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TOWARDS AN ENTROPIC APPROACH OF THE MOVEMENT

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Abstract

Entropy is a thermodynamic concept describing the degree of order present in a system. This parameter is used for the informational analysis of the dynamics of that system. Entropy and its forms of expression are used to evaluate the complexity of various physiological signals. In terms of human motricity, entropy can be used to quantify the degree of movement complexity. The motor adaptation of the human organism involves a process of conservation of energy and entropy, which implies a compensation of the entropy between the load, the body (effector motor result), and the environment. The variability of human motor performance is reflected by the non-linear manner in which individual abilities and motion characteristics vary over time. Also, neuromotor system redundancy implies a broad possibility of using multiple strategies to accomplish a given task. Human motricity is a dynamic and complex nonlinear process, involving the coordination of several allostatic regulation mechanisms, which aim at directing the operability of systemic functions to a minimum of energy consumption and maximum efficiency. An interesting ontogenetic approach to the entropy of the movement allows the analysis of the main stages of changing motor behavior, taking into account the stages of growth and development of the human body. Athletic performance implies optimal mechanical and energy processes that support complex motor tasks, realized at the level of an individual's maximum capacities. If we accept that entropy tends to increase the variability of motion patterns, it turns out that sports performance has, by excellence, an antientropic character.

Keywords: Entropy, human performance, motor behaviour, ontogenesis

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1. Introduction

Movement, in its various forms of expression, is an important feature of living organisms. Starting with Brownian motion, molecular motion, cell motion, visceral motility, and vasomotor, and ending with somatic motion (as a form of maximum refinement and voluntary control), we can develop an entropic approach to human motricity. Cell motility, controlled by molecular mechanisms, is essential for a variety of biological processes, such as morphogenesis (development of living organisms), neurogenesis, tissue healing, development of immune phenomena, internal migration of cells, tumor proliferation and metastasis, etc. (Ananthakrishnan & Ehrlicher, 2007).

From another perspective, the fine and gross motor skills of the human body, provided by the striated (skeletal) muscles, are ensured through the highly specialized function of muscular contraction, fast, repetitive, and/or endurance, to cope with various mechanical loads, in energy efficiency (Lodish et al., 2000). From a physical point of view, the human body is an open biological system, in constant interaction with the environment, capable of adjusting the homeostasis (constancy) of the internal environment. Its neuroendocrine regulation systems allow it to adapt to different forms of stress, extrinsic or intrinsic, under the conditions of respecting the first two principles of thermodynamics.

In fact, the conservation of homeostasis, in the form of maintaining the parameters of the internal environment within certain limits of normality, is the purpose of achieving the stability of any biological system to which we refer. This stability, masterfully described by the concept of allostasis (Bienertová-Vašků et al., 2016), involves physiological changes that necessarily integrate different forms of movement.

2. Problem Statement

Entropy could be considered as a tool for assessing the organization and complexity of a biological system. Entropy is a thermodynamic concept describing the degree of order present in a system. This parameter is used for the informational analysis of the dynamics of that system. Basically, the maximum entropy corresponds to a maximum number of possible states, that is a high fractality (Siciliano, 2017). Entropy reflects the degree of molecular disorder, and for a biological system, the entropy is even smaller as the system has a rigorous control network, which allows it to maintain stability in time and space. In other words, the allostatic stability of a system is synonymous with the decrease in entropy, a situation that can only be achieved and maintained by energy consumption.

The processes that determine the increase of the complexity of a biological system, with a limitation of the variability of its functional parameters in time, determine the decrease of the entropy. Thus, from the perspective of the neo-Darwinian paradigm, and considering the formal computational side of entropy, the natural models of natural selection, adaptation, phylogenetic evolution, embryogenesis, ontogenesis, longevity, etc. can be explained (Cohen, 2016; Shcherbakov, 2005). Moreover, the aging of living organisms, associated with reduced functional performance, involves increased entropy with nonlinear dynamics, manifested by loss of molecular fidelity and decreased fractal complexity of repetitive tissue structures (Hayflick, 2007). Conversely, diminishing the negative forces of entropy allows for the survival, prolongation of life, adaptation, and improvement of the representatives

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of a species, by stimulating the processes and physiological mechanisms of cooperation, diversification, and programmed cell death (Cohen, 2016).

