FRACTAL DIMENSION AND HUMAN AQUATIC LOCOMOTION

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The aim was to investigate the fractal properties of human swimming and analyze its relationship with swimming kinematics. Eighty-two male swimmers from the local level up to World-ranked athletes undertook a set of 3x25m maximal trials at Front-Crawl. Fractal dimension (D) was calculated from the speed-time series collected with a speedo-meter. It was also calculated the speed fluctuation as an energy cost estimator. Human swimming showed fractal properties ($1 \leq D \leq 2$). The relationship between D and dv was very high analyzed in absolute values (R^2=0.88; s=0.18; p<0.001) and Z-scores (R^2=0.88; s=0.34; p<0.001). It can be concluded that human swimming shows fractal characteristics, though with lower values than gait. Energy cost of swimming increases with the complexity of the swimming patterns.

KEY WORDS: swimming, nonlinear parameters, Higuchi's method, speed fluctuation.

INTRODUCTION: Swimming is a periodically accelerated motion. The swimmer is animated of an intra-cyclic variation of the horizontal velocity, also known as “speed fluctuation”. There is a solid body of knowledge describing speed fluctuation in human swimming (Barbosa et al., 2010). Energy cost of swimming increases with the speed fluctuation (Barbosa et al., 2005). So the kinematic variable can also be selected as an efficiency estimator.
Swimming patterns (as speed fluctuation) are complex and cannot be fully characterized only with classical kinematics. It seems that swimming exhibits nonlinear properties, such as (Neumeister et al., 2004): (i) persistence (i.e. the tendency to repeat a given sequence); (ii) redundancy (i.e. the relationship between the uncertainty of a signal and its length) and; (iii) scale invariance (i.e. the tendency for a signal to have the same structure when observed on different temporal or spatial scales). Therefore, human swimming is probably a nonlinear behavior, at least under these criteria. To understand this nonlinear variability, new parameters including fractal dimension (D) can be useful (Bravi et al., 2011).
Fractal analysis is based on the unconventional views of scaling and dimension. It has been applied to study a wide range of bodies/systems in Biology and Medicine but never before in human swimming. Data-time raw is analyzed as a fractal landscape. If D=0, there are 0-dimensional sets, D=1, there is 1-dimensional sets (i.e. length only, straight line), D=2, there are 2-dimensional sets (i.e., length x width, surface), D=3, there are 3-dimensional sets (i.e., length x width x height, volume). Applying this to human swimming, a uniform motion is expected to be D=1.0 and as speed fluctuation increases, D should likewise increase. Nevertheless, the fractal properties of human swimming remain to be studied.
The aim was to investigate the fractal properties of human swimming and analyze its relationship with swimming kinematics. It was hypothesize that human swimming will be between $1<D<2$ and show a relationship with the speed-fluctuation.

METHODS: Eighty-two male swimmers with different competitive levels (from the local level all the way up to World-ranked athletes and at least 4-y of experience) undertook a set of 3x25m maximal trials at Front-Crawl stroke with push-off starts.
A speedo-meter cable (Swim speedo-meter, Swimsportec, Hildesheim, Germany) was attached to the subjects’ hip (*f*=50Hz). Data was exported to a signal processing software (AcqKnowledge v.3.5, Biopac Systems, Santa Barbara, USA) and filtered with a 5Hz cut-off

low-pass 4th order Butterworth. Fractal dimension (D) was calculated with the Higuchi's method from the speed-time sets (Higushi, 1988). D is an index to characterize fractal patterns or sets and quantify their complexity as a ratio of the change in detail to the change in scale. Speed fluctuation (dv) was selected as kinematical parameter and is considered a swimming efficiency estimator (Barbosa et al., 2005; 2010).
The relationship between swimming kinematics and fractal characteristics was conducted in absolute values and standardized Z-scores. Simple linear regression models between dv and D were computed. As a rule of thumb, for qualitative interpretation of the effect size, it was defined that the relationship was: (i) very weak if $R^2<0.04$; (ii) weak if $0.04 \le R^2<0.16$; (iii) moderate if $0.16 \le R^2<0.49$; (iv) high if $0.49 \le R^2<0.81$ and; (v) very high if $0.81 \le R^2<1.0$. It was also computed the standard error of estimation (s) and the confidence interval for 95% of the trend line. Bland-Altman analyses were selected to assess the bias±1SD, as well as, the 95% confidence interval for the relationship between dv and D.

