OVERVIEW OF COMPLEX SYSTEMS IN SPORT

BALAGUE Natàlia · TORRENTS Carlota · HRISTOVSKI Robert · DAVIDS Keith · ARAÚJO Duarte

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Abstract The complex systems approach offers an opportunity to replace the extant pre-dominant mechanistic view on sport-related phenomena. The emphasis on the environment-system relationship, the applications of complexity principles, and the use of nonlinear dynamics mathematical tools propose a deep change in sport science. Coordination dynamics, ecological dynamics, and network approaches have been successfully applied to the study of different sport-related behaviors, from movement patterns that emerge at different scales constrained by specific sport contexts to game dynamics. Sport benefit from the use of such approaches in the understanding of technical, tactical, or physical conditioning aspects which change their meaning and dilute their frontiers. The creation of new learning and training strategies for teams and individual athletes is a main practical consequence. Some challenges for the future are investigating the influence of key control parameters in the nonlinear behavior of athlete-environment systems and the possible relatedness of the dynamics and constraints acting at different spatio-temporal scales in team sports. Modelling sport-related phenomena can make useful contributions to a better understanding of complex systems and vice-versa.

Key words Constraints-led approach, coordination dynamics, performer-environment system, self-organization, team dynamics.

1 Introduction

Statements which capture the intuitive and empirical knowledge of world-recognized soccer coaches include: "When I see them moving like a flock of birds I know they are playing well" or "Fitness by itself does not exist ··· all are in relation with the order in the field. It is not a matter of running more than the opponent; if we are organized we will run less"[1]. These comments often contradict the popular beliefs behind sport analysis procedures, coaching science, and pedagogical practice. The mechanistic view of human organisms inspired in analytic

BALAGUE Natàlia
INEFC, University of Barcelona, Spain. Email: nataliabalague@gmail.com.
TORRENTS Carlota
INEFC, University of Lleida, Spain.
HRISTOVSKI Robert
Ss. Cyril and Methodius University, Skopje, Republic of Macedonia.
DAVIDS Keith
School of Human Movement Studies, Queensland University of Technologies, Brisbane, Queensland, Australia.
ARAÚJO Duarte
Faculty of Human Kinetics, Technical University of Lisbon, Lisbon, Portugal.
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reductionism and classical cybernetics has deeply influenced sport theory, sport practice, and sport research in the last few decades[2].

Complex systems observed in sport (athletes, teams, games, etc.) consist of structurally and functionally heterogeneous components which interact (generally informationally or/and mechanically) with varying intensities and spanning different spatio-temporal scales. They are also adaptive and goal directed changing and fitting their behavior to emerging constraints. This property increases immensely their level of complexity and provides a big challenge for modeling techniques. In such systems new forms of behavior emerge continuously under changing constraints, without being previously designed or imposed. This is a major characteristic of sports-related phenomena. Complex systems may behave in a simple fashion because their interacting components may form large coalitions of cooperative elements which reduce the dimensionality of the behavior (e.g., the coherent behavior of the public in a stadium or movement synergies). In this way a complex system attains simple behavior and may be treated as a simple system on a macroscopic level. On other occasions the system has a very complex and unpredictable outcome (e.g., the movements of a rower during whitewater rafting).

Complexity sciences offer concepts and tools which make it possible to treat complex systems, such as those previously mentioned, in a relatively simple fashion. A better understanding of sport related phenomena and new opportunities for the development of theory, practice, and research of sport and complex systems will follow.

2 Main Approaches, Origins, and Development

Even though complexity sciences influence some particular trends in sport from more than 30 years ago[3−5], a systematic research has been established through the coordination dynamics approach[6]. Coordination dynamics is defined as the science of coordination, that describes, explains, and predicts how patterns of coordination form, adapt, persist, and change in living things[7,8]. The aim of this field of work is to understand principles and laws that lead the dynamics of behavioural pattern formation under changing constraints (i.e., boundary conditions). These constraints may be classified into three sub-classes: Task constraints, personal constraints, and environmental constraints. Such a conceptualization of biological systems has led to the emergence of a constraints-led framework in motor learning[9], which may be seen as a sub-discipline of the coordination dynamics.

It is challenging to define coordination dynamics not only at the level of coordinating neural systems, muscles, and actions but also at the level of interactions between psychological and physiological processes in performers during exercise. This direction of work in coordination dynamics aims at unraveling how cognition, and physiological processes, reconfigure and transit spontaneously under changing constraints imposed by exertion in sports performance settings, that is, the aim is to discover the generic principles on which psychobiological integration during exercise is based. Metastability may be one such principle[10,11].