In the same context, it is important to mention Schrödinger's paradox, of the violation of the second principle of thermodynamics by living organisms, which tend to organize during the evolution of species and not to increase entropy. The Austrian scientist Erwin Schrödinger, the winner of the Nobel Prize in Physics in 1933, considered one of the fathers of quantum physics, was the promoter of the concept of species evolution, associated with the production of entropy. In his book "What is life?", the author describes the ability of living organisms to avoid degradation (decomposition) by maintaining thermodynamic equilibrium and homeostasis by negative entropy, a parameter equivalent today to information in open systems (Schrödinger, 1944).

According to the second principle of thermodynamics, the entropy of an isolated system can only increase. Instead, the increase in the level of organization of a biological system implies a decrease in its entropy, a situation that can only be offset by an increase in disorder outside it, mediated by the heat dissipation in the external environment. In other words, Schrödinger's paradox can be understood and solved by the open nature of living systems, which exchange energy and information with the environment (Bienertová-Vašků et al., 2016).

Currently, new informational theories of the evolution of biological systems have been developed, based on the classical principles of thermodynamics, but which refines the way of interpreting the dynamics of ecosystems, starting from innovative concepts such as genetic entropy, genetic fitness, gene competitiveness, genetic clustering, etc. (Frost & Moore, 2014; Skene, 2015). Entropy has been introduced in the field of information theory for the non-linear measurement of signal complexity (Cui et al., 2017). From this perspective, entropy is defined as a loss of information in time series of data or signals (Yentes et al., 2013).

For the analysis of data series, several physical quantities have been proposed, calculable by mathematical algorithms, to capture the regularity, repeatability, or predictability of successive events. These forms derived from entropy, with wide applicability in the field of experimental physiological explorations, have been called approximate entropy and sample entropy, respectively. The two forms of entropy are extracted from the data series, characterized by parameters such as the length of the data segment to be compared (m), the similarity (r), and the length of the data string (N) (Richman & Moorman, 2000).

The interpretation of these indicators is as follows: the longer a time series of data has a more pronounced repetitive and predictive pattern, the lower its entropy (Richman & Moorman, 2000). It has also been shown that sample entropy is more appropriate for the analysis of shorter data sets (Yentes et al., 2013). Multiscale entropy is another parameter that has been introduced relatively recently by Costa et al. (2005) for the analysis of biological signals. Most of the time, biosignals are multiscalar, depending on the scale at which they are examined and showing different behaviors (nonlinearity, sensitive dependence on small disturbances, extreme variations, non-stationary, etc.) (Costa et al., 2005).

Biological systems are representative examples of highly integrated systems, which operate in the form of multiple time scales (for example, neuroendocrine process cyclicity, sleep-wake circadian rhythm, reproductive cycles, bone remodeling, DNA sequence coding, etc.) (Costa et al., 2005; Gao et al.,

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2015). Hence the need to use a parameter built based on several simultaneous time scales (such as multiscale entropy) increases the fidelity of statistical interpretations.

In conclusion, entropy and its forms of expression are currently used to assess the complexity of various derived physiological signals, including endocrine secretions, muscle activity, isometric force results, heart and respiratory rhythms, static and dynamic posture, gait, extremity tremor, brain rhythms and so on (Morrison & Newell, 2012).

3. Research Questions

Knowing the relationship between entropy and the vitality of biological systems, we considered it interesting to carry out a theoretical introspection on the current knowledge about this issue. Expanding the notions of entropy in several related fields requires an extensive effort to document and create an informational synthesis.

4. Purpose of the Study

The purpose of this theoretical approach is represented by the identification and the study of some current and relevant bibliographic references about the applications of entropy in the field of kinesiology. Practically, we tried to carry out a meta-analysis of the most relevant knowledge about the complex connection between the energetics of the human biological system and different contexts of expression of its motricity.

