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Mathematical and Statistical Concepts Applied to Health and Motor Control

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Abstract Variability and complexity are characteristic of human motor behavior. Research concerning movement patterns generation is a subject of interest shared by different areas like sports, health, or neurosciences. Among other motor abilities, postural control or gait, are abilities studied in normal and disabled subjects of different ages, using different types of methodologies and analytical approaches, including linear and nonlinear models. Nevertheless, depending on what we are looking for, these approaches can be more or less accurate for our purposes. Humans as biological systems, must be analyzed in a dynamical way, employing specific tools. The knowledge of the information given by these tools can be very helpful in medical research allowing the clinicians to identify and differentiate specific motor manifestations, like tremor, or postural instability, that are common to different pathologies, or even different levels of severity, like in Parkinson's Disease.

Keywords Motor Control · Movement dynamics · Variability and complexity · Parkinson's Disease

The research related with movement patterns generation, concerning sports and health, psychology, or neuroscience, uses concepts and methodologies related to the analysis of variability and complexity in human motor behavior. This type of approach includes mathematical models, as well as non linear tools, to explain movement dynamics. Several studies have been conducted in order to analyze motor behavior of different populations (normal subjects, PD patients, athletes, etc.), performing different tasks, such as postural control or gait tasks, in different conditions (with or without vision, with stable or unstable area of support, etc.).

Many clinicians specialized in medical research and clinical evaluation use linear models for prediction and intervention. However, it is very clear that linear models are considered limited in many cases and, in some specific cases, they are not the optimal approach [4].

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The term linear can be associated to only one dimension. Linear tools measuring variability give information about the quality, but not about the time-evolving dimension of the signal. These tools, including the statistics of range, mean, standard deviation, and coefficient of variation, while providing correct descriptions of inherent variability, are not helpful in explaining what is actually happening or varying within a system. They are incomplete in their justification about human movement variability. Mean values eliminate movement temporal variation and cover the correct composition of variability present in the movement action. The observed variations between the repetitions of a task are, usually, considered random and independent of past and future repetitions, which have been shown to be false. Perturbations to a dynamic system may lead to different patterns of macroscopic order that are not predictable by traditional methods [3].

The term nonlinear, in association with the term dynamics – *nonlinear dynamics*, can be associated to a system relating multiple dimensions, whose output is not proportional to its input. Nonlinear systems are related with the production of unpredictable responses revealing chaotic characteristics. Humans, as biological systems, are, generally, good examples of complex nonlinear systems, showing a great amount of inherent variability, in space and time, in their behaviors.

This variability, attested by differences in the observed behavior, when performing multiple repetitions of a task, reflects the numerous solutions available, traduced by the different adopted strategies. This plasticity, contrasting with the idea of an inflexible programming process, is guaranteed by the multiple complex synergies related to the neuromuscular system.

The idea of an optimal variability, associated to a characteristic movement behavior, is essential in a nonlinear perspective. For the Dynamical Systems Theory (DST) the increased variability in a system is related to an increasing instability which may indicate a possible change to another behavior. A biological system presenting no variability corresponds to an inert organism associated to a non dynamic condition. This invariance in movement behavior, must conduct to an atypical mapping of the sensory-motor homunculus, resulting in a disturbed motor function, usually related with more primitive behaviors, characterizing less complex systems.

The concept of optimal movement variability can be associated to a system whose dynamics lie between great variability and complete repeatability. Considering the great inventory of human motor actions, and more specifically gait as an example of a cyclic task, the different steps produced when walking cannot be consider either random or totally repeatable, showing instead a normal and healthy variability that can be considered optimal (within certain limits).

The problem of quantifying exactly the amount of optimal (normal) variability that a system should present, can be related to the identification and understanding of movement dynamic patterns.

1 Postural Tasks

Many studies tried to understand the strategies used by the postural control system to maintain the complex multi-degrees-of-freedom process controlled by the musculoskeletal system, in equilibrium with external forces, during quiet standing, or during the execution of an action.

