Non-linear dynamics and physical exercise: concepts and applications

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ABSTRACT

Physicians, physiologists, biochemists, psychologists and even professionals involved with physical exercise have been recently increasing their interests for the non-linear dynamics, a scientific theory developed mainly by mathematicians, which is generically known as the Complexity Theory. Although few investigations on Physical Education and Sports make use of this paradigm to solve their problems, a growing interest for this very approach has been noticed, mainly concerning the effects of physical exercise on changes in the variability and complexity of physiological temporal series. Usually, such changes appear as the decrease in its temporal behavior, denoting in decrease in the body complexity or in the components specifically involved in its regulation. According to the Complexity Theory, since non-linear interactions existing in biological systems are emphasized, it is observed that not only the increase (overcompensation) of the body components with the practice of physical exercises but also those which cause atrophy (decompensation) in parallel, once they can compromise the functionality of these systems. Thus, contrary to the emphasis that is given in the physical training to the monotonous repetition of intense physical activity and with emphasis on positive specific effects, that invariably promote the simplification of the body, larger qualitative and quantitative variation is recommended in the exercise practice. The objective is to preserve its natural complexity or neutralize its rapid decrease with aging. The present review has the objective, besides describing the possible complexity loss with physical training, to discuss some concepts of the Complexity Theory in an introductory way, with particular emphasis on issues involving health and physical training.

Keywords: Fractals. Specificity. Physical fitness and health.

INTRODUCTION

The triad mechanicism, reductionism and linearization of the data collection are part of the traditional thinking applied to solution of biological problems(1). The third item synthesizes such procedures, once it means that causal mechanisms may explain phenomena that, once involved with many factors, applies the strategy of fragmenting the system in many parts with their later sum(2). Concerning physical performance, for instance, the presence of factors which limit or promote development of fatigue is usually accepted(3-4). Currently there are so many reports on factors related with fatigue that almost none of them can be omitted. The only available means to explain it is by adding the effects promoted due to each factor investigated.

More specifically on data linearization, it is still currently verified the use of terms reflecting this way of thinking as a balance, homeostasis or steady state applied to the being. The concept of homeostasis will be further discussed below. For now, its precursors usually state that after any disturb occurred, a system tended to reestablish the steady state, and a system can also develop another kind of steady state, if and when the external disturb is prolonged(5). Life therefore, becomes part of a succession of steady states, a battle to constantly keep a certain balance between stress and a suffered disturb(6). However, it is currently accepted that the linear view point is only correct and applicable to simple and close to balance systems, which does not actually occur with live beings(5).

An essential aspect to organisms which justifies the previous criticism has to do with its extraordinary complexity. One should consider in the definition of complexity, the large number of structures and processes which non-linearly interact through refeeding mechanisms, with the possibility of emergency of other functions, as well as of many times unexpected behaviors(6). Within this context, physicians, physiologists, biochemists, psychologists and even professionals involved in physical exercise have been recently increasing their interest in this new way of thinking, which is derived from the Complexity Theory(7-8).

They are examples of emerging processes, among others, phenomena related with the non-stationarity notions (the fact that the frequencies spectrum of a signal vary during time) and non-linearity, typical from the measured signals of physiological and metabolic variables, during rest or physical exercise. In the latter case, the interest has been especially in the comprehension of the meaning of alterations occurred in the variability as well as complexity of these variables(9-11). The aim of this review is to establish which improvements can be obtained with the use of this theory concerning physical exercise practice, once the issue has been discussed by a limited number of professionals of this field(12). Therefore, the following concepts will be discussed: homeodynamics, non-linearity and fractals(13-15). Moreover, we have the aim to propose and justify the importance of physical exercise practice with varied qualitatively and quantitatively contents, in the sense of preserving or promoting the intrinsic complexity of human beings.

