

## **Constraints-induced Emergence of Functional Novelty in Complex Neurobiological Systems: A Basis for Creativity in Sport**

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**Abstract:** *In this paper we present a model of creativity captured as exploration and production of novel and functionally efficient behaviors, based on the statistical mechanics of disordered systems. In support of the modelling, we highlight examples of creative behaviors from our research in sports like boxing and rugby union. Our experimental results show how manipulation of practice task constraints changes the exploratory breadth of the hierarchically soft-assembled action landscape. Because of action metastability and differing task constraints, the specificity of each assembled movement configuration is unique. Empirically, a movement pattern's degree of novelty may be assessed by the value of the order parameter describing action. We show that creative and adaptive movement behavior may be induced by at least two types of interventions, based on relaxing task constraints which we term direct and indirect. Direct relaxing is typically a function of changing task constraints so that the number of affordances that can satisfy goal constraints increases. Indirect relaxing of constraints occurs when a habitual action is suppressed by, for example, stringent instructional constraints during sports training. That suppression simultaneously relaxes other correlated constraints that enable larger exploratory capacity and new affordances to emerge for the athlete or team.*

**Key Words:** sports creativity, motor creativity, ecological dynamics, affordances, action soft-assembly, replica symmetry breaking

### **INTRODUCTION**

Innovative and creative goal-directed behaviors in neurobiological systems, such as apes and birds, has been studied extensively (e.g., see Reader &

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Laland, 2001; Taylor, Elliffe, Hunt, & Gray, 2010) and involves the discovery of novel information and novel patterns of behavior by an organism. There has not been the same focus on creative behavior in sport, although much research in sport sciences and pedagogy has been aimed at improving athletic performance. Traditionally, performance optimization methods have been implemented to identify the set of movement parameters that might maximize outcomes for specific elite athletes (e.g., Bartlett, 2007). However, as in the case of Dick Fosbury, the elite high jumper, sometimes performance is not just improved, but actually pushed to a new (higher) level. Such advances occur, not by optimizing the model parameters of an existing well-established technique, but by invention of a new movement pattern. This creative advance can resolve some problems with a previous technique, shape performance outcomes and enrich movement culture, making specific sports more diverse and more aesthetically attractive. Emergence of novel performance solutions are a regular feature in sport and have been well documented in activities like track and field, exemplified by the O'Brien or rotational techniques in shot put or the Straddle and Fosbury Flop techniques which replaced more traditional and less successful Scissors and Eastern Cut-Off high jump techniques. In the last few decades alone in gymnastics 14 novel technical elements have appeared.

Idiosyncratic and efficient, i.e. functional, intra-personal and inter-personal actions form the basis of the extant, continuously-enriching movement culture in human activities such as sports and physical activities. Yet despite this process, creativity in sport performance has seldom been the subject of systematic research. This state of affairs is exemplified by the absence in sport science of established theoretical rationales for studying and explaining creative behavior.

#### **Traditional Explanations of Creative Innovative Behaviors: Abstract Rule-based Representations**

In neurobiology more generally, some attempts have been made to provide theoretical explanations for innovative behaviors in organisms such as primates and corvids with some claims that animals and birds are capable of using analogical and inferential reasoning during goal-directed activity (e.g., Chappell, 2006; Inoue & Matsuzawa, 2007; Seed, Tebbish, Emery, & Clayton, 2006; Taylor, Hunt, Holzhaider, & Gray, 2007). Observations of behavioral innovation in tasks such as feeding, has led to claims that some neurobiological systems, such as apes, corvids and parrots may exhibit 'complex cognition processes' consistent with the transfer of an abstract causal rule between performance contexts (Taylor et al., 2010). Explanations of innovative behaviour, based on internalised inferential mechanisms represented in neurobiological nervous systems, have recently been criticised (Davids & Araújo, 2010), leading to an ecological dynamics account of the emergence of creative behaviors.

In the study of human movement similar concerns surround the inability of the traditional 'motor program' metaphor for explaining movement novelty, especially with regards to the emergence of highly atypical novel

actions. Recently, Hristovski, Davids and Araújo (2009) empirically showed how the manipulation of task and personal constraints may enable emergence of innovative and functional tactical behaviors in athletes during sport performance. For example, under a specific mix of ecological constraints, performers in boxing created *collect* “or” *save* behavioral states. It was observed that changing the set of task constraints led to spontaneous, novel, alternating metastable functional *collect* “and” *save* behaviors. These observations of the emergence of human tactical innovative behaviors are important from the perspective of Boden’s (1996) definition of ‘transformational creativity’. They explain how under manipulation of constraints, a transformation within a neurobiological action system may be enabled without reference to abstract rule-governed behaviors. An ecological dynamics explanation eschews the need to conclude that neurobiological systems use an explicit abstract rule or operator like “and” “or” or “if-then” to govern creative behavior.

For example, in the generalized motor program theory (Schmidt & Wrisberg, 2004), pre-formed rule-based structures are the generalized motor programs and the production of movement consists of activating some variant of these structures. Such theoretical constructs may explain how variants of a general movement pattern may be generated, but are unable to explain the first time production of highly atypical actions. Of course, if the degree of generality of the program is not explicitly assessed and remains vague, even most atypical movements may be interpreted as a variant of some very generalized program. This is because any novel movement may be thought of as a product of a finite number of transformations of some other movement. Indeed, for any theory of motor learning, heavily based on the concept of explicit instruction or demonstration and imitation, the original emergence of ‘to-be learned’ target actions remains unknown, since it is not clear how these movement patterns emerged, if they had not been explicitly learned by their creators.

To counter such problems, in this paper we elucidate a model of neurobiological creativity and innovative behavior from the perspective of nonlinear dynamics (Hristovski, 2009; Hristovski & Davids, 2008), eschewing representational accounts. Using the context of sport performance, we illustrate how a model of creative behavior in nonlinear dynamics might shape a nonlinear pedagogy for developing movement innovation in sport and physical activity. In our modeling we propose why the study of online, soft-assembly and personal discovery of highly novel and efficient (i.e. creative) actions is a relevant direction of future investigation in sport science. We show how the emergence of highly novel movement forms requires a self-organizing system which, under suitable boundary conditions, can create new behavioral structures.

Hristovski (e.g., 1989) previously formulated creative intuitive action insights, in terms of the principle of least action, as *redundancy-free information creation*. But only recently have some more systematic efforts emerged in sport science to detect aspects of creative behavior (i.e. action ‘unusualness’ and statistical rarity), facilitating tests and analyses of creativity in team sports (Memmert & Perl, 2006; Memmert & Roth, 2007). More than a half a century

ago Guilford (1956) postulated that creativity is best explained as an ability to produce numerous responses to a specific problem as a consequence of divergent thinking, contrary to the strategy of convergent thinking which defines intelligence.

Currently, it seems that there is a wide consensus among creativity researchers that novelty (i.e. originality) and functionality (i.e. usefulness, effectiveness, appropriateness, success, or adequacy) are the two key dimensions that co-characterize a creative product or behavior (Amabile, 1995; Ford, 1996; Kasof, 1995; Mumford & Simonton, 1997; Runco, 2004; Runco & Charles, 1992; Sternberg & Lubart, 1996). The degree of uniqueness or novelty, as well as the outcomes of a behavior, need to be considered to characterize the property of movement creativity. This conceptualization of creativity is, to a degree, counterbalanced by the process-oriented definition of creativity which classifies as creative any exploratory behavior without regard to whether it leads to a novel final outcome or not (e.g. Drazin, Glynn & Kazanjian, 1999).

Neurobiological systems are well known for possessing functional properties, such as pleiotropy (see Davids et al., 2007), for attaining a task goal in different ways, a property also characteristic of sport collectives in performance. Actually, both action systems and sport teams may be treated as formally equivalent since they both have to solve an ill-posed problem: How to coordinate the extant system degrees of freedom to attain a specific task goal. In this respect a key property of systems being able to attain a performance goal by involving structurally and functionally different system components has been termed *degeneracy* (Edelman & Gally, 2001). Interestingly, this term has also been used for indicating existence of multiple solutions or states in statistical mechanics (e.g. Balesku, 1975, p. 405).

#### **Multi-stability as a Stimulus for Creativity in Neurobiological Systems**

The multitude of solutions or states available in complex systems is a consequence of the wealth of potential nonlinear couplings available between system components (or between system agents in social neurobiological systems (e.g. Challet, Marsili, Zecchina, 2000)). Degeneracy and multi-stability are consequences of such nonlinearity and complexity. Multi-stability is a prerequisite for the important complex system's property of metastability, i.e. the capacity to possess many co-existent pattern forming propensities (Kello, Anderson, Holden, & Van Orden, 2008). This capacity in neurobiological systems, allows states (as performance solutions) to be soft-assembled, emerging under some constellation of boundary conditions as constraints. These system states are not preformed. These ideas form the basic principles that underpin the constraints-led perspective on skill acquisition in sport (Araújo, Davids, Bennett, Button, & Chapman, 2004; Chow et al., 2006; Davids, Araújo, Shuttleworth, & Button, 2003; Davids, Renshaw, & Glazier, 2005; Newell, 1986).