The competence of maintaining an upright posture implies the use of a complex sensory-motor control system. We cannot adopt an upright position without producing a sway associated to an oscillation of the Center of Gravity (COG) or of the Centre of Pressure (COP). The analysis of the time-varying coordinates of the centre of pressure, known as a stabilogram, can show two types of control: a) a more reflexive closed-loop control in response to external perturbations; b) a more stabilizing open-loop control during longer periods of undisturbed stance. Earlier studies limited the analysis of these time series plots to statistics concerning the calculation of the length of the sway path, concerning both antero-posterior and medio-lateral directions, the average sway amplitude and radial area, ignoring the dynamic characteristics of the stabilograms (magnitude and direction of the COP displacements, the temporal ordering of COP time series coordinates, etc.). Mathematical techniques, employing non linear analysis, like stabilogram-diffusion analysis, recurrence quantitative analysis (RQA), can be applied to the study and interpretation of stabilograms, conducting to the extraction of repeatable, physiologically meaningful parameters.

The **Lyapunov Exponent(LyE)**, is a measure that quantifies the level of separation, or divergence with time, of nearby trajectories, in the state space. This separation of nearby trajectories is usually associated to instability, which can be characterized by Lyapunov Exponent, meaning that the higher the instability (divergence) of a system, the larger the value of the LyE.

The **Entropy** is a primary mathematical concept, firstly presented in information theory, representing a measure of the variability of a system. On the other hand, approximate entropy (ApEn) is a specific process to determine complexity, which quantifies the regularity or predictability of a time-series [8, 10]. Approximate entropy quantifies the probability that a series of data points, a certain distance apart, within a state space, will show comparable characteristics on the next incremental comparison [8, 9]. Time series presenting a greater probability of lasting the same distance apart upon comparison, will correspond to lower ApEn values, while time series presenting large differences in distances between data points will correspond to higher values of ApEn. In other words a more regular and predictable time-series is less complex than a less regular and predictable one.

2 Application in Medical Sciences and Research

The ApEn has been used in several medical settings during the last decade. It has been used to study different aspects like the effect of aging on cardiovascular dynamics [5], differences in heart rate control in normal and sudden infant death syndrome

Table 1 Analysis of the joint angular time series data from one PD patient and one healthy age-matched control subject during treadmill walking, using different non linear parameters. (Adapted from [[1], p. 39–43])

	LyE		ApEn		CoD	
	Control	Parkinson	Control	Parkinson	Control	Parkinson
Hip	0,117	0,102	0,314	0,278	2,012	2,015
Knee	0,166	0,191	0,353	0,505	3,151	3,441
Ankle	0,188	0,195	0,337	0,446	3,246	3,673

[11], or the effect of gender in growth hormone secretion [12]. Studies on the effect of aging on cardiovascular dynamics generally showed a good correlation between sickness and aging, and decreased ApEn values. These findings are in agreement with the general hypothesis advanced in the medical sciences that atypical physiological behavior can be related with more regularity, while normal physiological behavior is related with less regularity (great complexity) [9].

Some researchers have also used ApEn to characterize human movement. In such studies, learning and behavior reorganization are associated with changes in complexity [7, 15]. Morrison and Newell [6] used ApEn to analyze the level of active control during limb motion. In particular, they observed that the lower the ApEn value, the more active the control at the particular segment analyzed.

Different human movement studies have also used the ApEn measure with pathological populations. Vaillancourt and Newell [15] examined the complexity of resting and postural tremor in Parkinson's patients using finger accelerometer signals.

Buzzi [1] in his laboratory attempted to understand differences in locomotor variability of Parkinson's disease patients. The author examined the angular displacements of the lower limb joint for regularity changes in PD, during treadmill walking, at the off cycle of their dopamine treatment (Fig. 1).

The results reported in Table 1, concerning LyE and ApEn, showed that the knee and the ankle of both subjects presented more complexity than the hip, attested by higher values for these two joints, and also that the Parkinson's subject presented even more complexity in the time series than the control subject. An interesting observation was that the Parkinson's subject presented lower values for the hip joint. This finding possibly demonstrates an adaptation at the hip for the Parkinson's subject to compensate for the increased complexity and local stability at the more distal joints. The author suggested that a possible explanation for these results is a loss of independent sources of control due to the pathology.