HOMEOSTASIS AND HOMEODYNAMICS

One of the first steps to understand the meaning of biological complexity is the contrast between homeostasis and homeodynamics. It is implicit in the homeostasis concept that physiological systems normally operate with the purpose to reduce the variation and to keep hence the steadiness of the internal functions of the body(16-17). Thus, any physiological variable should return to its normal state after having been modified by environmental stimuli, such as physical exercise. The homeostasis principle imposes hence,

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that metabolic or physiological variations are merely transitory responses to the fluctuations promoted by stimuli(18-20).

Some clinical and physiological aspects recently discovered on the temporal behavior of physiological variables, such as heart rate, make the use of homeostasis impossible as a physiological paradigm. Actually, let us take as an example the heart rate of four individuals, measured and placed in an appropriate chart. Imagine also that only one of them is healthy; the rest of the patients have some kind of heart problem. In order to identify the normal register, physicians use the comparison between means and standard deviations of two or more individuals. Nevertheless, we may not detect through this procedure any difference in the behavior of this variable, once the individuals may for example demonstrate identical mean and standard deviations, suggesting inexistence of clinical problem(21-23).

The procedure alone does not work either because the interpretation of results using this kind of analysis does not consider the non-linearity intrinsic to this physiological variable(24-27). Non-linear systems which are the case of the mechanisms which regulate the heart rate variation, are unbalanced in normal conditions(9), being this characteristic presented by biological signs called homeodynamics by Lloyd *et al.*(16) and Yates(17). It has been suggested that continuous analysis of these variables instead of being solely based on mean values or standard deviations should be done(27).

Some factors justify this proposal: a) the response of healthy bodies may lead to reveal probable variations which lead the body to stand environmental demands which are not known up to the moment, and which need non-linear interactions among the organic components; b) the fractal characteristic of some components or organic variables seems to deteriorate with disease or age, decreasing the body's capacity to adjust to its environment (the fractal concept will be approached later on); c) in many systems, the decrease in complexity of response corresponds to the isolation of its components(23,28). In other words, as time passes by or due to influences of the environmental stimuli, parts of the system decrease the capacity to communicate with each other.

It is present in these suggestions that healthy bodies have the efficiency in communication between their parts and processes and that it can be harmed in sickness(21-23). Thus, both the notion of homeostasis and analyses based on descriptive statistics do not seem to be sufficient or even suitable in the study of the characteristics of non-linear systems, which will be better explained right now.

LINEAR AND NON-LINEAR SYSTEMS

Two important properties of linear systems are: proportionality and overlapping(25-27). Proportionality means that the response and stimulus have in an ordinated pair, linear behavior. Overlapping suggests that the behavior of a linear system composed of multiple components may be totally understood and predicted by their isolated study. In this analysis, the total response will be only recognized by the sum of the constituent parts.

However, even simple non-linear systems break the proportionality principle. One example is the system represented by the equation $y = a \cdot x \cdot (1 - x)$, known in Populations Biology as logistic equation(19,26). The non-linearity of this equation, which describes a parable, also evident in the curve of physical performance(29), results from the term x^2. In this equation, if there is an implementation of a refeeding procedure $[x_{i+1} = a \cdot x_i \cdot (1 - x_i)]$ in which a current value of response is used as stimulus value of the next equation solution, then (and depending on the *a* parameter value) the solution of this simple form equation may reveal a dynamics without any apparent preview observing the chart, but perfectly predicted by the applied rule(19). In the case of the bodies, for instance, the proportionality does not apply, since small alterations in the parameters or initial conditions of functionality of physiological variables may result in wide and unpredictable effects(16-17).

Another factor that adds to this analysis is the impossibility to comprehend the systems composed by multiple components by the study of isolated parts (overlapping)(30-32). This strategy does not succeed, because the components of a non-linear system interact(26) in such a manner that if a subsystem *A*, for example, may influence the behavior of a subsystem *B* and vice-versa, besides being influenced by other components not mentioned or known, it is difficult to recognize a cause-effect relationship between them(33-34).