Until recently, the focus of research within motor learning studies was directed toward simple perceptual and motor tasks, often decoupling perception from action, in contrived laboratory settings, and movements responses which were non-representative for much more complex and diverse actions found in sport[12]. The same can be said for the traditional approaches and large amount of research done in neurophysiology and neuropsychology on perception and action, and motor learning. While it is interesting to understand the structural rearrangements within the brain during learning and performing, at the moment and the foreseeable future it seems impossible to formally and elegantly conceptually capture all those levels up to the macroscopic level actions, especially when performed in stochastically changing environments.

Second, the majority of such studies adhere to a strategy that has been recently criticized for its "organismic asymmetry" due to their focus on what changes within the brain, but not paying attention to how embodied minds interact with and are constrained by continuously changing environments[13]. Taking this into account, the ecological dynamics[14] approach to perception, decision making, and action was developed. This approach treats the performer-environment system as a relevant level of analysis and explanation in sports settings. The approach is based on two theoretical and formal pillars such as: ecological psychology of perception[15] and Haken's synergetics approach[16], as a relevant one in dealing with problems of dimension reduction and self-organization in complex nonlinear systems and their dynamical formulation.

The application of the ideas and concepts of coordination dynamics and ecological dynamics in sports actions is not a trivial task, though. How and which constraints lead to which spontaneous reorganizations of intra-personal and inter-personal coordination seems to require a long-term research program.

Another useful approach to inter-personal coordination dynamics in sports has been the network approach. Networks of players have been analyzed and game tactics as well as statistically rare and functional, i.e., creative patterns of play[17,18] were analyzed by use of the modified Kohonen-Feature-Maps, i.e., dynamically controlled networks [19] and neural-gas techniques[20]. What would be really interesting for future work within this approach is the dependence of patterns of play, their probabilistic measures on the constraining influences of the other team, the current result, playing system formation and so forth. These problems also offer a fruitful and long-term prospect of research in order to come closer to a deep understanding of possible general principles of sports games.

3 Opportunities Offered by the Complex Systems Perspective

The adoption of the environment-performer system as unit of study helps understanding how sport techniques, tactical strategies, decisions, and actions emerge without over-reliance on encapsulated predefined hierarchical structures - such as brain processors or motor programs. Complexity science applications include: How groups of cyclists, runners, or sport fans are spontaneously formed during practice or competition; and, how decisions to shoot or to pass, to dribble or to score, to advance up field or to stay back, to attack or to wait emerge without previous programs stored in the brain of the players.

The integrated levels interact at different scales during performance: From molecular and cellular levels to physiological subsystems, athletes, and coaches, members of a team or team opponents, giving a global and coherent vision of sport related behaviour. Techniques, tactics, physical capacities, decisions, thinking, or physiological processes, creativity, or social dynamics (as fans violence) are no longer treated as isolated or independent aspects but have interdependencies and common traits.

Coordination dynamics unifies the different processes which share the same operation and behavioral principles independently of the scale of analysis and their specific context. What happens when we walk, while our heart beats, when skiing or jumping, when collaborating in team or competing, etc. supposes an intricate network of nonlinearly coordinated functions.

The training processes also benefit from the coordinative perspective. The often boring and overreaching analytic sessions based on series and repetitions of the same movements are challenged by new approaches (see practical applications to sport training section) trying to improve the effectiveness and efficiency of the mentioned processes. The new proposals allow generating multiple and individual learning and coaching strategies, escaping from the classical receipts that characterize the physical, technical, or tactical intervention programs. There is also no need of locating in the brain specific centers or processors for programming or controlling functions (to select relevant information, combine intentions, store patterns, make decisions, integrate information and make calculations to emit the necessary answer). With the self-organization concept systems do not need such central processors or "programmers".

Nonlinear phenomena occurring in sport practice (fatigue-induced failure, overreaching, and overtraining, bursts in learning, training curves, muscle-skeleton injuries, proto-groups of fans formation, etc.) can find less ad hoc and more suitable explanations which help to predict better their outcomes.

The variability of the system behaviors acquires a functional value and might provide information on the state of such system (its flexibility and adaptability to changes or the opposite: Its inability to adapt or disease). This is a challenge for the future sport diagnosis, intervention, and evaluation systems.

4 Research Contributions to Sport

4.1 Game Dynamics: From Perception-Action Couplings to a Network Approach

The first applications of complexity principles to human movement were focused on motor control and learning. Postural control or finger and limb movements were analysed and modelled using the concepts of self-organization, collective variables, control parameters, or metastability (see [6] for a review). Modifying non-specific control parameters, the motor system was moved to different attractor states of system phase space in ipsilateral[21] or contralateral interlimb coordination[22−24], clapping[25], and other rhythmic movements[26].

Coordination between different individuals showed similar behaviours[27], leading to the rejection of theories that, based on cybernetics, explained synergies in human coordination through motor programs or schemas. There is not a neural structure located between two persons organizing the resulting movements.