However, statistical analysis didn't show significant differences in the LyE and ApEn values between PD patient and the control (Fig. 1). Nevertheless, the results showed a decreasing regularity from distal to proximal joints. More studies are needed in order to understand Parkinson's disease motor behavior.

Schmit et al. [13], in a study concerning sport activities, compared the spatiotemporal profile of postural sway, of trained ballet dancers and track athletes, during four different balance conditions (standing on a stable, or unstable surface, with the eyes open, or closed). Linear analysis of the results did not present significant differences between both groups during the normal vision condition, but presented increased variability in both groups during closed eyes condition and on a foam surface.

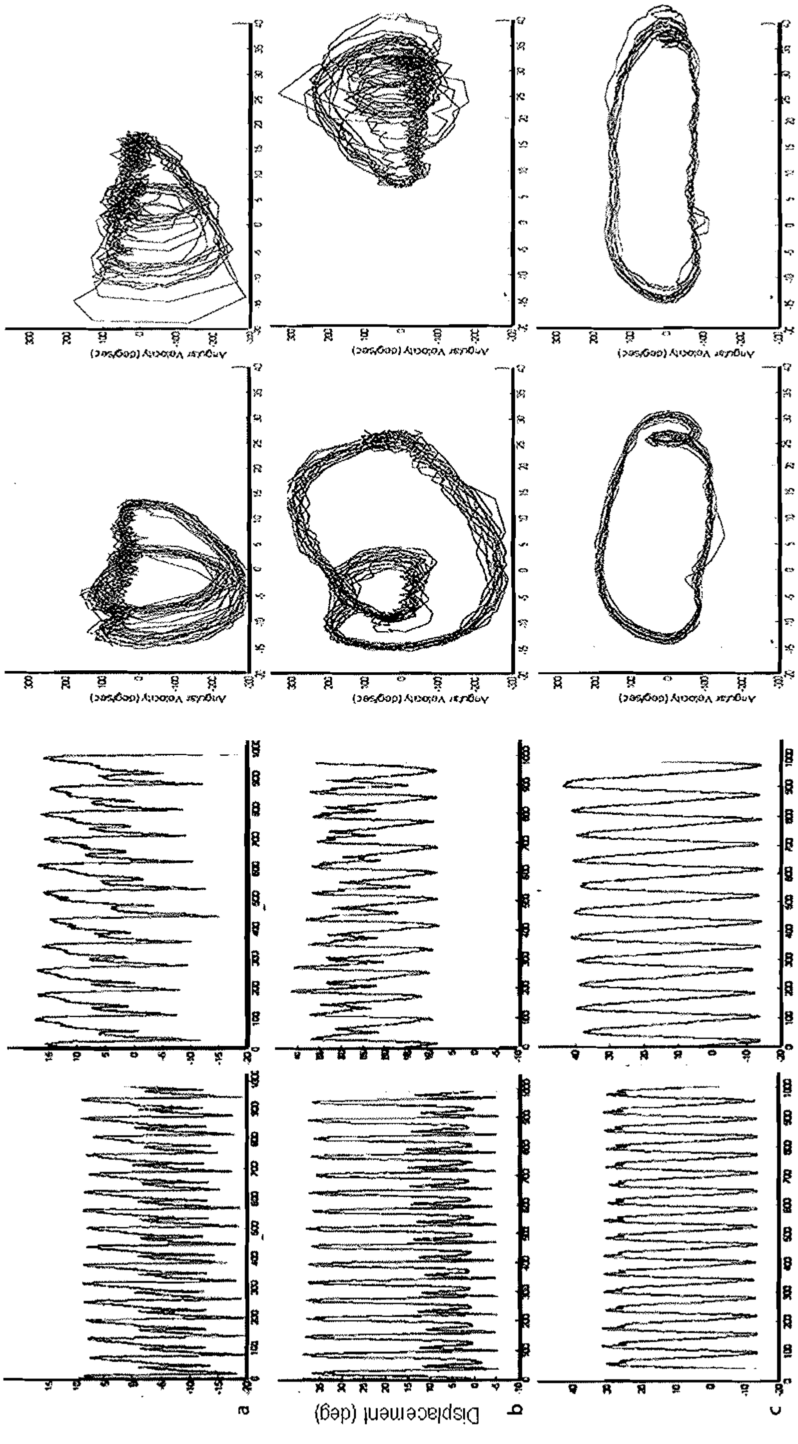

Fig. 1 Time series data (*left*) and phase plane plots (*right*) from different joints **a** ankle, **b** knee, and **c** hip) of one control (*right*) and one Parkinson's disease subject (*left*) when walking on a treadmill. (Adapted from [14])