RESULTS: The relationship between D and dv was very high when analyzed in absolute values ($R=0.94$; $R^2=0.88$; $R^2_a=0.88$; $s=0.18$; $p<0.001$) and Z-scores ($R=0.94$; $R^2=0.88$; $R^2_a=0.88$; $s=0.34$; $p<0.001$) (fig 1). When compared in absolute values the bias was -0.944±0.033 (-0.87;-1.01 for a 95%CI) and $-2.4 \cdot 10^{-7} \pm 0.350$ (-0.701; 0.701 for a 95% CI) in Z-scores (fig 1).

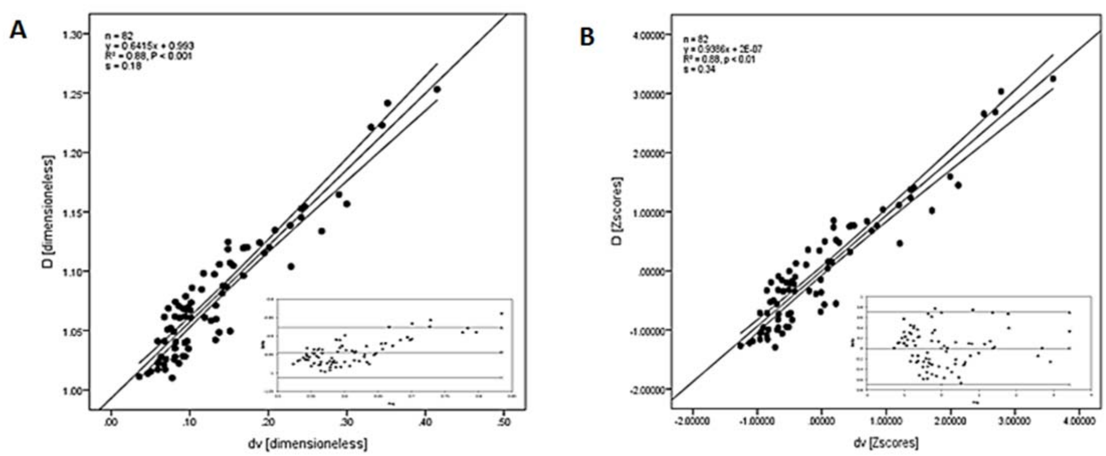

Figure 1: The relationship between speed fluctuation (dv) and fractal dimension (D) for human swimming in absolute units (panel A) and Z-scores (panel B).

DISCUSSION: A large sample size of eighty-two subjects from fair (those competing at local events) to very high competitive level (Olympic swimmers) enables to have a deeper understanding on the fractal characteristics of human swimming.
The dv data is within to what is reported on regular basis in the literature (Barbosa et al., 2010; 2013). Human swimming showed fractal properties ($1 \le D \le 2$) suggesting that this is a locomotion technique with the same characteristics as fish swimming and human gait. Gold fish was reported as having D~1.62 ($1.29<D<1.74$) (Neumeister et al., 2004) and human gait on land ($1.12<D<1.43$) (Schiffman et al., 2009). The D is lower than the average values found in the literature for human gait on land though (Schiffman et al., 2009). This might be due to the lower range of speeds reached swimming in comparison to walking, running or sprinting. But further comparisons between human locomotion techniques and between species should be carried out to have a better understanding on such mechanisms.
There was a very high relationship between D and dv (fig. 1). The dv is considered as a swimming efficiency estimator. It was reported that energy cost would increase with speed fluctuation (Barbosa et al., 2005). Therefore, a higher level of complexity in the swimming pattern (i.e. higher D) was related to a higher energy cost (i.e. speed fluctuation). There is

the need to have a better understanding of these fractal parameters in the near future. For instance: (i) compare the fractal characteristics among different strokes (e.g., front-crawl, backstroke, breaststroke, butterfly stroke and other unconventional strokes); (ii) compare the fractal characteristics between different cohort groups (e.g., based on expertise level and/or gender); (iii) the changes on the fractal characteristics with fatigue; (iv) the relationship between fractal characteristics and physiological, neuromuscular or other motor control variables.

CONCLUSION: It can be concluded that human swimming shows fractal characteristics, though with lower values than gait. Energy cost of swimming increases with the complexity of the swimming patterns. Hence, fractal characteristics should be considering a very promising approach to be included in further studies on human swimming.

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