Such discussion is justified once in a data collection there is a set of procedures which aim to change a biological sign into functions which accept overlapping(35-37). The signal is usually picked in symbols (actually, numbers which have no other meaning than numerical; mathematics has no relationship with the physical world: researchers are the ones who attribute this to it) which, once registered by an equipment especially designed for it, expresses the information and energy exchanges which occur in the parts which make the body in the time interval of measurement(38-39). Data model is the analysis of the signals picked with the aim to characterize a structure of the physical world, such as the cardiac muscle (electrocardiogram), the brain (electroencephalogram) or the skeletal muscle (electromyography), with no interference from the investigated structure in the analysis(39).

The data models described before are also known in Physiology as temporal sets. Therefore, despite the complexity which characterizes each human being and the singularity of their constituents, a certain degree of regularity may be in the behavior of its variables may be found. This statement will be explained when we discuss the fractal term. There is also the so called systems model (or model system), which tries through the presence of a concrete entity responsible for the observed variation (actually, diagrams or blocks which represent the stimuli and responses of each subsystem conceived by the researcher). In this model, this entity may represent redundant (identical structures performing the same function(40)) or degenerated structures (different structures performing the same function(41)), besides refeeding mechanisms.

Although the isolated study of this entity provide some solutions (as in the case of research on the turnover or clearance of substances), many problems also arise, since when the systemic components are individualized, the main characteristic is destroyed: the cooperation between the parts(42). The concrete entity behind the signal variation cannot, therefore, be analyzed (that is, divided in parts) under the semantic view point of the term; it should preferably be treated from concepts and theories which may consider the complexity of the system – in this case, the interest lies on the human being. Such concepts and theories should also make obsolete the task to build a puzzle, possibly not tangible to the human capacity, which would consider the minimal differences among the many subsystems of the body in order to justify the disparities in the several biological signs during the time(43).

FRACTAL GEOMETRY AND AUTO-SIMILAR ORGANIZATION

Temporal sets, such as the ones exemplified above, consider variables data registers considering the possibility of scale existence in the obtained spectrum. Moreover, each time the experiment is conducted, the temporal sets may be different, especially if they present chaotic behavior(44). The essential point is the consideration that, in this analysis there is the possibility of presence of data on the functionality of the components of the system(43-44). In the systems which show structural or functional regularity in their variables and which demonstrate power law with lack of typical scale, the temporal distribution pattern of the data obtained demonstrates a fractionated dimension (fractal).

Curiously, it has been recently described and extensively discussed by Garcia-Manso *et al.*(45) that long and medium distance runners, when the mean velocity in a given distance or the time spent in order to complete this distance are considered; power law of the following type is found: $v = cd^{-\alpha}$; where the constant (c) or exponent value varies with the physical condition or training time of the athlete and d represents the completed distance. Phenomena of this kind could be observed in each group of athletes regardless their individual characteristics and did not demonstrate a defined scale; therefore, no statistical difference was observed in the response. It is currently acknowledged that in phenomena which present this kind of behavior there are critical phenomena, in which a small stressing stimulus may induce the system to dramatic change of behavior. This meaning for the physical performance has nor been established yet.

Fractals may unpredictably appear for different reasons: in chaotic dynamics, growth or evolution processes, and so forth. Fractals may be categorized in two different groups: solid objects and strange attractors. The former type includes physical objects which exist in the physical space(43-44). The latter one is concerned with conceptual objects which exist in the phase space of dynamic chaotic systems. If the signal register of physiological variables reveal chaotic behavior, they will be inserted in the second example. In order to identify chaotic behavior in temporal sets it is necessary to use procedures which will not be described here.

According to Melendez *et al.*(46), a structure from the physical world with fractal characteristic of construction shows repetitions from the same initiating factor. Therefore, the terms which define the building process in the fractal geometry are the self-reference and self-similarity ones, since the structure should usually have the same appearance, regardless the measurement scale in which it is observed, and should be determined by the interaction of certain algorithm (set of instructions)(46-49).