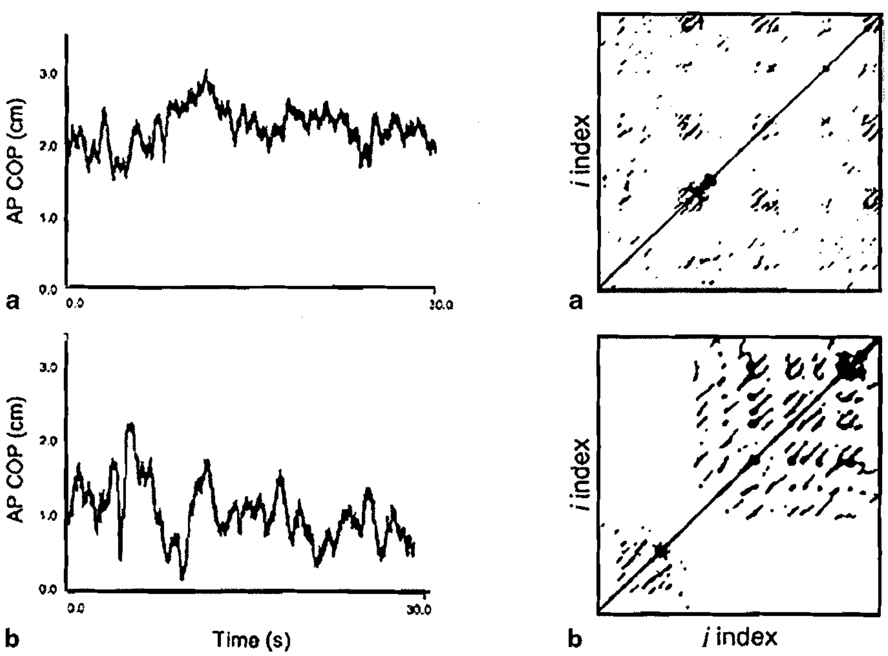

Fig. 2 Centre of Pressure (*COP*) time series in the anterior/posterior (*AP*) axis (*left*) and Recurrence Plots (*right*) of the data of *COP* time series of a dancer (**a**), and a track athlete (**b**). (Adapted from [13])

Non linear analysis (Fig. 2), and more specifically recurrence quantification analysis of the data, of both groups, revealed significant differences in postural sway. The postural sway of the dancers was less regular (lower recurrence), less sTable(lower maxline), less complex (lower entropy), and more stationary (lower absolute trend) than that of track athletes. Dancers, possibly as a result of focused balance training, exhibited different dynamic patterns of postural sway.

There are numerous oscillatory phenomena in motor control that occur regularly or irregularly, both in health and disease processes. These behaviors are clinically evaluated, during specific sessions. The observation of motor function time series presenting an irregular behavior, like tremor (Fig. 3), does not allow a clinician to infer, by visual inspection, whether the underlying process should be characterized as a deterministic (regular) or a stochastic (irregular) process.

Outcome assessment has become important in evaluating upper limb extremities in patients suffering from movement disorders. Nevertheless, some of the instruments used in clinical evaluation are quite generic, measuring grip strength, and range of motion, but are not able to evaluate daily life activities.

More instruments and methodologies of analysis are needed in order to accurately and objectively characterize patients' data during clinic evaluation sessions. Nonlinear analysis seems to provide promising methods to help diagnose and intervention in clinical settings.