5. Research Methods

As research methods, we applied bibliographic documentation, experimental observation, and interview with different specialists from several fields. Thus, we collected a series of theoretical information that was systematized for the completion of the meta-analysis.

6. Findings

6.1. Movement in the human body during ontogenesis as a premise for achieving allostasis and reduced entropy

Human motricity comprises the totality of effector actions and behaviors, oriented to achieve a given goal, based on the realization in an extremely diverse way of muscle contractions of various striated muscle groups. Regarding human motricity, entropy can be used to quantify the degree of complexity of movements (Yentes et al., 2013). The motor adaptation of the human body can be characterized as a process of conservation of energy and entropy, which involves the compensation of the entropy between the load, the body (motor effector result), and the environment. Thus, at least in the case of fine finger motricity, for the coordination of submaximal isometric contractions, in healthy young people, relations of correspondence have been demonstrated between approximate entropy, motor load complexity, and environmental feedback (Hong & Newell, 2008a).

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Basically, the lower the probability of achieving the goals of motor load (which increases the entropy of the load), and/or the lower the degree of environmental information (that increases the entropy of the environment), the fewer patents of coordination the subject will use, which develops an adequate force to achieve the objectives of the movements (Hong & Newell, 2008b). In other words, under the conditions mentioned above, the strategies of developing the muscular force necessary for the accomplishment of the motor load, with increasing complexity, will determine the appearance of a more regular contractile pattern, and the approximate entropy of the data series time/muscular force will decrease (Hong & Newell, 2008a).

Obviously, the human being is able to automate simple movements and increase his level of efficiency, while complex motor tasks involve increasing the risk of entropic disorganization of the functionality of the neuro-myo-arthro-kinetic system. However, motor performance is possible and accessible, especially in terms of stimulating the flow of information to the environment, which involves reducing the entropy of the system, and will improve the way of performing the proposed effector tasks. The variability of human motor performance is reflected in the nonlinear manner in which individual abilities and movement characteristics vary over time. In addition, the redundancy of the neuromotor system implies a wide possibility of using multiple strategies to perform a given task (Harbourne & Stergiou, 2009).

A remarkable applicability of approximate entropy has been highlighted in electromyography studies to interpret the dynamics of electrical signals in the context of muscle fatigue (Xie et al., 2010). For example, surface electromyography has been demonstrated that entropy decreases over time through isometric contractions that induce muscle fatigue (Cui et al., 2017). An interesting ontogenetic approach to the entropy of movement allows the analysis of the main levels of change in motor behavior, by reference to the stages of growth and development of the human body.

Throughout each stage of evolution, the human body achieves an optimal level of variability for functional movements, and deviations from these patterns involve errors, disruption of adaptability, stiffening and/or loss of movement accuracy, and finally, destructuration of motor acts, which induces the instability of the motor system and the body as a unit of integration. A relevant example of the applicability of entropy to the child's motor acquisitions is that of the dynamics of improving postural control. Thus, the young child gradually acquires the ability to maintain static postural balance, which is reflected in the progressive reduction over time of approximate entropy, by developing a repetitive pattern of movement of the center of gravity of the body (Stergiou & Decker, 2011).

From a metabolic point of view, muscle contractile activity will reach maximum energy efficiency in the young adult stage, when less entropy is generated in the muscles activated during physical exertion, heat dissipation being also minimal (Çatak et al., 2017). As for the later ontogenetic stages, after reaching the maturity of the human body, the explanations are even more attractive. Basically, the aging process causes the gradual loss of the complexity of the neuromuscular system, which is reflected at various levels, for example at the level of gait entropy. Thus, the pattern of muscle activation while walking, highlighted by electromyographic traces, is more complex in adults than in the elderly, especially in the case of fast walking. In contrast, slower walking, with less frequent steps, allows the elderly to optimize

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their neuromuscular function, while maintaining a low level of entropy, despite the multisystem decline induced by the aging process (Kang & Dingwell, 2016).