In order to comprehend the fractal geometry, we should remember firstly that the classic geometric shapes have complete dimensions (1, 2 and 3, respectively for the line, surface and volume), while the fractal ones have fractioned dimension. This does not mean that a three-dimensional fractal structure does not occupy three dimensions in space; the fractioned dimension concept is only a more accurate means to calculate the structure surface or volume(50).

A great variety of structures have this characteristic, including trees, broccoli, cauliflower, coral reef, sea shore and mountains. In the body, a certain number of pulmonary structures, arteries and veins, among others, also have a similar shape(51-52). From the mechanicist point of view, these auto-similar organic structures spatially distributed may favor the fast and efficient communication between systemic components, such as the circulatory, respiratory and digestive systems(52). Moreover, the fractal concept can also serve to certain data models(7), once the picked signs may demonstrate fluctuations which follow an algorithm more or less steady (for instance, physiological variables). The quantitative appreciation of the self-similar nature of physiological processes may be obtained when their fluctuations in different temporal resolutions are placed in a chart, as in the case of the heart rate of healthy and non-healthy individuals under three time scales(19).

Thus, the use of a limited number of algorithms which enable the appearance of complex behaviors seem to be valid for many processes and structures, with possible application of the fractal geometry in the analysis of the signals variability. For instance, fluctuations characteristically fractal have been observed in the systemic blood pressure, gait rhythm, number of white cells, kinetics of transportation of certain ions, heart rate and oxygen uptake(25). As new experiments have been confirming the previous statements, the consequences concerning what would happen to the body if it behaved extremely deceiving or monotonous could be generalized: occurrence of structures break and processes resulting in disease (e.g. cancer) or long stress(52).

Therefore, there is a paradox in the application of the fractal geometry in the analysis of diseases, since a great amount of them are remarkably associated with the periodic behavior of their variables, despite being qualified as dysorders(21-23). Moreover, the appearance of periodic dynamics in many sickness states has been related with loss of complexity.

Would there be a possible loss of organic and cellular complexity by the procedures of physical exercise practice which aim to immediately obtain performance through the early specialization or even daily practice with monotonous repetition of physical activity, stimulating only a few components of the body? There is evidence supporting this premise(12,29,47,53). Moreover, in the works previously mentioned, there are many examples of loss or insensitivity of organic and cellular components in these conditions. Other examples include modifications in the variability or regularity of heart rate due to overtraining(54). Some more examples will be mentioned below.

Therefore, the primary characteristic of the body, previewed and explained by the Complexity Theory, is the irregular behavior of internal variables, due to the occurrence of interactions among their components, besides possible environmental effects. According to findings of fractal geometry mentioned above, these constant interactions between systemic components occur through connections which are applied in all scales of space or time(40).

One should consider that besides the addition of structures and processes that physical exercise will come to overcompensate, there is constant need to respect the complexity inherit to the organic and cellular processes, especially in order to provide with this practice better conditions for suitable interactions among them. We highlight that procedures of sports practice or physical activity following the current paradigm, which invariably lead to specialization, does not let this happen, favoring hence the appearance of abnormal dynamics between the components and processes of the body, defined by the complexity researchers as dynamic diseases(15,44).

A recent example of the importance for the body to present with intact intracellular dynamism or in greater interaction level may be derived from anthropological studies involving Africans, African-Americans and Scandinavians. The physiological constitution of black people from Western Africa, for instance, Kenyans and Ethiopians, presenting higher interaction between the aerobic and anaerobic capacities than Scandinavians or African-Americans, suggests that the sportive success in prolonged activities is more related with the dynamic balance which exists in the body of these athletes than with their superior aerobic capacities(55). Consequently, they are able to train with great volumes, as well as with more intense rhythms than their opponents from other races once they demonstrate higher blood lactate concentrations and support them for longer than usual.