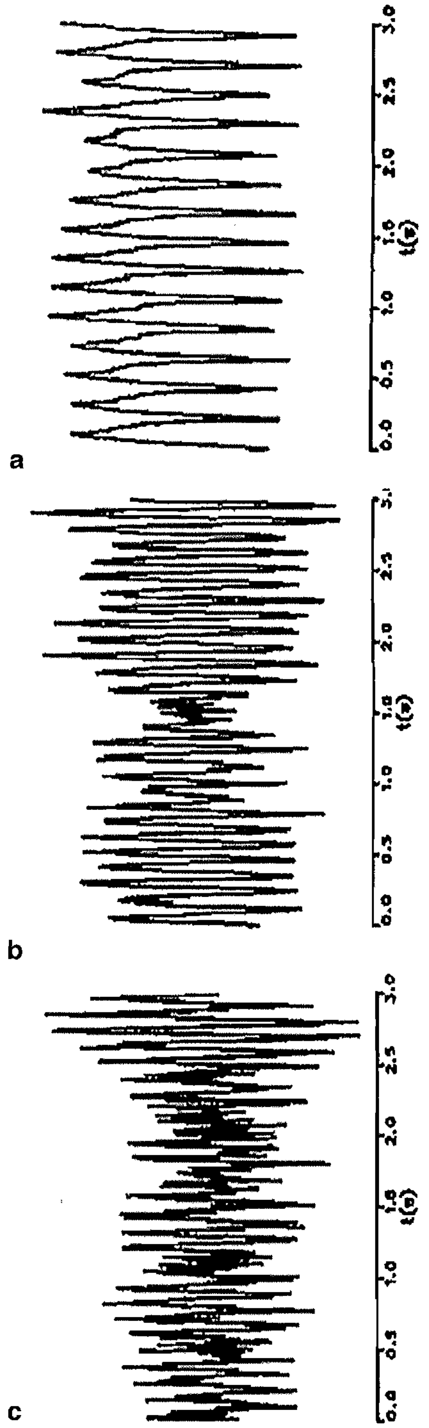

Fig. 3 Data concerning physiological (a), essential (b), and Parkinsonian (c) hand tremors. (Adapted from [2])

References

1. Buzzi UH (2001) An investigation into the dynamics of Parkinsonian gait. MS thesis, University of Nebraska at Omaha
2. Gantert C, Honerkamp J, Timmer J (1992) Analyzing the dynamics of hand tremor time series. Biol Cybern 66:479–484
3. Goldberger AL, West BJ (1987) Applications of nonlinear dynamics in clinical cardiology. Ann N Y Acad Sci 504:195–213
4. Habourne R, Stergiou N (2009) Movement variability and the use of nonlinear tools: principles to guide physical therapist practice. Phys Ther 89(3):267–282
5. Kaplan DT, Furman MI, Pincus SM, Ryan SM, Lipsitz LA, Goldberger AL (1991) Aging and the complexity of cardiovascular dynamics. Biophys J 59:945–949
6. Morrison S, Newell KM (1996) Inter- and intra-limb coordination in arm tremor. Exp Brain Res 110(3):455–464
7. Newell KM (1997) Degrees of freedom and the development of posture center of pressure profiles. In: Newell KM, Molenaar PCM (eds) Applications of nonlinear dynamics to developmental process modeling. Erlbaum, Mahwah
8. Pincus SM (1991) Approximate entropy as a measure of system complexity. Proc Natl Acad Sci USA 88:2297–2301
9. Pincus SM, Goldberger AL (1994) Physiological time-series analysis: what does regularity quantify? Am J Physiol 266:H1643–1656
10. Pincus SM, Gladstone IM, Ehrenkranz RA (1991) A regularity statistic for medical data analysis. J Clin Monit 7(4):335–345
11. Pincus SM, Cummins TR, Haddad GG (1993) Heart rate control in normal and aborted-SIDS Infants. Am J Physiol 264:R638–646
12. Pincus SM, Gevers EF, Robinson ICAF, Van der Berg G, Roelfsema F, Hartman ML, Veldhuis JD (1996) Females secrete growth hormone with more process irregularity than males in both humans and rats. Am J Physiol 270:E107–115
13. Schmit JM, Regis DI, Rilley MA (2005) Dynamic patterns of postural sway in ballet dancers and track athletes. Exp Brain Res 163(3):370–378
14. Stergiou N (2004) Innovative analysis of human movement. Analytical tools for human movement research. Human Kinetics, Champaign
15. Vaillancourt DE, Newell KM (2000) The dynamics of resting and postural tremor in Parkinson's disease. Clin Neurophysiol 111(11):2046–2056