LINEAR AND NONLINEAR COMPLEX SYSTEMS APPROACH TO SPORTS. EXPLANATORY DIFFERENCES AND APPLICATIONS

Hristovski, R., et. al. : LINEAR AND NONLINEAR COMPLEX

INTRODUCTION

The complex linear dynamic systems approach to biological systems

Complex systems are systems containing many interacting components. It is needless to say that biological and socio-biological systems in sport like athletes and teams belong to this class. However, components may interact in two general ways: linearly or nonlinearly. The linear approach to complex biological systems started with the advent of old cybernetics (e.g. Ashby, 1966) within the research program headed for finding commonalities between the living organisms and machines. This approach today is mostly represented by the theoretical and engineering, i.e. applicative, work within the realm of the control theory. The basic premises of this field of research is that living organisms may be successfully understood and modeled as technical devices decomposed on control and controlled components with explicit feed-forward and feedback loops among them. Components themselves are usually presented in a form of spatially encapsulated, pre-formed entities which activate or deactivate as soon as their function is being affected by other clearly defined subsystems. The analogy of anatomical-structural and functional identity is tempting and thus represents a fundamental assumption within this approach. A strong pre-formed structure-functional compartmentalization and modularity is hence hypothesized. In other words, each structure is a pre-formed module that serves one and only one function and is wholly responsible for its functional performance. Thus, its contribution to the overall performance can be isolated and linearly combined with other component contributions giving a linear superposition, i.e. a sum which then defines the overall performance. This is also the assumption behind all statistical methods of the Gauss-Rao linear model. Linear systems are proportional in a sense that the output of the system is always proportional to the input. If the input is continuous then the output is also continuous and vice versa, i.e. for a small or large change to be detected at the output a small or large change in the input is required, respectively. Small change at the input can not produce large, not to speak a qualitative, change at the output. In sports realm this means that the performance should be proportional to its causes (inputs).

For the components giving rise to the system’s performance to be successfully controlled, a superordinate control device must contain the whole specific knowledge in an explicit, rule-based way. It is important to understand that the program, by definition, contains detailed specific instructions of how each component should behave. Hence, by using feed-forward specific commands/programs it would affect the state of controlled components and eventually the overall behavior of the system.
These components then would feed back the information about their current state or change of the state, so that the control unit detects errors and feeds forward new correcting commands/programs downwards to them. That there are efferent and afferent pathways in biological systems is a well established fact. However, the problem arises in understanding the dynamics of such systems and the functions that are formed as a result of it. The pre-formed hierarchy is a necessary ingredient in such linear complex dynamical systems with an encapsulated super-ordinate controlling unit, i.e. a central governor, on its top. Needless to say, such a structure is subject to fundamental explanatory problems, such as the infinite regress or the “homunculus” problem: If the super-ordinate control device programs the subordinate devices, i.e. system’s components, then who programs the super-ordinate device itself? Who puts the specific knowledge into it? For technical systems the answer is easy: computers are programmed by human beings called programmers, and computers can control a whole factory. In this sense programmers are super-ordinate to computers. They put the knowledge into computers. But who programs living systems? Two answers may be offered. One is that another, higher controller, is responsible for programming them (e.g. the brain). However, this explanation just shifts the same problem to a higher level and remains unresolved. If this is true, then who programs the brain? Another answer would be: The super-ordinate device self-programs, or better to say, self-organizes. Here, it is very important to note that this super-ordinate device does not have to be pre-formed at all, although it would necessarily depend on extant biological material substrates like the neural, metabolic or hormonal systems and their components. The super-ordinate device may self-organize or emerge under some suitable conditions. Also, depending on the conditions, different super-ordinate devices may form, stabilize and dissolve from the same components of the system. This possibility and evidence for it will be discussed more extensively in the next subheading.

The control theory also deals with possible nonlinearities by explicitly defining their type for one or few system’s components (see Agrachev et al, 2004). However, this is an ad hoc solution that merely mimics the nonlinear behavior. In engineering, this mimicking is acceptable solution due to the tasks and problems under scrutiny. One has just to project and construct a technical device that has predictable and controllable behavior. Thus, by designing such mimicking device with inherent nonlinear behavior one solves the problem. However, the task of explaining the behavior of living systems such as athletes or sport teams is essentially different. One has to explain how such behavior emerges in the first place, without ad hoc interventions. In other words, the task is not one of constructing but one of explaining a certain extant living system. The researcher has to construct a nomothetic system, i.e. a theory, which has explanatory as well as predictive power that captures such phenomena in a general way. Not merely finding special, ad hoc, explanations for each separate phenomenon, but capturing those separate phenomena as special cases, i.e. instantiations, of a general explanation.