The distinctive configurations of constraints between learners, based on a platform of system degeneracy and pleiotropy, are manifested in how each individual attempts to satisfy specific task constraints during practice. Hence, it

is futile to try and identify a common, idealized motor pattern towards which all learners should aspire (e.g., learning a classical technique in a sport like tennis or cricket). This idea has tyrannized talent development programs in sport for some time (Phillips, Davids, Renshaw, & Portus, 2010). Different individual constraints suggest that it is dysfunctional to seek to establish universal optimal learning development pathways to which all learners should adhere. The non-proportionality of non-linear neurobiological systems clearly emphasizes the significance of creating individualised solutions to movement problems in the learning process. Individual creativity is a product of the interactions of three nonlinear properties: cause-effect non-proportionality, parametric (constraint) control and multi-stability in complex systems (Hristovski, Davids & Araújo, 2009). Within these interactions, nonlinear pedagogy frames the individuality of learning pathways and individual creation of performance solutions for a given movement task.

#### **NONLINEAR DYNAMICS, SOCIO-CULTURAL ORDER PARAMETERS AND CREATIVITY IN SPORT**

Boden (1996) classified creativity with respect to a “novelty judgement” criterion in two distinct classes: P (Psychological) creativity and H, or historical, creativity. In her view, P creativity is manifested each time a performer discovers a unique solution to a performance problem without regard to whether such solutions already exist in the socio-cultural environment of the performer. H creativity or H novelty is judged with respect to the extant socio-cultural background. In the sports performance context, for example, P creative behavior occurs when a learner, performing under suitably designed learning task constraints, discovers a functional behavior that was not a part of an extant repertoire, regardless of the fact that such an action may already have been performed by other individuals. This definition fits neatly with what has been called a “mini-c” type of creativity (Beghetto & Kaufman, 2007). A H-creative act is much more unique and is exemplified by the discovery of the Fosbury-Flop technique in track and field or the Pegan vault in gymnastics. These are movement forms that did not exist in a specific movement culture prior to their creation by an individual. It is important to note the subtle relations between these two forms of creativity. Recently, it was argued that although creativity is not identical to learning, skilled performance or expertise, neither are these processes a necessary or sufficient condition for many kinds of creative behavior (Simonton, 1999), stimulating mini-c creativity during learning may enhance more eminent, so called, Big-C creative acts later in life (Beghetto & Kaufman, 2007).

#### **Intrinsic Dynamics and Creativity**

These arguments suggest that the frame of reference with respect to which type of novelty is defined is an important element of creativity research. In nonlinear dynamics, the concept of *intrinsic dynamics* introduced by Kelso (1995) is particularly suitable to account for the personal frame of reference with

respect to which P-creativity may be defined. The intrinsic dynamics of each performer refers to the inherent, stabilized dispositional patterns of behavior which emerge under some set of interacting constraints. These processes were exemplified by the emergence of an in-phase inter-limb coordination pattern emerging from an anti-phase movement pattern influenced by an environmentally-imposed frequency stimulus (Kelso, 1984). These patterns appear to be an extant stable property of the performer-environment system. It is important to emphasize that although these patterns were emergent, apparently 'created' by frequency scaling acting as a source of behavioral information on the movement system, the transition from anti-phase to in-phase mode cannot be regarded as a particularly creative act. Instead these movement patterns represent *adaptations* of the individual to changing task (informational) constraints. This is important to understand since obvious movement system bi-stability yields **too much predictable behavior to account for creativity** (see for similar arguments Simonton, 2004).

Therefore, it seems that pattern emergence is a necessary, but not sufficient, condition for creativity. At the moment when a previously stable system state loses stability, in bi-stable systems there is only one pre-determined state that will be realized. However, a system with three stable states, one of which is the current state, may show a minimum degree of indeterminacy at the point of state transition. In this sense multi-stability is one of the necessary conditions for the emergent behavioral pattern to be unpredictable, and, thus, not pre-determined. Generally speaking, the **emergent (i.e. not imposed from an external source or instructed) and indeterminate nature of action patterns, during adaptation, may, therefore, be defined as a *minimal definition* for creativity** (see also Simonton, 2004). In this regard, system nonlinearity is a key component of creativity in neurobiological systems since it provides a platform for bi/multi-stability of solutions. **Multiple possible (i.e. degenerate) solutions are always needed for innovative behaviors** of a neurobiological system under changing ecological performance constraints in sports. Moreover, meta-stability, i.e. a property of a multi-stable system constrained to dwell between stability and instability, is a viable candidate mechanism to facilitate novel, unpredictable and functional behaviors in neurobiology (Hristovski et al., 2009).

The system's intrinsic dynamics represent the background on which P-creativity may be defined through the emergence of a behavioral pattern which is not part of a performer's biological or epigenetically-acquired, extant intrinsic dynamics. Thus, any novel movement that has not been performed previously by an individual can be considered a P-creative act. Obviously, here, the frame of reference for novelty is the previously acquired movement repertoire of the performer. These acquired patterns of movement behavior, within a nonlinear dynamics framework, can be considered as attractors of some order parameter under well-defined boundary conditions (i.e. constraints).

For H-creativity to exist, a novel movement product has to be original, not only to an individual, but also to the whole socio-cultural performance context before its emergence. When defining different types of creativity one

needs to recognise the social embeddedness of individual performers since individuals are always situated in and acculturated by their socio-cultural environment. This acculturation process in sport is traditionally driven by an explicit and socially-imposed convergence to a common optimal performance model (e.g. a putative 'champion' model or a classical technique). For example, in sport, it has been shown empirically that the movement patterns of elite javelin throwers contained clear traces of their unique national styles, i.e. a specific type of shared national performance 'philosophy' (Schöllhorn & Bauer, 1998). Although not targeting this specific issue, that study exemplified how the acculturation process might explicitly constrain movement behaviors during long periods of learning in formalized, national performance development and training programs that athletes need to undergo.

A consequence of this distinction is that any H-creative act is a P-creative act but not vice versa. Thus, H-creativity is a subclass of P-creativity. This extant socio-cultural influence on the perceptual-motor landscape of the individual may be formally represented as a source of *environmentally-specific* (i.e. explicit) information to be learned (Zanone & Kelso, 1992). For example, it may be a target to-be-learned movement introduced by modeling and imitation. This specific information may be given as an order parameter value which explicitly contains the extant to-be-learned patterns in a particular sport discipline.

Understanding the socio-cultural potential landscape of a sport discipline is essential for defining the type of creativity shown by an individual performer. Thus, any measure of atypicality (Schilling, 2005), if focused on assessing H-novelty or H-originality, has to take into account not only an individual's personal background (i.e. an individual's intrinsic dynamics or extant repertoire), but also the influences of the extant socio-cultural landscape. Thus, considering the socio-cultural background in the study of creativity is not only important for defining the measures of creative behavior (i.e. degree of atypicality), but also because it is a key active constraint on an athlete's performance behavior.

The acculturation influence may play a conservative role with regard to the novelty tendencies of the individual, tending to 'align' the performer in a collective direction. On the other hand the idiosyncratic tendencies of some performers might compete with such environmental influences, rather than cooperate. This competitive process may be extreme in performers with great tendencies towards originality, like Dick Fosbury, for example. It may require strongly expressed personal psychological traits, i.e. constraints, like non-conformity, individuality and unconventionality (Simonton, 1999) to enable the attractor formed by idiosyncratic intrinsic dynamics to overcome the 'aligning' influence of socio-culturally imposed influences. Hence, considering socio-cultural influences as a key environmental constraint in an interpretation of creativity in sport from a nonlinear dynamics perspective may prove an especially useful direction from theoretical and practical standpoints.

Based on these arguments, in the following section we outline a model of creativity in sports and physical activity which might underpin theoretical and practical developments, from a nonlinear dynamics viewpoint.



### CONSTRAINTS-INDUCED SOFT-ASSEMBLED ACTION HIERARCHY

The empirically-confirmed, hierarchical structure of human movement variability (e.g., see Chow, Davids, Button & Rein, 2008; Schöllhorn & Bauer, 1998) provides an explanation of this behavioral characteristic within the framework of statistical mechanics of disordered systems, particularly the replica symmetry-breaking framework first developed by Parisi (e.g., Parisi, 1979). The hierarchical structure of movement variability strongly indicates a rugged landscape with many metastable minima (Hristovski & Davids, 2008). In Fig. 2 one such landscape is depicted for fixed task constraints.