Also, for other muscle groups, changes in the activation processes of the motor units during aging have been highlighted. For example, according to recent studies, there are significant differences between young and elderly adults in the coordination of agonist and antagonist muscles during voluntary isometric contractions of forearm flexion-extension, emphasized by the study of the entropy of surface electromyographic signals (Sun et al., 2016). Experimental studies have also shown that aging-induced neuromotor functional decline, more evident in complex motor tasks, can be offset by intrinsic adaptive strategies (reorganization of muscle coordination patterns, synchronization, recruitment of motor units, gradation of muscle strength, adjustment of sensory-sensory inputs, etc.) or extrinsic (load modification depending on constraints) (Morrison & Newell, 2012; Vernooij et al., 2016).

The decline in the functional capacity of the elderly, easily identifiable in terms of motor function, was also interpreted from an entropic perspective, thus issuing the hypothesis of loss of complexity. This hypothesis allows the application of fractals and chaos theory to explain senescence (Lipsitz & Goldberger, 1992), in the case of motricity suggesting a progressive reduction in the ability of muscles to respond to work tasks. Clearly, although there is a common pattern of aging in the human body, there are inter-individual differences in the pace of this process, which involves varying degrees of impaired motor performance in daily physical activity (Morrison & Newell, 2012).

It becomes obvious that any pathology added to orthogonal aging can negatively influence the motor skills and performance of the elderly, a situation that can be objectified by increasing entropy, under its various forms of manifestation (reduced regularity, predictability and complexity of motor acts). To conclude this discussion, we return to the metabolic-energetic interpretation of physical exertion. If we accept the hypothesis that aging involves the accumulation of entropy in the human body, then we understand why muscle performance will gradually decrease with age, ultimately resulting in reduced energy generation due to mitochondrial oxidative processes.

At high energy loads of physical exertion, the generation of muscle entropy will increase (Çatak et al., 2017), and structural and/or functional damage to the striated muscle fiber may occur. This is reflected in the elderly's lower tolerance for sustained physical exertion, as well as in the risk of developing early muscle fatigue and a traumatic pathology or wear and tear of the musculoskeletal system. The constant attempt to reach the stage of allostasis, that is the stability of the human body, involves adaptive mechanisms which, over time, can affect cellular structures, especially in the myo-arthro-kinetic system. Thus, the price of adaptation can be paid in terms of wear against the background of chronic allostatic loading (Seeman et al., 1997), the boundary between normal and pathological being often easy to overcome in these conditions.

6.2. Analysis of sports performance from an entropic perspective

Sports performance involves optimal mechanical and energetic processes, which support various complex motor tasks, performed at the level of the maximum abilities of an individual. The complexity of these motor acts, which end up being performed at a performance level, necessarily involves ensuring the stability in time and space of the inherent movements. If we accept that entropy tends to increase the

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variability of movement patterns, it follows that sports performance has an anti-entropic character by excellence. Moreover, many researchers interpret the variability in the field of application of sports science as a factor that forces the athlete to adapt and stabilize his actions in relation to the constraints of the tasks to be performed (Couceiro et al., 2013; Couceiro, Clemente, Dias et al., 2014).

Most sports involve events with nonlinear properties. Therefore, the analysis of various branches of sport from the perspective of entropy has emerged as a modern direction of research, generating new horizons of knowledge. For example, performance-specific swimming tests can be analyzed and classified separately according to the complexity of repetitive motion cycles, velocity fluctuations, and movement fractality (Barbosa et al., 2016).

The evaluation of the entropy in the performance sport can bring very useful information regarding the sports selection procedures, the level of preparation of the athlete, the quality of the sports training, the prediction of the results, etc. In this regard, it has been shown that measuring entropy in team sports by mathematical algorithms can help determine the spatial distribution of players on the field, the group behavior of athletes (synchronization, dispersion, interaction, etc.) and the level of individual performance, in relation to the reference group (Silva et al., 2016). A study of this type, conducted for the computational analysis of individual and collective performance in the game of football, allowed, based on entropy measurements, to describe the predictability of the evolution of players depending on specific roles on the field. Thus, according to the reported results, the most predictable player is the goalkeeper, and the least predictable are the midfielders. At the same time, the maximum stability in the game characterizes the lateral defenders, and the minimum one belongs to the goalkeeper (Couceiro, Clemente, Martins et al., 2014).

