expert behaviours' is somewhat reactive and could lead to frustration and a prolonged skill acquisition process, as novices may encounter difficulties in matching required behaviours. Practical applications of these ideas emphasize the adaptation of the intrinsic dynamics of an individual learner by enhancing his/her relations with the performance environment. This aim can be achieved by implementing the process of task simplification in representative practice simulations, rather than task decomposition, as the latter may distort or decontextualize the integrated relations between subsystems. A task can be simplified by maintaining information-movement relations during practice without isolating an individual from the ecological constraints of the performance environment. It is possible to use artificial aids to amplify or add information in order to promote perception-action coupling (i.e. to increase the level of exposure of an individual to affordances [41]). For example, in swimming, it is possible to artificially increase the propulsive surfaces to teach the effective hand position and hand underwater path by equipping the swimmer with paddle or fins that simplifies the task without decomposing it. Seifert et al. [116] also showed that a frontal snorkel can be used to balance arm coordination in front crawl when it is asymmetric, instead of correcting the breathing pattern through verbal instruction or the demonstration of an expert swimmer.

Using a process of constraints manipulation in representative learning designs could lead to the emergence of individualized movement responses directly related to the intrinsic dynamics of a performer. Brunswik proposed the term 'representative design' as an alternative to 'systematic design' more than half a century ago [117, 118]. Brunswik [117] advocated the study of human behaviours at the level of performer-environment relations, an ideal focus for sport scientists interested in research and practice. In practice simulations, perceptual variables should be sampled from the typical performance environment to be representative of the information sources from which they have been adapted. [117]. To make a learning environment representative of a performance environment, sport practitioners can exploit the interacting constraints shaping the intrinsic dynamics of a complex movement system and ensure that cognitive, psycho-emotional, perceptual and motor subsystems function in an integrated manner [39].

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