This approach has proved successful for the formal capture of complex behaviors of systems with many metastable states on widely-separated levels of organization. These studies have examined spin and fragile glasses (Parisi, 2006), soft glassy materials (Sollich, Lequeux, Hebraud, & Cates, 1997), self-organization in protein and RNA folding (Cao & Chen, 2005; Taverna, & Goldstein, 2002; Wolynes, 2005), DNA conformation and regulation (Völker, Klump, & Breslauer, 2007; 2008), RNA and cytoskeletal remodeling and cell movements (Fabry et al., 2003; Sunyer, Ritort, Farré, & Navajas, 2009), as well as associative memories in artificial neural networks (Dotsenko, 1994) and heterogeneous interacting agents (Challet et al., 2000).

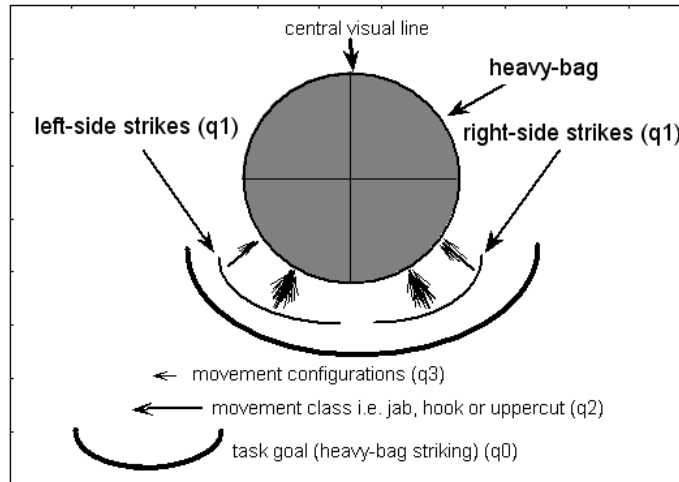
These ideas were empirically supported in our earlier work examining hitting actions of boxers (Hristovski et al., 2006) where we showed how the emergence of fist-target directions underwent bifurcations as a function of changes in the scaled distance ( $D$ ) to target. This observation implied that the fist-target angle configurations were a viable candidate order parameter constraining single movements prescribing the relation (i.e. coordination) between a performer's fist and a ('punchable') environmental object acting as a target (see also Hristovski, 2010). In martial arts, as more generally in performance of fundamental goal-directed activities, single limb movements are typically coordinated simultaneously or sequentially with movements of other body parts.

#### Overlap Order Parameters and the Soft-assembled Hierarchy

The potential order parameter relating single fist-target directions we proposed as an overlap of fist-target configurations. This parameter may be defined as the cosine of the angle ( $\alpha$ ) between unit vectors representing directions of fist-target impact  $q_{ij} = \cos(\alpha)$  among any two fist-target directions, ( $i$ ) and ( $j$ ), within the same class of movements as well as configurations belonging to different classes of movements (see Fig. 1). Each fist-target configuration has a self-overlap  $q_{ii} = 1$ . The formulation of the order parameter as a cosine between two vectors may be interpreted as a correlation between two random vectors (see for example Domany, Hed, Palassini, Young, 2001). This order parameter may be more general and may be used in a multidimensional case or simply as a relation between two angles of fist-target impact. Overlaps within the framework of statistical mechanics of disordered



systems are treated as *order parameters* since they represent the degree to which the system's configurations are correlated, i.e. ordered. Thus, not fist-target angle configurations *per se*, but their co-relatedness is treated as a degree of order in the system.



**Fig. 1.** Movement configurations of performer 1 defined as fist - target impact angles for scaled distance  $D = 0.86$ . Single movement configurations with self-overlap  $q_i = 1$  are being co-related by  $q_3$  order parameters and the latter form movement classes i.e. states ( $q_2$ ). Further  $q_3$  states form general action states of the left and right-body side ( $q_1$ ). The task goal, i.e. to hand strike the heavy-bag positioned in front, encompasses all actions ( $q_0$ ).

This potential order parameter functions to relate, i.e. coordinate, any two fist-target impact directions. It prescribes or imposes the relation between directions of punching actions. By correlating directions of simultaneous or subsequent actions, such an order parameter enables a coordinated spatially-defined goal-directed activity to persist over some prolonged time period. Note that even in the case when the overlap is identically equal to zero it means that the order parameter has prescribed fist-target directions which are orthogonal to each other. At the same moment it informs on angular similarity-differences of fist-target directions.

The horizontal covariation between fist-target directions forms the  $q_3$  level. Covariation between  $q_3$  levels assembles classes of action ( $q_2$  level). Their covariation assembles left-right action sequence possibilities ( $q_1$  level) and these, in turn, assemble general directedness of a performer's action i.e. general goal-directed performer-target interactions, i.e. the  $q_0$  level (see Fig. 1). This is the process by which the horizontal covariation assembles the higher order dynamic structures. It is important to note that single fist-target action configurations are just discrete samples of an otherwise temporally continuous

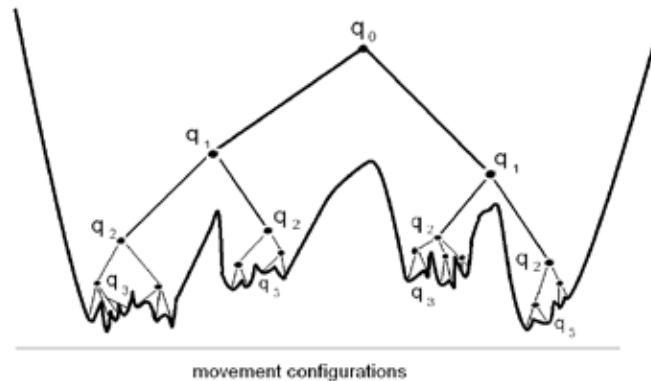
global dynamical state within the brain-body-environment system. Hence, the horizontal co-variation between discrete action configurations reflects a continuous dynamical state with nested correlated processes. Vertically taken, hierarchical order parameters, assembled by horizontal covariation of lower placed action components, could be defined as constraints-induced soft-assembled dynamical structures responsible for the variation and co-variation of lower placed components. As the attractors inside the global one, i.e.  $q_0$ , are, in fact, its descendents (see Fig., 2), they become necessarily correlated. This observation implies that higher level order parameters enslave lower level parameters and treat them as further system degrees of freedom. On the other hand the correlated (coherent) interactions among such degrees of freedom form and stabilize the higher order collective variables in the system. In this sense the hierarchy possesses circular, rather than unidirectional, top-down causation within the nested levels.

In our previous research (Hristovski et al., 2006), we observed that the perceived efficiency of movement solutions constrained the probability of occurrence of those and concurrent action solutions. This finding implies that individual actions provide a bottom-up feedback loop that enhances action efficiency and suppresses less efficient moves (see Fig. 3B). The concurrence between different actions on the other hand stabilizes the probabilities of occurrence by enabling a negative, suppressing, reciprocal feedback loop. In this way the bottom-up perceptual efficiency information of individual actions serves to enhance the growth and stabilization of the affordance-regulated, global dynamical goal-directed action organization at the  $q_0$  level. This level, in turn, in a top-down fashion causally constrains, i.e. correlates or enslaves, the lower placed order parameters. In short, the bottom-up action efficiency feedback mode of action regulation constrains the global intentional content of the action system  $q_0$ . In turn the intentional content, flowing downwards to  $q_3$  level, stabilizes the fist-target coordination processes over time. In this way, action affordances determine the intentional content and intentionality effects are distributed across all action levels. Note, however, that these levels are not reducible to specific brain-body functional modules (for a general discussion on such circular causality see Juarrero, 1999; Van Orden & Holden, 2002).

### **Replica Symmetry, Symmetry Breaking and Task-induced Phase Transitions**

In neurobiology, systems exhibit a replica symmetry when a vast set of movement configurations, i.e. replicas, are not correlated, i.e. possess a zero mean overlap (Hristovski & Davids, 2008). Replica symmetry signifies that all the possible configurations of a neurobiological system (e.g. action-target directions in hitting an object) are equally available at any moment. If loosely constrained, a perception-action system might produce movement configurations which differ extremely with respect to their parameters such as, direction, amplitude, velocity, relative timing and so on, and their overlap  $q$ , i.e. correlation would be typically zero. In other words, the existence of replica

symmetry signifies that a neurobiological system is ergodic, i.e. from any initial condition (initially chosen movement configuration) it can attain other imaginable movement system configurations in the long term. This characteristic would correspond to the emergence of totally random behaviors under absolutely relaxed task constraints. In short, a perception-action system which is not subjected to continuous constraints is ergodic and is replica symmetric. In such a situation the statistical average of the overlap between system states (i.e. correlations) would be zero.