Of course, the linear approach is obviously suitable for constructing engineered systems (telecommunication systems, computers, automated control in factories etc.) where an external explicit designer or programmer in a form of a human being is engaged, but the inverse assumption, namely, that living organisms can be approximated as engineered machines does not need to be necessarily true. A support for this claim comes from decades old and unsuccessful endeavor of roboticists and artificial intelligence researchers to construct a realistic biological isomorph, i.e. a system which would behave as a real biological system. This problem is put to an extreme in the area of robotic motorics where biped robots are announced as ‘the state of the art’ if they are able to perform skills of a one year aged toddler. The claim of the pioneering researchers in these fields that problems would be solved once the processing and computational abilities of artificial systems become powerful enough seems a far fetched assumption. Supercomputers today outperform their early ancestors by a factor of million, and yet no biological isomorphs are in prospect. Maybe the core assumption of the technical-biological system analogy is a wrong one. Maybe living systems are not technical systems after all. In robotics engineering this was understood as a major challenge and alternative, biologically inspired, ways of hierarchical self-organization started to take place in the 1990-es and more recently (e.g. Paine & Tani, 2005). Nevertheless, the linear approach to living
complex systems have had a wide impact over the past several decades in different areas of biology and its subfields and consequently in sports sciences in general. However, the new wave of biologically inspired engineering have already started a new era of building technical systems. The epilogue, so far, may be concisely formulated as: Instead of explaining and modeling biological systems as technical systems lets try to engineer technical systems as real evolving biological systems. Time will tell whether this endeavor is feasible and, if yes, to what extent.

Without disregarding the insights produced by the experimental work in a vast set of scientific disciplines investigating biological order within linear control theory approach, it seems increasingly likely that it is the dynamics of these systems rather than their structure that gives the essential information on the real basis of their functioning. Of course, the structure, being dynamic itself and a product of that very dynamics, may be a strong, even sometimes the dominant constraint on the biological dynamic order (Edelman, 1987, Edelman et al, 1999). However, it seems, that without finding dynamical laws that create, maintain and dissolve the biological functional order, one could not proceed further even to explain how biological structures themselves come about in the first place.

The complex nonlinear dynamic systems approach to biological systems

In the previous text we defined the problem of finding dynamical laws that create, maintain and dissolve the biological functional order. More precisely, we asked: what are the dynamical laws of the creation, stability and dissolution of biological order? Or, even more precisely, what are the dynamic laws responsible for these phenomena (e.g. performance) in sports settings? First and foremost, is their dynamics linear or not? Lets make it simple: If one finds non-proportional effects in systems under scrutiny their dynamics is non-linear. The answer comes quickly: Sports itself contains innumerable non-proportionate phenomena, such as: action selections i.e. decisions, sudden task disengagements under accumulated effort, onset of overtraining, stable and unstable performance profiles, emergence of a new technique or a movement form, lactate and ventilatory thresholds (thresholds are hallmarks of nonlinear dynamics) to name a few. All these phenomena arise when a small change of certain parameters have taken place. For example, a small change in the distance from the opponent may bring about a qualitative reorganization of the action. A small change of the exercise intensity brings about the onset of blood lactate accumulation. These facts make sports a fertile ground of investigation of complex biological nonlinear dynamical systems.

What are the characteristics of nonlinear biological systems? First, interactions between their components are non-linear. Components in such systems influence other components, but in return are being influenced by them. Hence, components posses a property of self-influence, sometimes direct, but generally indirect. The number of such components is vast. Only the brain contains hundred of billion neurons and thousands of times more synapses. Making an explicit and detailed dynamic model of such complex system is unfeasible in foreseeable future. Furthermore, the brain-body system is embedded in an environment which is infinitely variable in space and time. To adapt to such environment a linear system with pre-formed rule-based devices would need to contain infinite number of programs or rule-based representations to perform the adaptive flexibility required by the task and the environment. However, nonlinear systems have one general characteristic which enables such flexibility. It is called multistability. This term signifies the ability of nonlinear systems to have multiple semi-stable states for the same or similar values of some contextual variable that represents the environment. This means that such systems may perform more than one function in a same or similar environmental context. For example, one can perform different movement organizations to satisfy the same task requirements.