The same principles used for understanding human coordination were applied to the study of sport actions and dynamical behaviours were observed in complex sport patterns, such as skiing[28] or swimming[29], or in the relations between individuals in team sports[30]. Ecological dynamics stressed the importance of the environmental realities that are relevant for the performer, in particular, the affordances, or the real, perceivable opportunities for action offered by the environment[15]. Decision making processes during a competitive game were no longer seen as the result of a program stored in the brain but were analysed as self-organizing processes that emerged as a consequence of the interaction of the athlete with the stochastically changing environment[14]. It was observed that control parameters related with the relative velocity or the interpersonal distance between players constrained the decisions that emerged from attacker-defender dyads in different sports like soccer[31] and rugby union[32]. The players involved in the dyads influenced the behaviour of all other players and self-organization and interpersonal coordination tendencies arise between the members[12,33]. Consider for example the decisions or action selections that an athlete has to make negotiating continuously with his immediate environment. Araújo, et al.[14] showed that the athlete-environment system exhibits qualitative changes, i.e., phase transitions, for some critical area of key constraints combinations in three different sport performance contexts: basketball, sailing regatta, and martial arts. In basketball, the interpersonal distance was revealed as a control parameter of the attacker-opponent social system that controls the stability of such dyad. In sailing the role of a key control parameter takes the angle of the wind and the starting line which regulates the position of the regatta boat. In martial arts, the change of athlete-heavy bag distance as a control parameter leaded to a cascade of bifurcations of different types of hand strikes some emerging and some vanishing.

Such investigations showed how the abundant degrees of freedom that existed within performer-environment systems, in critical areas, are sensitive to small changes of constraints and lead to qualitatively different organizations of dynamical variables or order parameters. Critical phenomena such as fluctuation enhancement of dyadic social behaviour, position of the regatta boat, and enhanced probability of hand strike formation close to critical points were clear markers of the dynamic properties of such transitions. The success of these investigations was in showing some universal features of complex systems dynamics which is essentially invariant of the level of organization of the matter.

The dynamic approach, used for describing between individual cooperation[34] and competition[30], was also applied to the detection of space-time patterns in games[35,36] helping to predict team performance and outcome. More recently, Passos, et al.[37] showed that values of interpersonal distance between an attacker and defender may be an important control parameter that channels the relative coordination between players in settings consisting of more than two performers. This clearly pointed to the possibility of applying network models in the research of sport phenomena[38]. Researchers argued that interactions between athletes during competition may possess a small-world topology, a specific type of networks that possesses power-law properties and may be important in unravelling some problems in social coordination in general, by studying sport interpersonal coordination. We note that such analyses in sport would be of really large importance and impact if they paid serious attention to the constraints acting within such network systems. Moreover, such constraints may be themselves emergent and occur at more spatial and time scales. The constraints dwelling at larger spatio-temporal scales govern the lower order dynamical variables dwelling on smaller spatio-temporal scales and vice versa, the processes at shorter-smaller spatial and time scales form more global patterns. As one may note this is the problem of the circular causality or top-down vs bottom-up relations, very much present in complex dynamical systems. One solution to this problem was Haken's[39] synergetic approach. However, these issues may need a somewhat different approach especially those concerning team sports. Particularly, the emergent phenomena occurring at larger spatio-temporal scales are usually, at least epistemologically, irreducible to the laws and dynamics existing on lower scales. However, they may possess formal structural analogies which may ease the problem. Associated with this is the issue of which are the microscopic parameters that remain relevant on the macroscopic scale. Such issues are solved in physics through the renormalization procedures. Is such an approach viable also in investigations of team sports dynamics?

Neural network approaches have been employed to identify tactical patterns in different team sports[40] and other network approaches have provided tools for quantifying the contributions of individual players to the overall team performance[41].

Traits of complex behavior have also been found in the temporal sequences of ball movements[42] and goal distributions in soccer matches[43,44].

4.2 Psychobiological Adaptation to Exercise

Having its origins in motor control, coordination dynamics seems to have only implications for sport techniques. Nevertheless one can ask how the integration/adaptation between the human neurophysiological subsystems is produced during exercise. Is this adaptation to multiple and constant internal and external changes based simply on central controllers and simple feedback loops? As long as one deals with conceptual descriptive modeling, the approach seems fine. The problem arises when trying to add more than a couple of components interlaced together; then the system becomes quickly impossible to treat in terms of feedback circuits[6]. The psychobiological adaptation to exercise performed until the termination point has been recently studied under the scope of coordination dynamics perspective[10,11,45]. The authors explain the changes occurring during exercise through the nonlinear interactions between the central and peripheral subsystems. They contend that the adaptation is constraints based, consisting of context sensitive cooperative configurations of system's psychobiological components that dwell on different time scales.