**Fig. 2.** A schematic (i.e. one dimensional) presentation of the corrugated hierarchically-assembled potential landscape accounting in more detail for the actual one graphically illustrated in Fig. 4B. The performer-target scaled distance is  $D = 0.86$  and exploratory breadth  $Q = 0.265$ . Note the nested structure of the metastable action modes. The super-basin associated with the order parameter  $q_0$ , corresponding to the stable hand-striking intentional goal, constrains all lower order metastable basins of attraction sets,  $q_1$  which relates left or right sided movement combinations;  $q_2$  movement classes, which further contain basins of intra-class movement configurations  $q_3$  down to the self-overlap of each configuration. Note also that the high potential barriers on both sides confine the exploration within a limited movement configuration space. The task goal (target-striking) and boxing rules (only hand-strikes) constrain exploration, brake the ergodicity, produce phase transitions (forming a confining super-basin of attraction) and constrain the movement fist-target configurations to become more correlated.

Obviously during performance and training in sport, task constraints give rise to *replica symmetry breaking*, and the occurrence of phase transitions in the action system. Phase transitions determine the functionally relevant actions with respect to task constraints (goal, rules, etc). In fact, replica symmetry breaking is responsible for the actual self-assembly of the action hierarchy. Within the deterministic approach to nonlinear dynamics, a bifurcation or a phase transition is indicated by a change in the number and characteristic of the system extremes, the potential landscape. Within the

framework of the stochastic approach, a bifurcation or system transition is characterized by a change in the number and character of the probability density extrema (Sugakov, 1998). In a study of boxing actions, Hristovski et al. (2006) have shown how continuous subtle changes in the scaled performer-target distance  $D$  brought about abrupt changes in the number and character of action mode probability densities. Within the soft-assembled action hierarchy approach, this observation implies that a neurobiological system under constraints is more or less in a permanent critical régime exploring only a small set of minima. Sufficiently small changes in the constraints acting on the system can alter the number and character of potential landscape extremes. This characteristic, which is generic for disordered systems, is a variant of self-organized criticality (Parisi, 2006).

Under the influence of task constraints, the system cannot arbitrarily explore extensive regions of the available action space. That is exactly what the replica symmetry breaking picture predicts. It is worth noting in Fig. 2 that there are high potential barriers on both sides of the super-basin of attraction. They confine all the functionally relevant actions inside the super-basin. A phase transition enables a formation of correlated perception-action attractors by narrowing the set of possible action configurations. In other words, this kind of symmetry breaking leads to a formation of associations between possible configurations of the system and larger overlaps, i.e. values of the order parameter. Hence, the symmetry breaking of the movement replicas leads to a formation of a hierarchical structure of order parameters defined as overlaps (i.e. correlations) between movement configurations (Parisi, 1979). As the attractors inside the global one, i.e.  $q_0$ , are in fact its descendents (see Fig., 2), they tend to become correlated out of necessity. This observation means that higher level order parameters enslave lower level parameters and treat them as further degrees of freedom. On the other hand the correlated (coherent) interactions among such degrees of freedom form and stabilize the higher order collective variables. In this sense the hierarchy possesses a circular, rather than linear, unidirectional, top-down causation within the nested levels.

### **Creativity in a Generative System within Constraints-led Perspective**

Within the framework of a nonlinear pedagogical approach to sport and action creativity (Hristovski & Davids, 2008; Hristovski, 2009), the generative perception-action system is defined as a union of two sets: the set of task, personal and environmental constraints (i.e. boundary conditions of the dynamics) and the set of a neurobiological system's action degrees of freedom. The set of interacting constraints act on the set of action system degrees of freedom forming action configurations (movement patterns) of different complexity. For a given set of task, personal and environmental constraints there is always a well defined set of metastable potential minima i.e. a set of possible actions. For example, in Fig. 1 it can be observed that, under the constraints of extant competitive boxing rules (i.e. use of hand-strikes only), at a scaled boxer-

target distance  $D = 0.86$  from a static heavy bag, the set of possible actions is 4, that is, right and left jabs and hooks. These task constraints form the boundary constraint on opportunities for creativity in this activity. Exploration by the generative action system may be defined as a hopping dynamics on a constraints-dependent rugged hierarchical potential landscape or alternatively as a random walk on a tree (see Figs. 2 and 3). In other words, exploratory activity may be defined as a subsequent realization of a large number of movement configurations which reveals the hierarchical action landscape under specific constraints of each performer.

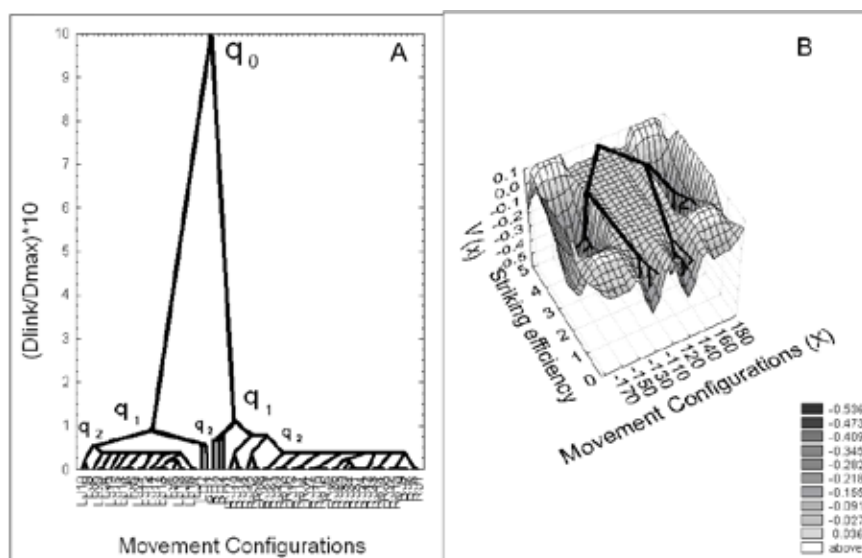
Therefore, exploratory activity is strongly dependent on the set of constraints imposed on the set of action system degrees of freedom. This observation implies that, during training programs, no explicitly prescriptive list of possible actions needs to be provided beforehand to the performer so that s/he might realize them. The system's capacity for exploration satisfies the *minimal criterion* of creativity suggesting that a performance solution should not be explicitly imposed on the performer by an external agent, for example, in a form of a to-be-learned *target movement (or technique)* by a coach. In other words, the minimal criterion of creativity captures all the *individual* movement solutions for an immediate or more stable task goal. Any subtle and efficient variation of some general class of movements may be considered to exemplify a creative performance solution. However, this approach gives an opportunity to distinguish the degrees of novelty generated by a perception-action system by using the context-dependent hierarchical structure of order parameters.

#### **Stability and Creative Flexibility: Divergent Approaches for Achieving Stable Task Goal**

Due to the inability of neurobiological systems to reproduce a movement in an identical way in every performance trial, it may be observed that, even a repetition of a movement is actually an exploration of some small set of movement configurations (see Fig. 2). Due to small differences in initial conditions (i.e. specific task constraints) of the action, each repetition is actually slightly different from others. This neurobiological characteristic was noted by Nicolai Bernstein (1967), the eminent movement scientist, who conceived of practice as a form of "repetition without repetition." In Figs. 2 and 3 it can be seen that the overlaps between trials are high so that they form classes of movements (i.e. states) at the second level. Hence, the question of *stability* and *flexibility* of action patterns is predicated on the level at which stability or flexibility is defined.

Stability at the level of task goal  $q_0$ , causally constraining and stabilizing the set of all relevant hand-striking combinations, shows flexibility in attaining the goal through using left and right arms striking combinations  $q_1$ , and diverse movement classes (jabs, hooks, etc) i.e level  $q_2$ . Stability at the level of movement classes,  $q_2$ , shows flexibility at the level of repetitive organization of single movement configurations  $q_n$ . Thus, a stable goal may contain creative flexibility in solutions at many levels. The secondary structure of metastable

potential minima, i.e. any level  $q_i$  inside one super-basin, represents the metastable action configurations of one class of actions which becomes a super-basin itself at the second level  $q_{i-1}$  (see Figs. 2 and 3). For example, the self-overlap of configurations is  $\langle q_i \rangle = 1$ ; the average overlap at the level of movement classes is:  $\langle q_i \rangle = 0.97$ , and between the same sided movement classes the overlap is  $\langle q_{ij} \rangle = 0.93$ . Between, all 4 actions the average overlap is  $\langle q_{ij} \rangle = 0.45$ .