Moreover, one can switch between such states and show significant behavioral versatility i.e. demonstrate multifunctionality. This is enabled by a dynamic mechanism called a meta-stability (Fingelkurts & Fingelkurts, 2004, Freeman, & Holmes, 2005, Friston, 1997, Izhikevich et al, 2004, Kello et al, 2008, Hristovski et al, 2009). For example, one and the same neural network may produce a large number of patterns depending on the inputs i.e. external constraints. The multistable system can dynamically shift among available component configurations which are selected by the confluence of constraints that impinge on
them. Note that in this case there is no need of a pre-formed super-ordinate device, a knowledgeable homunculus, which will make the selection. It is the immediate constraints that make a selective pressure and mold the system’s configurations to be functional. The notion of constraints is instrumental for understanding the behavior of nonlinear systems such as athletes and teams. It is their role to form the context within which complex nonlinear systems such as athletes, self-organize in a certain functional way. Constraints may be classified as: task and environmental demands and organismic properties (i.e. athlete’s morphology, psychological traits, motor abilities, synaptic networks etc.) (see Newell, 1986, Chow et al, 2011). Their interaction creates the web of influences which form the control parameter space of the system. Now, if we change these control parameters in a certain way we can witness interesting phenomena. For certain values of control parameter, the system, i.e. athlete or a team, changes slightly or does not change at all (another example of non-proportionality). Then, for a further minor change of the control parameter a qualitative change of the behavior occurs. This is called a critical point.

However, here we are challenged to define the behavioral variable or variables we would use to capture system’s behavior. In complex biological systems there is a vast set of potential variables. It happens that the variable which shows an abrupt change is the relevant, essential, variable that best captures the system’s behavior. This claim has a rigorous mathematical justification. It is called a “central manifold theorem” and its physical, chemical, biological and sociological interpretation is articulated in Haken’s “enslaving principle” (see e.g. Haken, 2000). This principle says that: close to critical points only one or a few variables enslave all other variables (system’s components or degrees of freedom) and make them behave cooperatively, so that to enable their own existence. In other words, a large number of components become dependent on the behavior of only one or few components. Then, by knowing the behavior of these few components we actually have information on the behavior of all other components. They behave cooperatively as the enslave, collective, variable dictates. What happens is a spontaneous separation within the system on variable(s) that govern and variables which are being governed. Variables which govern are called order parameters because they reflect the ordered behavior of the system, or equivalently, collective variables because they reflect the macroscopic cooperative effect of the enslaved collectives of components, i.e. synergies. This mechanism provides an immense reduction of information as a consequence of the system’s dimension reduction (Haken, 2000, Hristovski et al, 2010).

The emergence of such macroscopically ordered patterns and the information reduction of behavior enable us to understand how complex systems are being coordinated and controlled and how macroscopic synergies emerge. Here, the term ‘synergies’ have to be understood in a general sense, not only as motor synergies. Psycho-physiological synergies (Balague et al, 2012) and team synergies (Passos et al, 2008) also show this kind of behavior. It actually solves the problem of infinite regress in super-ordinate control devices acting in linear control systems discussed in the previous subsection. Order parameters, i.e. collective variables, are themselves super-ordinate devices that exert control on and coordinate the enslaved, i.e. subordinated components, but this time they are not pre-formed. They are self-organized devices which emerge under the influence of control parameters, i.e. the interacting web of environmental, task and organismic constraints (see e.g. Fox et al, 2005). They are emergent (not pre-structured) and task-environment-organism specific synergies or functional modules. This mechanism is based on the circular causality in a sense that: subordinate, enslaved, components by their collective, synergic, action form the order parameters and the latter impose the order on them. Each enslaved component is subject to the collective influence of all other components, i.e. the collective variable, and is forced to behave cooperatively.

In this sense we can understand how biological as well as sociological substrate self-organizes and engages itself in purposeful functional behavior under specific set of constraints that form the control parameter space. These control parameters are usually non-specific. They do not convey the same information as the collective variable. For example, the perceived distance from the opponent does not contain the same information as the action toward the opponent. Perceived distance is a perceptual variable and the action may be studied as a kinematic, kinetic or muscular synergy variable.
So, perception is a non-specific control parameter that does not contain the same information as the movement itself, but it influences i.e. constrains, it. On the other hand a movement action intention is a specific control parameter because it specifies the movement in the same terms of movement parameters. For example, intention to move on the right hand side contains a specific information of moving on the right hand side.