Thus, one may predict that due to what has been described, that the mesh structure of physiological and biochemical connections may be altered when physical training is based on the overload and specialization principles, which, according to what has been shown, is harmful to the body. This fact happens once it is possible that the control of the interactive processes played by the endocrine, immune, behavior and autonomous nervous systems, responsible for the maintenance of the physiological and biochemical variables at steady varied dynamism, is harmed by this procedure.

Concerning the endocrine system, there is evidence for instance that the hormone serum concentrations such as the testosterone are reduced with intense and prolonged continuous exercise(56); is fairly well-known that intense exercise causes negative changes in the functionality of the immune system(57), the opposite occurs with the exercise at 50% of $\dot{V}O_{2MAX}$; adrenergic b receptors in the muscular tissue and in the adipose tissue are progressively sensitized with physical training(58) and, besides this, athletes present modifications in behavior with overtraining(59).

COMPLEXITY MAINTENANCE: PHYSICAL HEALTH AND PERFORMANCE

Based on what has been seen, one may affirm that when a system becomes too predictable, once it monotonously repeats its activity, its response does not fulfill the environmental demands; as seen before, this is a reflex from its progressive loss of complexity. This behavior pattern is also observed in parameters of certain diseases, once the studied ones are characterized by remarkable decrease in the complexity concerned with a healthy state. In other words, the physiological systems become less adjusted or adjustable, imposing restrictions to their capacity to deal with constant changes occurred in the environment(60). In addition to that, in order to generate information or interpret stimuli, a system needs to be able to unpredictably behave, since a repetitive signal does not have information that it has not been known it, that is, it becomes redundant.

Concerning this issue, despite being little considered by physical exercise professionals, the opposite has been recently observed, especially concerning the variation of heart rate, which is widely reduced in intense physical exercise(10). It has been observed in some cases, even in the ones with no epidemiologic importance, a possible occurrence of serious problems such as sudden death(61). Nevertheless, the fractal geometry teaches us that a physiological behavior can be very varied and simple and also on the contrary, little varied and complex(19,21). Therefore, the decrease in the variability of physiological temporal sets as well as loss of complexity are not synonyms. Further research is still needed in order to establish the possible loss of complexity of the fractal type in these variables with physical exercise training(61).

Yun *et al.*(60) have suggested that the progressive decrease in the variation width of environmental stimuli to which the body is daily submitted, may contribute to health dysfunctions and, on the contrary, that the expansion in this width through possible strategies such as physical exercise, may be beneficial. The authors highlight that three different systems as the endocrine, autonomous and skeletal-muscular may suffer deletereal effects due to this loss of variation in the environmental stimuli.

Concerning physical activity, is has been described that the decrease in its variation with the environmental stress caused by the modern societies due to the new life style they offer, may reduce the width of the dynamics of the autonomous nervous system. The expected result is the possible decrease heart rate variation as well as functionality of many organic systems. Therefore, it is recommended that physical exercise when activating the autonomous nervous system could positively contribute to the maintenance of this important physiological function. Nonetheless, even with its practice, there may be the monotonous repetition of standardized exercises, resulting on not very clear benefits for this system concerning its complexity, as exemplified above(62).

CONCLUSIONS

The existing interactions between systemic components which occur through connections which are applied in all space or time scales in the body may be reduced with sportive specialization or repetitive practice of standardized exercise. The simplification of the body's functionality, according to he Complexity Theory is an important factor to be considered in the study of the physical performance barrier; therefore, it is crucial that training is varied, both qualitatively and quantitatively, previously to applications of specific training workloads. Early sportive specialization is a serious problem; however, no suitable proposal has been offered to solve it. The motor experiences variation is also emphasized in the sports field, but it does not have theoretical knowledge yet. We believe that the Complexity Theory may help to propose the variation in motor experiences and overloads in the beginning of the training process (avoiding thus early specialization), in a more scientific and less folkloric manner. Thus, it is concluded that the training variation could play a minimizing effect in the physical performance barrier.

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