**Fig. 3.** A. Soft-assembled action hierarchy of a performer under conditions of  $D = 0.86$  and  $Q = .265$ . Order parameters  $q_0$ ,  $q_1$ ,  $q_2$  and  $q_3$  signify levels of action soft-assembly. The distance between configurations is  $d_i = 1 - q_i$ . The dendrogram was computed by the average linkage algorithm. B. The same order parameter hierarchy projected on a rugged metastable attractor landscape of fist-target configurations. The depth of attractors is proportional to the absolute probabilities of the movement configurations defined as fist-target impact angles. Note how the attractor depth depends on the value of perceived striking efficiency.

In other words, the action levels can be seen as soft-assembled dynamical products of a neurobiological system with the purpose of continuously striking a target under specific constraints (i.e. boundary conditions). As Van Orden and Holden (2002) argued, **task goals**, i.e. **intentions**, are extraordinary constraints on the soft-assembled dynamics of neurobiological system. Note that the task goal (i.e.  $q_0$  level) is also a part of this self-assembled hierarchy. It may be imposed (as in the experiment or under explicit instructions of the coach), but it also may emerge for the individual athlete under some non-specific boundary conditions (Hristovski et al., 2009).

### Creative Search as Exploratory Breadth of the Perception-action System

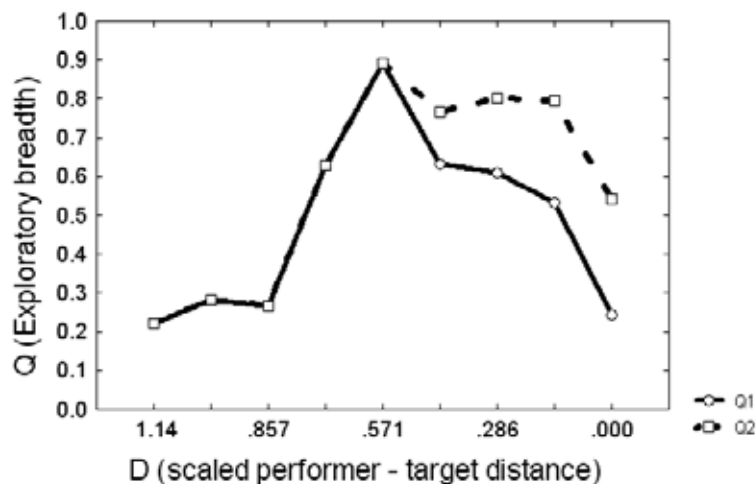
Sequential production of actions may be defined as a sampling of the configurations of some extant global dynamic state of the neuromusculoskeletal system of the performer. A natural property of exploratory dynamics in hierarchical landscapes is that it is slow and out of equilibrium. For example, observing the time scales of dynamics in such a hierarchy, one can define several time scales in only one trial of 60 punches. While unit action is of the order of 60-80 ms, the mean passage time of one arm combinations may take hundreds of milliseconds and the full set of double hand combinations may span even on seconds scale. The equilibration, i.e. exploration time, may, therefore, be extremely large (Bouchaud, Cugliandolo, Kurchan, & Mezard, 1998). This observation means that the exploration and the simultaneous coupling propensities formation live on a vast number of time scales and never cease. We define exploratory breadth  $Q$  as being equal to the average escape probability over all possible state attractors (see Saxton, 1996),  $Q = \langle W \rangle$ . Escape probabilities for each movement mode are defined as  $W = 1 - W_e$ , where  $W_e$  is the conditional probability of staying inside the same attractor (Hristovski et al., 2009). In other words,  $W_e$  measures the trapping strength of the attractor, i.e. the probability of being able to achieve the same performance outcomes sequentially. The larger the average escape probability  $\langle W_e \rangle$ , the larger the exploratory breadth  $Q$  of the system and vice versa.

It is clear that, for very low values  $Q \rightarrow 0$ , the escape probabilities, are negligible and the movement system is trapped inside one attractor and explores its detailed landscape. In this process it generates sequences of repetitions, i.e. variations of the same movement corresponding to a detailed walk inside any of the  $q_2$  basins of attraction. Which of the four  $q_2$  attractor basins in Fig. 2 will be selected by the system during practice depends on task constraints or perhaps explicit task instructions (for example, “use only left jabs” or ‘side foot passes’ in football). In this case, for some defined time interval, the fine and detailed structure of a single  $q_2$  basin is explored and deeper valleys within are reached (see Fig. 2), since all repetitions during that time interval are of the same class. For higher  $Q$  values, sequential repetitions (a walk inside a  $q_2$  basin of attraction) are less probable and an inter-mode switching regime becomes more probable (hopping among  $q_2$  basins, and assembling dynamics on  $q_1$  and  $q_0$  level). For  $Q \rightarrow 1$  sequential repetitions become extinct and the system, with overwhelming probability, explores switching, i.e. combinatorial possibilities between different movement modes. In this case the fine and detailed  $q_2$  to  $q_n$  structure is smeared out and not relevant for the exploratory dynamics within the given exploratory time interval.

The dependence of  $Q$ , at a scaled distance  $D$ , is depicted in Fig. 4. The  $Q(D)$  dependence is important because it shows that exploratory activity (intra-modal repetitive or inter-modal combinatorial), is highly dependent on key informational task constraints, such as scaled distance  $D$  to target and more generally on task variability. By manipulating task constraints one can



manipulate the exploratory breadth  $Q$  of the perceptual-movement system activities. Task constraints change the elementary hierarchical scale on which exploratory dynamics unfold at the level of order parameters  $q_n, \dots, q_1, q_0, q_1, q_2, \dots, q_n$  (see Fig. 2).



**Fig. 4.** Dependence of exploratory breadth  $Q$  of a performer's action system, under the task constraint  $D$ . The data curve matches the entropy curve in the study by Hristovski et al. (2006). The bold line shows the  $Q$  dependence for a static target and the dashed line for a stochastically-moved target in a direction perpendicular to the performer's central line of vision at the last four distances.

In the soft-assembled hierarchy approach to situated action creativity, the role of enhanced exploratory breadth consists of forming an ever-growing set of *task dependent* propensities of couplings among various perceptual and movement degrees of freedom. For example, the enhancement of extant or formation of new connections in the brain (i.e. neural plasticity) create propensities of coupling between large neural groups. These connections act as personal structural constraints. However, neural groups become dynamically coupled and specific activities emerge only under a certain constellation of perceptual informational constraints, that is, they are soft-assembled. The value of escape probabilities also enables establishment of the fundamental level at which exploratory activity unfolds. Note that exploratory activity can be narrowed by making task constraints maximally stringent. For example, by defining the task by only one action mode, narrowing the target marker on the heavy-bag in boxing, and providing a very narrow set of initial conditions exploration of arm actions in boxing, may lead to a very narrow potential minimum with secondary rugged structure within. This type of task constraints manipulation would lead to a hopping dynamics within one of the  $q_2$  basins of

attraction. Enlarging this set of task dependent propensities enlarges exploration space for the learner. Therefore, the meaning of order parameters  $q$  depends strongly on  $Q$ . If  $Q$  is low, then the exploration (equilibration) inside one attractor will be more complete. In that case  $q_2$  level would become  $q_0$ . In other words, the goal-directed behavior  $q_0$  will consist of only one class of actions  $q_2$ . The relevance of other attractors  $q_0$  in Figs. 2 and 3 will vanish. Thus, the exploratory breadth shows what is actually explored (whether the propensities of adaptive situated coupling within one-limb action configurations as in low  $Q$  values, or couplings between two, three, or all afforded classes of actions, for higher  $Q$  values).

Hence, enhanced exploration enables the availability of a larger set of intra-mode and inter-mode variations to become correlated, and as an effect to enlarge the set of information-dependent propensities of mutual couplings. These propensities become actualized under the strong influence of task constraints. The larger the exploration, the larger the domain growth of perception-action and action-action propensities. This observation suggests that enhanced exploration makes it possible to couple (simultaneously or sequentially) more distant actions, that is, the system may explore not only the subtle landscape within one attractor basin, but can also explore and associate configurations of super-basins of attraction (higher order parameters).

#### A Measure of Atypicality and Creativity in a Performance Solution

From this conceptualization it seems that atypicality, i.e. uniqueness or novelty, of an action solution, with respect to previously established criteria, may be defined as an overlap  $q$  between the *criterion action configuration* or state ( $i$ ) and the current system state ( $j$ ) whose atypicality is being assessed. Hence, the atypicality or novelty of a performer's action solution for a task problem may be represented as the distance:

$$d = 1 \pm q_{ij} \text{ for } -1 \leq q_{ij} \leq 1; \quad (1)$$

where  $+$  indicates mirror symmetry actions,  $-$  indicates ipsilateral actions, and  $q_{ij}$  is the overlap between the action configurations of the performer and the configurations of the socio-cultural potential landscape for the same task constraints (e.g.  $D = 0.4$ ). This observation means that, if the configuration is identical or a mirror image of some other movement system configuration, the novelty vanishes, since no new structure is involved, and the configuration is a pure imitation of an existing configuration, i.e. there is a maximal transfer between the configurations. Note that as the overlaps corresponding to higher levels in the hierarchy possess necessarily lower values, their atypicality is necessarily higher. So atypicality at the level  $q_2$  (novel class of actions), is necessarily of a larger novelty degree than that at the level  $q_n$  (a unique configuration within a certain class of actions). Atypicality at the level  $q_1$  or  $q_0$  would involve changing the task constraints (boxing rules) and allowing, for

example, leg kicks or back hand strikes, which would create another sport discipline, like kick-boxing or karate.