5 Practical Applications to Sport Training

The implications for training methods and the new role assigned to athletes and coaches have been studied by different authors. The differential learning approach[46] proposes to assist athletes to find individual optimal performance patterns by training with added noise in practice sessions. These are composed by a large variety of between-exercises differences, assuming that an action is never repeated. The athlete explores the state space until finding the best solution.

The constraint led perspective proposes tasks and environments that constrain performer-environment interactions. Research has focused on decision making and creativity in sport to reinforce this proposal. Novel actions might emerge by enabling an athlete or team to explore the metastable region of the action workspace through carefully manipulating key practice task constraints. For instance, in boxing where manipulating the distance of the target to be punched led to spontaneous alterations in preferred punch sequences[47,48]. The stochastic movements of target, or generally the environment, may give rise to invention of novel and functional actions by athletes[49].

The emergence of self-organizing coordinated movement patterns occurring at all scales and in all type of situations in sport dilutes the extant boundaries between technique and tactics[48,49]. The difference between these two concepts will depend on the scale of the behaviour, whether it is individual or responds to an opponent or team action. There will be a variety of ways to achieve the tactical goal and the athlete's expertise will be characterized by the efficacy and efficiency of the motor coordination to successfully achieve it[50].

The interaction between the intrinsic dynamics and the external constraints of the system will produce the emergence of individual solutions and coordinated motor patterns. It won't be necessary to inform the athlete about a theoretically ideal motor output, but create tasks and contexts where the technical skill can solve the constant changing situations. Solutions will emerge by the exploration of the environment and the perception of affordances. Instead of memorizing a great number of rules and sequences of actions, athletes need to develop their capacity to perceive informational constraints and adapt their actions according the specific goals[51].

The interaction between the teams will define the game, and the exact prediction of performance outcomes is not possible. The emergence of sport actions will depend on the task, personal and environmental constraints, and the aim of the coach should be to train athletes to adapt their behaviour to the constant changing and unpredictable environments.

6 Challenges for the Future and Benefits

It is a challenge for the future to enlarge the study of the emergent behaviour in sport observed at small scales (individuals, dyads of opponents, and teams)[52,53] to larger scales as dyads of teams, mass-start competitions, leagues of competition, etc.[54].

A very important direction of research would be to unravel how the constraints acting at larger spatio-temporal scales govern the lower order dynamical variables dwelling on smaller spatio-temporal scales and how the processes at shorter-smaller spatial and time scales, respectively, form more global patterns. Hence, within this line of research it is of major importance to investigate the possible relatedness of the dynamics and constraints at different spatio- temporal scales. Such spatio-temporal scales may show separate but also may show correlated behaviour. Hence, the basic question of the possibility of separation of spatial- time scales of the dynamics is still unsolved problem in team sport performance settings. These are far from trivial problems and researchers in this area still do not know how to proceed further with some degree of certainty. This means that a thorough and long term fundamental work is needed in the area to come closer to some more basic law-like behaviours of systems under investigation. If we succeeded, it will open a vast field of applications because as James Clerk Maxwell (1831–1879) once said: There is nothing more practical than a good theory.

Summarizing, some specific and also general benefits can derive from the study of complex systems in sport. On the one hand it might promote improvements in the area of sport and human performance creating new strategies for teams, coaches, and individual competitors. An increased understanding of human social networks including psychological drivers of competition and group participation; development of sport participation policy and education for youths and marginalized social groups as well as induction of violent attitudes in fans and political groups[55] can derive from it. Principles governing these group interactions are predicted also to apply to other biological collectives where dynamics emerge from a mix of competitive and physical principles. These include super-organisms such as ant colonies; bird flocks, fish-schools, sperm aggregates, herds, penguin huddles, to name a few[56]. See Duarte, et al.[57] for an application to sport.

On the other hand the study of complex systems in sport might lead to better understanding of evolutionary processes, optimization of resource extraction / allocation, and economic transactions; strategies for economic and ecosystem resilience and sustainability. Similarly, it is predicted that principles of mass-start sports (such as triathlons, cycle races, and marathons) have application to mixed top-down and bottom-up human dynamics, such as traffic-systems, economic interactions, and managed eco-systems[58].

Sport is not only a social phenomenon of our world but a real bank of human behavior experimentation. It provides a chance to effectively and efficiently study the effects of intense perturbations in complex living systems at many levels (physiological, psychological, social). The possibility of getting rapid empirical feedback in relation to formal models makes modeling sport-related phenomena a field of special interest for science and for complex systems theory.

In conclusion, complexity sciences can contribute to change the prevalent mechanistic view in sport and can make useful contributions to the understanding of complex systems.

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