During sports activities, rigorous control of movements is imperative, any random movement can affect the performance of the imposed task, a situation that can be highlighted by the computational analysis of entropy. In this regard, a study by Lee and Sun (2015) on the variation of multiscalar entropy during exercise with multimedia support (exergames), static and dynamic, for balance training, showed that maintaining posture involves different adaptability of the subjects depending on the complexity of the tasks. Basically, in the case of games involving the adoption of static postures, postural variability depends on the complexity of the balance movements in the frontal and sagittal plane, and in the case of games based on dynamic postures, an important role is played by the speed of leg elevation (Lee & Sun, 2015). In fact, in any case, to maintain postural stability, a good sensor-motor synchronization is necessary, as evidenced by the balance disorders that occur in various sensory pathologies or during the aging process (Busa & van Emmerik, 2016).

In sports that involve a focus on postural control, in the context of complex effector tasks, entropy variations are even more relevant. For example, in the case of biathlon events, the static resting position of elite athletes involves an increase in entropy, and targeting and maintaining the shooting position causes a decrease in entropy (Juras et al., 2016). Another important feature of the relationship between entropy and repetitive movements, found in many sports branches, is the correlation between the regularity of fluctuations in muscle electrical signals (which characterize the activity of recruited motor units) and the intensity of effort. For instance, in the case of cycling, self-correcting neuro-muscular strategies make the short-term fluctuations in registered electromyographic signals in the muscles of the

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lower limbs to record a more stable pattern of variation when the ergometric load increases, as confirmed by analysis of sample entropy dynamics (Enders et al., 2015).

For the most part, sports performance involves decreasing entropy. However, the explanations can be refined depending on the contextual factors, in the sense that we can identify inherent situations, with limited duration, in which increased entropy can circumscribe the evolution of a performer athlete (Davids et al., 2014). Another exemplary case in which low entropy distinguishes performance from non-performance is that of mountaineering. Thus, the minimum values of entropy imply the choice of the most regular climbing trajectory, which is also reflected in the spatial indicators of climbing fluency (Orth et al., 2017). Conversely, the increase in entropy occurs particularly when the athlete has reduced skills in relation to the difficulty of the chosen route or when he temporarily encounters more difficult motor tasks (Guadagnoli & Lee, 2004).

New perspectives on interpreting the variability of motor behavior regarding sports performance have led researchers in the field to reconsider the definitions and traditional methods of linear analysis of motricity. Thus, through the use of analytical techniques for the evaluation of entropy, through the mathematical modeling of nonlinear parameters, it has become possible to direct the interest in elite sport towards new development directions, such as: promoting variability during learning and training, promoting differences in between athletes, focusing on the development of postural control, etc. (Komar et al., 2015).

7. Conclusions

The human body, as an open biological system, through its differentiated capacity to move at different levels of the organization, respects the thermodynamic principles that support the functioning, conservation, and evolution of all living organisms. Human motricity is a dynamic and complex nonlinear process, involving the coordination of multiple allostatic regulation mechanisms, which aim to direct the operability of systemic functions towards minimum energy consumption and maximum of efficiency. The study of the variation of the entropy of the human body during movement has become a field of maximum interest in the last decade, as a result of the intensive development of computational modelling. The area of application of the study of entropy in human motricity is currently expanding, covering the field of medical rehabilitation, sports science, geriatrics and gerontology, robotics, and mechatronics.

The complexity of human movements, defined as the ability to use different strategies to perform a given task, undergoes progressive changes during ontogenesis, reaching an entropic maximum in the stage of adulthood (Bisi & Stagni, 2018). In terms of sports performance, we are still at the beginning of the research, remaining a vast and attractive field of study of the behavior of the human body in various types of demands imposed by the practice of sport. In any case, in this field as well, the organization of dynamic movements and positions appears as a fractal process, which can be quantified through the various physical quantities of entropy.

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