Because in the product-oriented definition of creativity the functional efficiency of an action (with a reference to a sub-goal or a final goal) is necessary to convert atypicality into creativity, we use the multiplicative form:

$$C = dE, \quad (2)$$

where  $C$  is creativity and  $E$  is action efficiency, i.e. functionality, of the action with respect to some task goal, or sub-goal criterion.  $E$  may be defined in a binary fashion by 1 (efficient, functional or successful action) and 0 (inefficient, unsuccessful or dysfunctional action). It may also take some continuous form in between these extremes. Hence, even a highly atypical, novel action, if not functionally efficient, with respect to a sub-goal or a goal, would be considered as not creative and an action with a small degree of atypicality, i.e. uniqueness, if successful, would possess negligible but non-zero creativity. The highest level of creativity would produce actions which have high degree of atypicality and functional efficiency.

In the following sections of the paper, using the task vehicles of martial arts and rugby union, we show how relaxation of the constraints may lead to creation of novel movement modes defined with respect to the performer or the socio-cultural constraints in sport performance.

## **HOW CREATIVE BEHAVIORS EMERGE UNDER ECOLOGICAL CONSTRAINTS IN SPORT**

### **Emergence of an Innovative and Efficient Movement Form**

One of the most important abilities in martial arts as well as other sports is to perceive affordances occurring under severe time constraints and performing the afforded action against an opponent. Very often in real combat under such severe time constraints it is not wise to translate one's center of mass by applying footwork, with aim of applying some classical handstrike, because this process takes a large amount of time. What is needed, instead, is a quick strike according to the concrete short-termed situation. Some gifted martial artists being aware of the limitations of their own discipline adopt a non-orthodox way of blending that discipline with another one by relaxing the rules (i.e. task constraints) and exploring other action possibilities. Brazilian Capoeira is one such example of blending martial arts with dancing patterns. This is one of the reasons why the general approach in our experiments for discovering the dynamical perception-action landscape of sport performers involves probing system activity by letting it evolve autonomously under specific task constraints manipulations over a period of time. Typically, explicitly detailed instructional constraints are minimized in our experiments and participants are asked to use any action they find efficient to satisfy the task goal constraints. For example, a recent experiment showed how, by manipulation of informational task constraints, capacity for exploration and the creation of innovative and efficient,

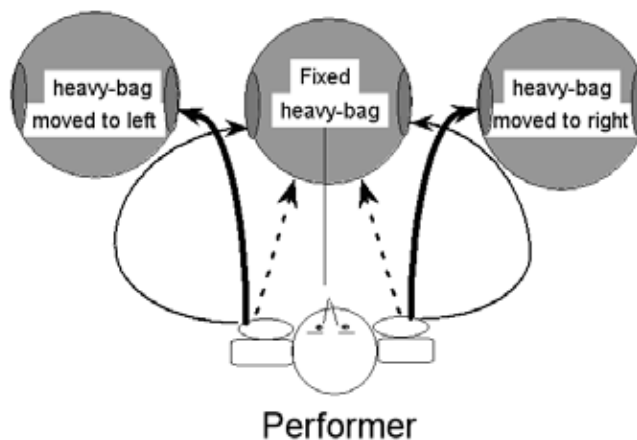
striking action modes may be facilitated (Hristovski, 2009). An innovative action mode was defined with respect to the previous repertoire (i.e. socio-cultural landscape) of a certain sport discipline. For example, jabs, hooks and uppercuts are classical boxing action modes. They may be considered as movement configuration values of some socio-cultural potential landscape as defined above. An innovative striking movement is simply a movement that is not a part of this socio-cultural landscape. In particular it was shown how stochastic variability in visual space may sustain a greater level of exploratory capacity, which, under more static constraints (as in Hristovski et al. 2006), vanishes.

In this experiment, consistent with the experimental paradigm described in detail in the work of Hristovski et al. (2006 a, b) participants were asked to perform 60 punches at a static heavy-bag from 10 different scaled distances. However, in the new task, for the final 4 scaled distances ( $D = 0.4$  to  $0.0$ ), the heavy-bag was stochastically moved by an assistant to the left and right hand side (perpendicular to the central visual line of the performer with a maximum elongation that crossed the shoulder width of the performer (see Fig. 5). The assistant was controlling the perpendicular movement of the heavy bag movement with respect to the performer actions by minimizing all its possible spatial responses, especially in the plane sagittal to the performer. The interaction between the performer and assistant working with the heavy bag may be a useful topic for future research.

In that study, the discovery by participants of an existing classical boxing repertoire, while changing the scaled distance  $D$  to the target, replicated findings of Hristovski et al. (2006). These data showed that jabs, hooks and uppercuts were afforded at scaled distances from the heavy bag. These actions belong to the socio-cultural order parameter of boxing action classes. However, within the scaled distance interval  $D = 0.4 - 0.0$ , where the heavy-bag was stochastically moved, 2 out of 4 performers created a novel outward-directed, arched striking movement with their right arms when the heavy-bag was displaced at widths greater than the widths of their right shoulders. This innovative striking movement is depicted in Fig. 5.

As can be seen from Fig. 5, the innovative striking action differs from classical boxing strikes (jabs and hooks as well as uppercuts) in its outward directed (divergent) impact with the target. This observation contrasted with classical boxing strikes which are inward directed (convergent) with respect to the central line connecting the performer and target. For example, for performer 1 at  $D = 0.3$ , whereas the average overlap between the classical action configurations, i.e. ipsilateral jabs and hooks, was  $\langle q \rangle = 0.42$ , the average overlap between the innovative strike and the jabs was  $\langle q \rangle = 0.14$ , and the hooks  $\langle q \rangle = -0.88$ . These observations signified an emergence of a qualitatively different, i.e. innovative, divergent fist-target angle action configuration, with respect to the central visual line (see Fig. 5). This innovative movement pattern is, of course, illegal within the boxing rules context. It is similar to the Uraken-Uchi (back fist) strike in karate and it shows how relaxing

task constraints may give rise to a creative cross-fertilization of actions, i.e. blending of actions among two or more sport disciplines or creating a new sport discipline.



**Fig. 5.** As the target, a heavy bag, was moved to the left and right, from the fixed position for scaled distances  $D < 0.6$ , a novel type of punch emerged given by the bold arched line directed outwards. The darker ellipses on the both sides of the heavy-bag were marked surfaces which performers were asked to hit for scaled distances  $D < 0.6$ . Classical boxing patterns like jabs and hooks are depicted by dashed and thin arched lines respectively. The straight line between the performer and the heavy bag depicts the central line of vision.

It might be puzzling at first to observe that individuals might explore methods for achieving a task goal which are not constrained by the rules of a specific sport as a major task constraint on actions. But why should the search for novel ways of achieving a task goal, such as hitting a target with the hand, not explore some methods which are illegal in sport? There are so many examples of this behavior in high level sport performance and it can be considered a form of creativity by highly skilled athletes. The exploration of the boundary between legal and illegal actions has become an art form in many dynamic sports and physical activities as individuals seek to gain a competitive advantage. The gait of competitive race walkers is a classic example, captured in the regular controversies over judges' attempts to establish whether competitors have maintained full knee 'lock out' at foot contact, as well as maintaining continuous contact of the feet with the ground during sprint walking. In rugby union the activities of the cleverest players at the break down of the ruck and maul phase of the game, when the ball is open for possession by both teams, deliberately borders on legal and illegal activities. Indeed some top class rugby

union players are well known all over the world for their 'creative' talents in this open area of the sport. In association football, skilled defenders have learned how to go through an attacking player to get the ball (fouling an opponent first but also making contact with the ball to make a tackle appear legal). In contrast, attackers have learned how to entangle their legs with the defender's movements at the last second to simulate a foul in the penalty box, leading to a penalty. In boxing another case of novel exploration is the 'low' punch. When can this illegal action be definitely classified as low and not? Clearly, creative exploratory behavior is not restricted to legal actions in high level sport performance. Through exploratory practice performers can create novel actions which can 'ride' the boundary between legality and illegality to gain a competitive advantage over opponents.