Stable states of collective variables, i.e. order parameters, are called attractors because they attract the behavior toward a stable mode of functioning (see e.g. Lundqvist et al, 2006). Stability itself is defined as a resistance to perturbation. If for the same magnitude of perturbation the system quickly converges to its previous state we say it shows remarkable stability. The attractor is stable because it attracts the system quickly. If not, than, we say the system shows tendency to be destabilized. The attractor state or dynamics has weaker forcing to pull-in the system. In cases when the system qualitatively changes its state we say that the system has lost its stability. Loss of stability is what happens at the critical points. Close to these points interesting phenomena arise and are general predictions of the nonlinear dynamics theory. One of them has been already described. As control parameters change the system becomes less stable and more time is needed to recover from the perturbed state. This is called a critical slowing down phenomenon. Enslaved components by the order parameter close to the critical point are not "well enslaved" but show larger degree of independence. Their cooperativity weakens and they are not strongly pulled toward the attractor any more. So, to restore the previous order, the one before the perturbation took place, the system needs more time. So, the restoration takes more time. This weakening of their cooperativity and the enlarged restoring time makes the system to fluctuate in an enhanced manner. Fluctuations, i.e. irregular oscillations around the attractor, enhance for the same reasons described previously. This enhancement of fluctuations is another hallmark of the impending critical point and an abrupt qualitative change.

Some practical applications
Detecting the order parameters has important practical consequences. Because they are the variables that govern the synergic system components, than they should be studied in each sport discipline separately and be used as behavioral variables for either explicit or implicit learning settings. Defining the task in terms of order parameters enhances the formation of coordinative structures that have to be learned. For example, telling to the learner that s/he has to make a strong impact of his/her front fist with some surface posited under various angles will immediately form a coordinative structure that resembles a hook, uppercut or jab pattern. Thus, the angle of impact acts as a collective variable that enslaves all other components of the arm, i.e. specific joint angles and their relative accelerations. This happens because the angle of impact is the macroscopic variable, i.e. an order parameter, which the brain uses to plan this discrete action. Instructing the learner explicitly, how each joint angle of the arm should relate to each other angle may take much time and lead to information overload. Because the order parameter contains this very information in a reduced way the learning is much quicker. Studying the constraints that give rise to different forms of self-organized patterns is another important direction of research in each sport discipline. This approach emphasizes the individual way of exploring and finding idiosyncratic task solutions of athletes. Much less explicit information would be needed for the learner to find her/his own behavioral pattern. Less explicit information leads to a more robust acquirement of the perception-action couplings and less instability in ego-threatening situations such as sports contests (Poolton et al, 2007). Generally this approach leads to a more independent decision/action making abilities in athletes. Furthermore, learning and training within well defined constraint sets optimizes the action versatility and coordination switching abilities in athletes (Hristovski, 2006, Pinder et al, 2011). Training at the areas of action reorganization, i.e. critical points, would enhance the sensitivity of detection of specifying perceptual information for regulating the action. The induction of environmental-task noise, i.e. fluctuations, strongly facilitates the exploration and the emergence of novel solutions to the task goals, even creating novel task goals, which on the long term may prove instrumental in facilitating the creative athlete-environment relationships (Hristovski et al, 2011). Coping strategies and attentional focus during hard exercise show instabilities akin to those described


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above. Their success strongly depends on their stability profile. Thus, different specific coping strategy training would be required for different phases of exercise (Balague et al, 2012). Many other practical interventions stem from the nonlinear pedagogy approach (see e.g. Chow et al, 2011 and the references therein). In summary, the view of nonlinear complex systems approach changes the theoretical basis, the research concepts and the practical applications to sport related phenomena.

REFERENCES
PRIMENA NA LINEARNI I NELINEARNI KOMPLEKSI SISTEMI VO SPORTOT. EKSPLANATORNI RAZLIKI I PRIMENA

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Апстракт:
Даваме оглед на најважните експланаторни разлики помеѓу линеарниот и нелинеарниот теоретски пристап кон сложениот динамички системи во спортот. Накратко се осврнуваме и на некои примери кои се во развој во рамки на нелинеарниот пристап.

Клуни зборови: сирои, линеарни и нелинеарни динамички системи, комплексни системи

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