In addition to understanding these socio-cultural performance constraints of competitive sport, it is also important to emphasize that the production of a novel and efficient, but illegal under boxing task constraints, hand strike was discovered as a consequence of two other factors. First, the action dynamics were metastable at the  $q_2$  level due to the higher values of  $Q$  (see Fig. 3). Higher values of  $Q$  were formed by a stochastic variability of the target which, at times, provided a *functional relaxing* of the task constraints for this highly innovative strike to emerge. This relaxing of functional constraints increased the probability of the movement system components being coupled in a novel way. As a consequence, an *action insight* emerged in the form of perception of an opportunity for action under short – living, but functionally relaxed, constraints. In this sense the creative insight and act may be seen as a perception of a novel affordance, i.e. as a discovery of an action opportunity.

However, it is also important to mention that two other performers in that study discovered this type of striking action only when they were explicitly constrained by instructions not to use the left-hook to strike the left side of the heavy-bag (and vice versa for the right side of the heavy-bag). In these two participants there was a kind of perseverance behavior, in adhering to established (rule-constrained) patterns of activity, such as the right-hand-right target side hooks and vice versa. This movement transition was enabled by adding the question: 'how *else* would you strike the marked surface on the target'? This question helped to destabilize adherence to the established classical punching patterns and guided the learning system to exploit its capacity for system degeneracy.

This example showed how performers considered the possibility of striking the left-side of the heavy bag with the right fist (with its dorsal or frontal surface) when the perpendicular elongation of the heavy bag afforded this kind of strike. They enlarged the *set of possible striking hand surfaces* (i.e. relaxed task constraints after making the other task constraint more severe, by providing explicit instructions to avoid a habitual performance solution). Although task variability and the scaled distance  $D$  was the same as for the other two performers, the exploratory activity for these individuals was lower. Task variability was not a sufficient condition for breadth of exploratory activity and

the production of a novel performance solution. Other immediate or longer-term dispositional *personal constraints* were obviously quite important as well. Thus, for these two performers a combination of relaxed task constraints (variability of the heavy-bag position), and the stringent task constraints (explicitly inhibiting the habitual action), brought about a novel action insight (e.g. spontaneous enlarging of the set of possible striking hand surfaces). Hence, not just metastability alone, but rather metastability under *adequately re-structured task constraints* led to a novel, efficient and creative insight. This idea fits neatly with the results of Hristovski (1989) where the intuitive, i.e. non-discursive, creative action insight was formulated as an information creation, i.e. negentropy increase, without redundant content.

Action creativity under the context of severe (spatio-temporal) task constraints may be envisioned in this way: as an ability to quickly suppress an adequate subset of task constraints which would bring forth a new afforded action when habitual or ongoing actions are prevented by an opponent. In this way, creativity of athletes stems from the ability to adequately *self-re-organize* the task constraints, especially with respect to sub-goals, without externally explicit instructions to seek another specific performance solution. It appears that how the athlete copes with the self-restructuring of task constraints defines his or her creativity level. The self-restructuring of task (including environmental) constraints creates new contexts in which novel opportunities for action emerge. In this way, the continuous reinforcement of self-experimentation with task constraints may be a viable way of stimulating creativity in athletes.

#### Spontaneous Creation of Idiosyncratic Sequential Action Motifs

As demonstrated in previous work by Chow et al. (2009) and Hristovski et al. (2009), striking activity in performers produces sequences with different temporal coupling strength, i.e. different time lags of constraint of previous on future punches. The emergence of a novel technical element enriches and diversifies not only the set of efficient actions, but also the combinatory creativity of individuals. The emergent sequential action motifs in a heavy-bag hand-striking task may be construed as a recurrent hopping dynamics on the hierarchical landscape as discussed previously. From the examples below it becomes obvious that each participant preferred specific performance solution pathways over others, which pointed to the personal idiosyncrasy of the action landscape. Table 1 elucidates the notated hand-striking sequences of two performers at the same scaled distance  $D = 0.6$  from the target (i.e. under the same task constraints).

The data show that the longest recurrent sequences in the two performers (bold letters) are different. Under equivalent hand-striking task constraints ( $D = 0.6$ ), the observed personal action idiosyncrasies probably stemmed from the unique personal constraints of performers. These probably included different action effectivities and different immediate or longer term action coupling strengths in their neuromusculoskeletal systems. As identified in



the previous section, here we also observed the effect of personal constraints, but this time in relation to the creation of sequential motifs. Interrelated sequences of actions where the desired goal was not directly related with the first action have also been observed in animals other than humans (Taylor et al., 2010). Research has shown that New Caledonian Crows could link several actions with novel sequences to solve a task problem (obtaining food) on the first trial. However, contrary to Taylor et al.'s (2010) inferential explanation, these creative behaviors can be explained with the notion of affordances in multi-scale dynamics (see Davids & Araújo, 2010) in line with our previous arguments, instead of the transfer of an abstract causal rule (Taylor et al., 2010). From previous example it becomes clear that the emergent intrinsic dynamics are strongly constrained by personal boundary conditions. This example may provide an insight into how, in sports and physical activities such as gymnastics, artistic gymnastics and dance, the creation of sequential action motifs may be emergent, idiosyncratic and probably significantly constrained by immediate or longer term personal traits.

**Table 1.** Hand-striking Sequences.

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*Performer 1: scaled-distance  $D = 0.6$ , sequence length = 60*

*j u h h j j u h h h j j j j h u h j j h j j u j j j j u h h j j j j h u h h u h h j j u h h h j j j j j u h h j j u j h h*

*Performer 2: scaled-distance  $D = 0.6$ , sequence length = 60*

*h j j h h h h u u h j j h h h h h j j h u u u h h h h h h j h u h h h j u j j h u h h h j h h h u u h h j*

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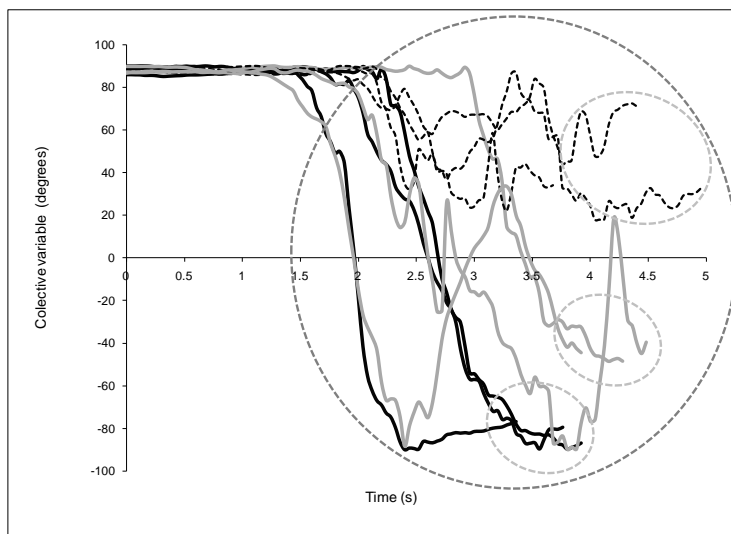
*Legend: j = right jab; ĵ = left jab; h = right hook; ĥ = left hook; u = right uppercut; ũ = left uppercut.*

## CONCEPTUAL MODELLING OF CREATIVITY IN THE TEAM SPORT OF RUGBY UNION

### Creativity in Behaviors of Attacker-defender Dyads

Modelled as dynamical social neurobiological systems, multi-agent systems like team sports display relevant features of complexity due to the potential for interactions that emerges between system agents (i.e. players) over time. Previous research in pattern forming dynamics in team sports identified power law distributions in behaviors of attacker-defender dyads (1 v 1 sub-phases; see Passos, Araujo, Davids, Milho & Gouveia, 2009a). These results supported the existence of regions of self-organized criticality (SOC) which highlight the existence of metastability. The SOC is a region where small changes in a critical system parameter (e.g., speed of a player) can lead to

qualitative changes in particular collective variables. Within SOC regions players' interactions are characterized by a punctuated equilibrium, identified through the existence of a subtle balance between periods of stability and volatility.



**Fig. 6.** Metastable regions in rugby union attacker-defender dyads. The SOC metastable region is depicted (black dashed circle). There are three attractors (small dashed grey circles), for different performance outcomes: a. Effective tackles (black dashed line); b. Unsuccessful tackles (grey line); c. Clean tries (black line).

As stated earlier, there is a large consensus among creativity researchers that a creative behavior is characterized by two dimensions: uniqueness (novelty) and functional efficiency. These two dimensions are largely independent. For example, a highly unique behavior, product or outcome, that is not functionally inefficient, may be evaluated as bizarre, but not as creative. Previous research aiming to describe and explain intrinsic dynamics of attacker-defender dyads identified existence of a collective variable and two nested control parameters (i.e., emergent task constraints) that were useful in modelling creativity in rugby union dyads (see Passos et al., 2009b). The collective variable (i.e., the angle formed by a vector from the defender to the attacker and an imaginary horizontal line parallel to the try line) was useful to assess the novelty or uniqueness of a movement configuration between attackers and defenders. The intrinsic dynamics of dyads led to system behaviors that evolved over time, mainly sustained by information created by interactions

amongst the attacker and defender, which is crucial to the emergence of unique and creative patterns of interactions amongst an attacker and defender. The flow of trajectories pulled the attacker-defender system to metastable SOC regions. Despite the variability of the player displacement trajectories the system will always be attracted to one of three possible stable states for the system formalized as attractors: (a) try situation; (b) tackle but the attacker passes the defender; or iii) an effective tackle occurred (Fig. 6).

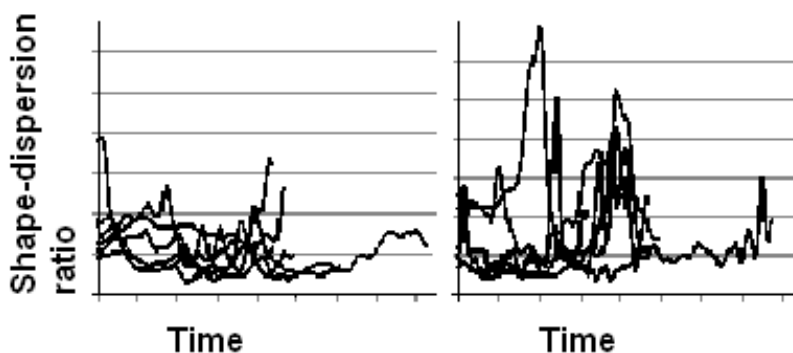
Thus, to model creativity in 1v1 attacker-defender dyads, there exists a 'super-basin' of attraction i.e., the SOC regions where metastability exists, and within this 'super-basin', there are secondary basins of attraction that characterized the three outcome attractors. What moves the dyad to one of the three basins of attraction is a nested relation between two candidate control parameters: players' interpersonal distance and relative velocity, with the former gaining influence over system outcome as interpersonal distance decreased (Passos et al., 2008). An attacker's creativity is expressed, for instance, by the ability to slow down the defender's running line, which afforded (created) a space - time window for the attacker to increase velocity and pass the defender. From this observation it follows that creativity in dyadic interactions is manifest as a *creation of affordances*, i.e., opportunities and context for *efficient* action (compared with the boxing example above). This behavior can be measured by analysing the fluctuations of the system collective variable, which was dependent on the values of control parameters such as relative velocity and distance. In this sense, a creative attacker or defender uses these constraints to produce unique and efficient outcomes. In summary, the dyadic dynamics used to characterize creativity can be assessed by analysing collective variable structure and control parameter values. For example, an abrupt transition in the values of the collective variable means that the attacker's co-adaptive, and thus, unique, action patterns were highly creative, i.e., functional in suddenly breaking the attacker-defender balance (see Fig. 1). In this sense, given that each pattern formed by the co-adaptive actions of the players was unique, it is the functional efficiency (in satisfying the task goal) of the performance solution that defined the creative behavior of the dyad sub-units. If a tackle by a defender in rugby union was effective, then the unique actions of the defender were creative.

### Creativity in Collective Behaviors

When the number of players involved in the sub-phases of team sports increased, varied patterns of behavior emerged due to co-adaptation amongst system agents. These ideas imply that, regardless of whether one is studying global patterns of interactions of several agents in a game sub-phase, or the local interpersonal dynamics of two key individuals (in dyads) constrained to function in a subsystem, creative behavior is an emergent property of each system's intrinsic dynamics. Metastability is a paramount feature of collective decisions and actions. Creativity is an emergent property that emerges due to players' context dependency within specific interpersonal distance values: to 'make things happen players must be where the things happen' and this is within SOC

metastable regions. Within these regions new constraints emerged (Juarrero, 1999) used the term ‘second order constraints’) that characterized players’ context-dependency, meaning that a new behavioral repertoire was available, and that is a dominant feature for creativity to emerge.

In recent research on collective decisions in rugby union in a 4 v 2 situation (four attackers against two defenders), Passos et al. (2009a) identified emergent intra-team grouping tendencies within a range of mean interpersonal distance values between 2 to 4 m in attacker sub-units. These grouping tendencies led to the emergence of self-organized structures that can be characterized by two main features: the regularity of the shape and the players’ dispersion. As in 1v1 dyadic situations, collective behaviors are emergent due to co-adaptation, which means that each player adjusted his behavior according to the behavior of nearest players (regardless whether they were teammates or opponents). Thus, in more complex performance situations like 4 v 2 we can identify basins of attraction to where the entire system is moving. These basins of attraction are characterized as metastable regions where individual player tendencies coexist with task constraints of performing co-adaptively with neighbouring players, whether opponents or teammates (Kelso, 2009).



**Fig. 7.** Unique movement patterns in attacker sub-units. A. Sub-units with players showing a less dispersed and more regular structure (grey lines). B. Sub-units with players showing a more dispersed and less regular structure (black lines). Y axis - a ratio between the shape regularity and player dispersion.

Before we account for inter-team (i.e., attacker-defender systems) pattern forming dynamics, we need to consider intra-team coordination patterns (i.e., amongst teammates). As stated before, empirical data sustained the hypothesis that players in attacker sub-units are attracted to a mean of interpersonal distance between 2 to 4 m, which could be viewed as an intra-team basin of attraction. The players were attracted to a given interpersonal distance value, but with the decreasing of attacker-defender distance, those mean values were disturbed. The attackers’ adaptive behaviors were required to deal with tasks

constraints forced by the defenders' provoked changes in the shape or dispersion of the attacker sub-unit. This adaptive behavior can be measured by a ratio that describes the shape regularity and dispersion of the attacker sub-unit structure (Passos et al., 2009b). When the values of this ratio are plotted over time, the data highlighted the uniqueness of each trial (Fig. 7). This observation reinforced the idea that players explore space and time co-adaptively at an ecological scale, leading to nonlinear creative behaviors. It is obvious that longer patterns possess short term structure.

Passos et al. (2009b) identified shape regularity and player dispersion as two features that described the adaptive behavior of four players within an attacker sub-unit; thus, creativity in collective sub-systems might be captured by exploratory space-time behaviors of players. The ratio between shape regularity and player dispersion might be a useful tool to measure different creative patterns. Nevertheless, we should keep in mind that the current data do not suggest that creativity is a predictor of success, an issue under study. Further research is needed to relate how the increased fluctuations in the ratio values are related to performance creativity that leads to successful outcomes.

In this way the process-oriented concept of creativity, that is based on, amongst other things, exploratory space-time behaviors, may not be a reliable predictor of performance success. In the product-oriented definition of creativity (which includes the effectiveness or the success of actions as a criterion), the success of the team would be an important predictor of its creativity. This is because always evolving, and thus unique, co-adaptive patterns of a winning team are likely to be more functional. Nevertheless, a paramount issue is related to the criteria used to define *functionality*. If these criteria are only based on the ultimate performance goals of the game (i.e., to score a try in rugby union or a goal in association football), performance situations that were full of creativity in attaining performance sub-goals, might be not defined as such, due to individual errors (e.g., a support player in rugby union fails to catch the ball). To define creativity, based on the ultimate performance goal of winning is a highly reductionist criterion. In this line of argument, creativity should be defined according to achievement of identified performance task sub-goals. For instance, every time that a team (or an attacking sub-unit) performs a collective movement that creates a space-time window in the opposition's defensive structure, this act could be classified as unique and creative (as displayed in Fig. 7 some situations might be classified as creative collective movements when they allow a sub-unit of four players to pass a defensive line). In both dyadic and collective systems, highly unique (atypical) and functionally efficient action patterns are likely to possess a larger degree of creativity, due to a higher level of atypicality.

## CONCLUSIONS

In this paper we have highlighted criticisms of representational, abstract-rule based accounts of creativity in neurobiology, eschewing them for a description of emergent creative behavior in ecological dynamics. We presented

a model of a soft-assembled action hierarchy in neurobiological action systems as a consequence of a constraints-induced replica symmetry breaking and the onset of phase transitions that defines the set of functional metastable actions. The exploratory breadth of the action system is also heavily dependent on the set of influential constraints. By adequate manipulation of task constraints innovative and meaningful behaviors may emerge. We drew attention to the functional efficiency of creative movements in sport, exemplifying our ideas with reference to research in martial arts and rugby union. The data suggested how creativity in sport is, at least partly, based on exploratory activities of individual athletes and teams with the interdependent ecological constraints leading to the creation of new opportunities for action. Further dynamical modeling is needed to unravel the specificities of creativity in different sports and physical activities.

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